Cooling Down the U.S. With Maximum Heat Pump Adoption

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Acknowledgements

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Table of Contents

List of Tables

List of Figures

Executive Summary

A Study with a Purpose

Communities in the United States (U.S.) will face pressing challenges as global temperatures rise. Demand for cooling technologies is expected to increase across much of the nation, including in temperate and cold climate zones. What can be done to ensure that cooling is widely accessible while reducing greenhouse (GHG) emissions to address climate change?

This report provides insights to inform policy and program design in the U.S. to equitably reduce emissions through the expanded adoption of heat pumps for both cooling and heating needs. By motivating stakeholders and supporting actions across a broad range of institutions and market actors — policy and equity advocates, regulators, the philanthropic community, utilities, program administrators, equipment installers, appliance manufacturers and more — we can establish effective pathways towards a sustainable future.

The research presented here quantifies the anticipated building thermal-related emissions for eight northern U.S. climate zones out to the year 2050 for eight residential and commercial building prototypes, assuming weather changes and no interventions. Potential GHG emissions mitigation strategies are evaluated in a subset of four prototypes using the vast majority of energy, with a primary focus on air-source heat pumps (including variable-speed and variable-refrigerant-flow systems) as well as weatherization, lighting efficiency, plug load controls and a range of refrigerant solutions. These technologies offer significant emissions reductions when compared to stand-alone air conditioners and furnaces, and when combined with near-clean, renewable grids, we estimate a best-case scenario of 94.5% reduction in GHG emissions below business-as-usual (BAU) conditions by 2050.

Context for Action

The U.S. has one of the highest rates of air-conditioning in the world, using nearly 392 terawatt-hours annually (EIA 2021), nearly equivalent to electricity use of California and New York combined. In March 2020, the Energy Information Administration (EIA) projections for 2050 pointed to air-conditioning as the end use with the largest projected increases in energy use.

Notably, air-conditioning demand at present is significantly lower for households in the eight northern climate zones focused on in this report compared to the U.S. average, suggesting this number will continue to increase as temperatures warm (EIA 2019). However, in BAU conditions aggregate increasing temperatures will alter both cooling and heating activity, leaving GHG emissions from the built environment almost unchanged, an insufficient reality for meeting global emissions targets.

Currently, centralized heating, ventilation, and air-conditioning (HVAC) equipment is prevalent in residences, especially in single family homes. Window and wall units are common in multi-unit buildings. In commercial buildings, packaged units are dominant for both air-conditioning and heating.

Heat pumps are commercially available products for providing efficient cooling and heating using electricity. Due to their efficiency and use of increasingly clean electricity instead of fossil fuel-based heating and electric-resistance heating, they cause dramatically lower GHG emissions even with the increased use of refrigerants. Heat pumps range in types, efficiencies, and sizes. For this report, we examined air-source heat pumps: single-speed and variable-speed (also known as variable-capacity or inverter-driven) determined by the compressor speed, and variable-refrigerant-flow (VRF) systems. The “variable” technology responds to cooling and heating demands more efficiently and improves occupancy comfort compared to conventional single-speed furnaces and heat pumps.

Figure 1 provides a promising snapshot of heat pump adoption in the U.S., illuminating that there is significant traction.

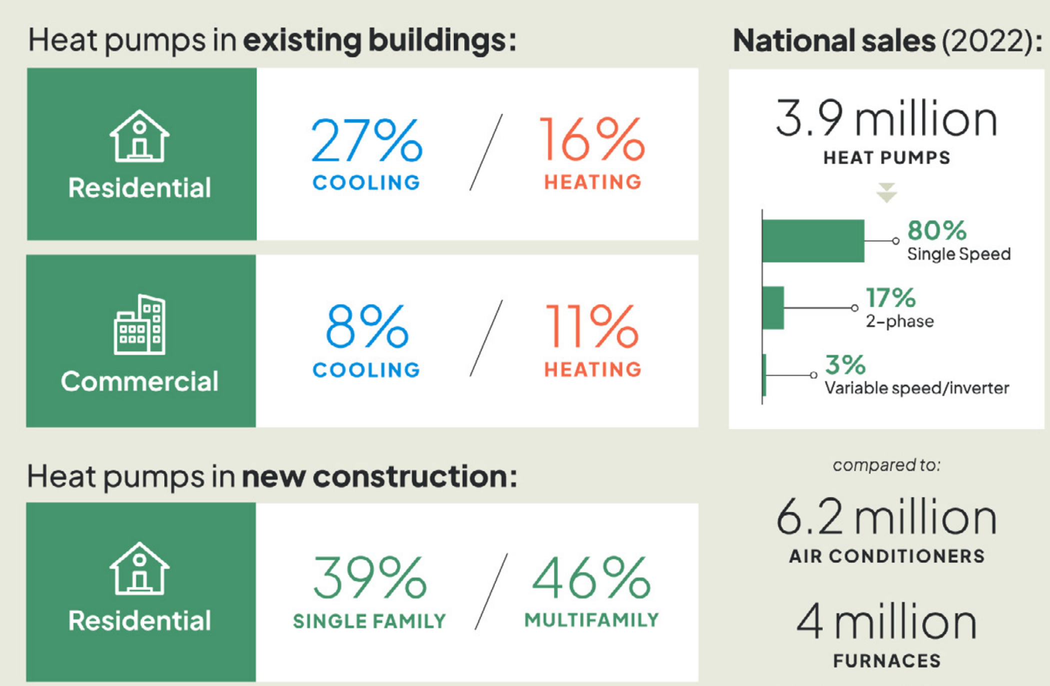


Figure 1. Current heat pump adoption in the U.S.

Sources: (EIA 2015/2020/2022; AHRI 2021; DOE 2020; NAHB 2020; Industry Interviews 2021)

We are seeing significantly higher adoption of heat pumps in new construction due to both increasing requirements of building codes that are encouraging all-electric buildings to meet climate goals and ease of installation of one versus two systems. New residential construction also can take advantage of economies of scale by ordering large numbers of units at the same time and those orders are usually well in advance of installation dates.

In existing buildings, aging HVAC systems are typically replaced upon failure in emergencies, as are some new, first-time installations, so opportunities for heat pump purchases are limited by several factors: distributor stocking, contractor proficiency, upfront costs and existing site design. All of these can present barriers to heat pump adoption. Programs and policies addressing these issues vary widely across the U.S.

While aiding consumers and businesses toward efficient, climate-friendly dual-purpose system selection is critical to GHG mitigation, investment in technology improvements in areas of cold climate performance, lower global warming potential (GWP) refrigerants and grid capabilities will bring additional benefits. Effective installation, operation and user behavior are also essential. To some extent, over-cooling buildings has become a dilemma for responsible energy management, due to behavioral norms around air-conditioning in the U.S. Further research into behavioral factors can aid in achieving GHG emissions reductions as culture, normative influences, and knowledge of alternatives all play significant roles in space-conditioning. Interventions aimed at each of these factors operate on different scales that must be considered.

Summary of Findings

Top Insights

1. Regional weather shifts across the eight climate zones evaluated will lead to **more hotter days and fewer colder days, e.g., 45 additional days above 90°F in the Cool Dry region.** The timing of extreme heat waves is difficult to forecast but cities, with their heat island effects, should be prepared.

2. Shifting to high-efficiency electric heat pumps instead of using stand-alone furnaces and air conditioners in residential buildings (single family and mid-rise apartments) and a subset of commercial buildings (medium office and strip malls), we can remove approximately **80 million metric tons of annual GHG emissions**. With additional building measures, shifts in a cleaner grid, and advanced refrigerants, reduced emissions could increase to **180 million metric tons annually**, equivalent to the electricity use emissions of Texas.

3. **Heat pump adoption is growing rapidly**, especially in new construction applications, and is now nearly equal to furnaces in sales nationally, but **barriers remain**. Variable-speed technology is still in the early adoption phase at 3% of heat pump sales.

4. **Achieving true market transformation involves implementing solutions tailored to disadvantaged populations**, who are most at risk to climate hazards. An equitable approach to heat pump deployment requires attention to the upfront costs, baseline housing conditions, and operating costs implications beyond general market dynamics and specific to the circumstances of low-income and historically underserved households.

Other Key Findings

5. Assuming no technology change in the heating and cooling sectors, by 2050 climate change in the northern two-thirds of the U.S. will lead to an insignificant net decrease of emissions, as demand for heating falls and for cooling rises. This small change is insufficient for meeting global emissions targets.

6. When accounting for the heat pump replacement of electric-resistance heating and expansion to other commercial buildings, these emissions reductions can be even greater.

7. Single family residential buildings are responsible for the bulk of total heating and cooling emissions and therefore reductions from interventions at 70% of total building stock floorspace and approximately 80% of emissions.

8. Even with an increase in new refrigerant use, replacing all furnaces with high-efficiency heat pumps still means an overall emissions decline.

9. Recent data shows national average upfront cost savings from installation of ducted heat pumps compared to both air conditioners and furnaces: approximately 40% in new construction (RMI 2018) and 25% in retrofits (LBNL 2021; RMI 2018).

10. Variable-speed air-source heat pumps and VRF systems are superior technologies relative to single-speed heat pump technologies (comfort, emissions, peak demand reductions and utility load management). However: a) as the grid becomes more renewable, the difference in emissions caused by their use becomes less significant, and b) single-speed heat pumps when packaged together with weatherization, lighting efficiency, and plug load controls are still beneficial in terms of GHG reductions.

11. Heat pumps that use existing technology work at cold temperatures, at 5°F and below; even as their efficiencies decrease in even colder temperatures, they still function with electric-resistance back-up. They can also be supplemented by back-up non-electric heating systems, if needed. Technology advancements are and will continue to increase the efficiencies of heat pumps at ambient temperatures of 5°F and below. The reduction in very cold hours due to warming will also minimize the need for this technology; nearly half the climate zones analyzed reach and are projected to reach zero or near zero hours below 5°F.

12. The connection between building decarbonization and cooling efficiency in states' climate action and building decarbonization plans is light and nascent. Such plans primarily note increased incidence of extreme heat as rationale for climate mitigation and a need for adaptation activities such as cooling centers. Some more recent plans note the ways that a heat pump's ability to provide efficient cooling serves as a customer benefit and affects cost effectiveness as well as its potential to reduce summer electric demand peaks.

Benefits of Variable-Speed and VRF Heat Pumps

- Lower emissions (enhanced with increasing renewable grid), even when accounting for an increase of refrigerants
- One appliance versus two (most relevant when both need replacing, or for buildings without cooling)
- Lower utility bills for customers with electric-resistance heating (under current rate structures)
- Lower utility bills for customers with fossil-fuel burning heating (with deep rate reform)
- Improved occupant comfort (more consistent temperature)
- Load shifting potential

Call to Action

With a holistic market transformation approach, we have identified **30 policy and programmatic actions** to increase adoption of efficient, climate-friendly heat pumps for both cooling and heating, organized by barrier—Industry, Technology and Affordability—and then alphabetically by key groups involved. Some actions will likely involve multiple groups, in which case the primary group is listed first. The groups are:

- **Federal regulatory agencies + Congress**
- **Manufacturers**
- **Philanthropic community**
- **Policy advocates** *(should consider all the recommendations)*
- **State regulatory agencies + state legislatures**
- **Utilities + utility commissions**

Actions for Industry Barriers

Action Reference	Who	Barrier - Detail	Action Description	Action Type	Time Horizon	Scale
A	Manufacturers Philanthropic Community	Workforce knowledge and capacity	**National education / re-branding campaign** (e.g., heat cool pumps).	Program	Intermediate: 1–3 years	National
B	Utilities (+ Regional Energy Efficiency Organizations)	Workforce knowledge and capacity	Develop a "**Heat pump Nation**": a National Heat pump installer network, education and training hour requirements of training gateway to incentives, expanding the number of contractors who have familiarity and trust in heat pumps as a solution for their customers' needs. Incorporate basic building science education on envelope improvement and system sizing to increase HVAC efficiency.	Program	Intermediate: 1–3 years	National
C	Utilities	Lack of installer value proposition	Integrate **grid flexibility enablement programs** at time of installation and/or through repair, maintenance contractors.	Program	Intermediate: 1–3 years	State Regional

Actions for Technology Barriers

Action Reference	Who	Barrier - Detail	Action	Action Type	Time Horizon	Scale
D	Federal Regulatory Agencies (DOE*)	Emergency purchases	Require **reversing valves** on all air conditioners, thereby making them reversible heat pumps (DOE standard).	Policy	Intermediate: 1–3 years	National
E	Federal Regulatory Agencies (DOE)	Emergency purchases	Explore opportunities for **regional heat pump standards** to optimize for climatic difference beyond the existing single, national heat pump standard.	Policy	Intermediate: 1–3 years	National
F	Federal Regulatory Agencies (DOE)	Lack of realized value from variable speed	Modify the Standards Test Procedure to ensure **repeatability and reproducibility below 5°F**.	Policy	Intermediate: 1–3 years	National
G	Federal Regulatory Agencies (DOE)	Lack of realized value from variable speed	Modify the Standards Test Procedure to include **manufacturer-recommend-ed controls** to help ensure equipment + controls are optimized to meet the performance rating.	Policy	Intermediate: 1–3 years	National
H	Federal Regulatory Agencies (EPA*)	Lack of low- and no-GWP refrigerant options	Make currently optional provisions specified for **refrigerant charge verification** in ENERGY STAR© version 6.1 for air conditioners and heat pumps a requirement in the next specification.	Policy/ Program	Intermediate: 1–3 years	National
I	Federal Regulatory Agencies (EPA)	Lack of low- and no-GWP refrigerant options	**Expand the new refrigerant-based filter** to the product finder pages for ENERGY STAR© certified Central Air Conditioner and Heat Pump Equipment.	Policy/ Program	Intermediate: 1–3 years	National
J	Manufacturers(AHRI) Federal Regulatory Agencies (EPA)	Lack of realized value from variable speed	Make the compressor type field visible in databases, or make requirement in AHRI and ENERGY STAR© to make **whether a product is variable-speed** easily findable.	Other	Short: less than 1 year	National
K	Philanthropic Community Federal Regulatory Agencies (DOE)	Emergency purchases	**Spur market transformation among manufacturers**—through technology prizes/competitions to inspire technology innovation and replace inefficient incumbent technologies for window units, particularly for multifamily renters.	Program/ Other	Intermediate: 1–3 years	National
L	State Regulatory Agencies (Building Code) State Legislatures (+IAPMO's Uniform Mechanical Technical Committee)	Lack of low- and no-GWP refrigerant options	**Change the mechanical codes to allow lower-GWP refrigerants**, including updates to certain mechanical codes (e.g., Uniform Mechanical Code) and supporting state adoption. Certain states, through both legislative and regulatory actions, are already in the process of addressing state-specific building code updates to allow the use of equipment containing low-GWP alternative refrigerants.	Policy	Short: Less than 1 year	National State

*DOE = Department of Energy EPA = Environmental Protection Agency

Actions for Technology Barriers, continued

Action Reference	Who	Barrier - Detail	Action	Action Type	Time Horizon	Scale
M	State Regulatory Agencies	Emergency purchases	Explore opportunity for **NOx standards through air quality** regulators (example: California Air Quality Management District to adopt with 14 n/j rule to align with South Coast for interim reductions).	Policy	Intermediate: 1–3 years	State
N	State Regulatory Agencies	Lack of realized value from variable speed	Require **tests of capacity and total static pressure** to within original equipment manufacturer specs on install.	Policy	Intermediate: 1–3 years	National State
O	State Regulatory Agencies (California Air Resource Board, Regional Greenhouse Gas Initiative) Federal Regulatory Agencies (EPA) Congress	Lack of low- and no-GWP refrigerant options	**Include refrigerants in existing carbon markets and create federal carbon market** for reclamation and destruction of high-GWP refrigerants.	Policy	Intermediate: 1–3 years	National State Regional
P	State Regulatory Agencies (Appliance Standards and Building Code Agencies) State Legislatures	Lack of realized value from variable speed	**Adopt grid flexibility standards** to develop the market for grid flexible HVAC solutions (enable the full benefits of variable-speed technology to be captured).	Policy	Intermediate: 1–3 years	State
Q	Utilities (+ Local governments)	Emergency purchases	Implement programs for **new temporary heating/cooling units** that can serve as emergency purchases while heat pumps are sized, installed, etc.	Programs	Intermediate: 1–3 years	State Regional Local
R	Utilities Manufacturers (+ Software developers)	Lack of realized value from variable speed	**Improve modeling** of variable-speed heat pumps in standard modeling software to account for accurate gains in efficiency.	Other	Intermediate: 1–3 years	National
S	Utilities Philanthropic Community	Lack of realized value from variable speed	Invest in **third party test lab capacity** for cold climate heat pumps.	Program/ Other	Intermediate: 1–3 years	National
T	Utilities (+ Regional Energy Efficiency Organizations)	Lack of realized value from variable speed	Develop **contractor training** on how to use published data to properly size heat pump equipment in colder climates.	Program	Intermediate: 1–3 years	State National

Actions for Affordability Barriers

Action Reference	Who	Barrier - Detail	Action	Action Type	Time Horizon	Scale
U	Federal Regulatory Agencies (The Federal Housing Finance Agency)	High upfront costs	Incorporate **heat pump replacement costs** in **green mortgage and refinancing**.	Policy	Intermediate: 1–3 years	National
V	Philanthropic Community	High upfront and operational costs	**Develop roadmap to address cost barriers** —What investment? Who pays? How do we unlock it? (e.g., unlock includes health and safety value from NOx reductions).	Other	Short: Less than 1 year	National
W	Utilities Federal Regulatory Agencies (DOE)	High upfront costs	**Establish national or regional upstream incentive program** featuring: • Extra incentives for variable-speed systems • Limitation-free installation qualification • Free-installs for industry participants • Extra incentives for Low-GWP refrigerants and leak-tight installation verification • Exclude EER requirements which make it less difficult for variable-speed / inverter technology or include a tradeoff between EER and grid connectivity.	Program	Intermediate: 1–3 years	National
Y	State Regulatory Agencies Utilities	High upfront costs	Coordinate **group purchasing power** of heat pumps.	Program / Other	Intermediate: 1–3 years	State Regional Local
Y	Utility Commissions	High operational costs	Enable **deep energy rate reform** (e.g., reducing the electricity rate base, marginal cost rates), essential to pull in private capital and build an industry, like the rooftop solar industry.	Policy	Intermediate: 1–3 years	State
Z	Utility Commissions	High upfront costs	Expand **Tariff On-bill Financing**.	Policy	Intermediate: 1–3 years	State

Action Reference	Who	Barrier - Detail	Action	Action Type	Time Horizon	Scale
AA	Utility Commissions State Regulatory Agencies	High upfront and operational costs	Properly **evaluate, quantify and unlock non-energy benefits** of heat pumps into state/utility policy (e.g., cap + trade funds, cost-effectiveness tests, health + safety funding mechanisms). Ensure those metrics are included in policy decision-making.	Policy	Intermediate: 1–3 years	State
BB	Utility Commissions Federal Regulatory Agencies (Department of Health and Human Services)	High upfront and operational costs	**Modify energy assistance programs** offered by utilities as well as the **federal Low-Income Home Energy Assistance Program** (LIHEAP) to incentivize electrification and cover cooling costs.	Policy / Programs	Intermediate: 1–3 years	National
CC	Utility Commissions	High upfront costs and operational costs	**Promote fuel switching for low-income households** through comprehensive programs that address health and safety measures as well as weatherization and appliance efficiency measures.	Programs	Intermediate: 1–3 years	National
DD	Utility Commissions State Legislatures	High upfront costs	**Modify incentive policy to eliminate barriers to stacking and braiding of federal funding**, including for electrification and heat pump deployment.	Policy	Intermediate: 1–3 years	State

01

Introduction

Background and Approach

Communities in the United States (U.S.) will face pressing challenges as global temperatures rise over the coming years. Demand for cooling technologies and techniques can be expected to increase across much of the nation, including in temperate and cold climate zones that currently use less air-conditioning than the southern tier. What can be done to ensure that cooling is widely accessible while not exacerbating the problems of climate change?

This report provides an analysis of dual cooling and heating solutions for residential and commercial buildings in geographies that have historically been dominated by heating demand but where demand for cooling is increasing as global temperatures rise.

The research centers on presently cool and temperate climate zones of the U.S., but the findings have relevance for other parts of the world with similar climates where cooling demand represents an increasing share of building emissions and there is an opportunity to adopt more efficient cooling technologies while simultaneously decarbonizing space heating systems. This report offers sound intelligence on how greenhouse gas (GHG) emissions will change in the U.S. as cooling demand increases in temperate climates and offers recommendations for near-term actions to reducing both cooling- and heating-related emissions.

Setting the Context Around Extreme Heat

In June of 1995, Chicago experienced a heat wave that spanned five days and accounted for over 700 heat-related deaths (Uchoa 2020). All five days the city experienced temperatures exceeding 100°F and heat index values reached as high as 126°F. Most deaths were the elderly and low-income residents who did not ventilate homes overnight with open windows due to fear of crime (AdaptNY 2016). The event resulted in a dramatic shift in the city's heat response and preparedness planning which now serves as a national model to mitigate heat mortalities.

As global temperatures continue to rise, cooler climates that have not historically experienced severe heat events can be caught off guard. This was the case for Portland in 2021, where an unprecedented heat wave swept through the Pacific Northwest. Given the prevalence of humidity in the region, relative heat index values climbed as high as 124°F, claiming more than 500 lives across Oregon, Washington, Idaho, and Canada. The magnitude of this event set record temperatures for Portland, which now exceeds those in Dallas, Houston, and Atlanta.

To compound this issue, the American Housing Survey estimated about 22% of households in Portland did not have access to some form of primary air-conditioning prior to the heat wave, far more than the 9% national average (U.S. Census Bureau 2019). Of those with access, less than 50% of households were connected to central air-conditioning systems that have proven to be more reliable in preventing heat mortalities (Wilson and Chakraborty 2019). Other nearby cities, such as Seattle, fare much worse with only 22% of households having access to a central air-conditioning system.

Similar to Chicago, Portland recognized the need to adapt to a new climate and quickly implemented new measures to address heat wave mitigation planning and programs. Following the heat wave, the Portland Clean Energy Fund (PCEF) established the New Heat Response Program to install portable heat pumps or cooling units in vulnerable households (PCEF 2021). The City also cites the need for revised building codes, increasing greenery, and increasing access to efficient cooling technologies to increase Portland's adaptation efforts.

Though space-conditioning is important in mitigating heat related illnesses and death, not all systems are created equal. Access to a central air-conditioning system has been found to be predictive of positive health outcomes during heat events, while window units, though may offer relief, do not have this predictive power (Wilson and Chakraborty 2019). This is likely due to a variety of reasons, including less efficient systems being unable to cool more than a room. Additionally, while window air conditioners have a lower upfront cost and are a more realistic option for renters and low-income households, those with less financial means might limit or avoid use during extreme events to avoid incurring higher than normal electrical costs. Moreover, as shown in Figure 2, Sharma et al. (2018) found electrical consumption from air conditioners to be lowest in highly vulnerable neighborhoods. These patterns are similar to data from the recent Residential Energy Consumption Survey where households lower on the income spectrum are more likely to own individual air-conditioning units and operate them in a different manner than high income households (see Behavior and Efficient Cooling).

The predictive power of central air-conditioning finding by Wilson and Chakraborty (2019) alongside sociodemographic research on heat vulnerability has significant implications for what kinds of policy must be crafted to reduce heat-related illness and deaths. For example, subsidizing air-conditioning units for low-income households should be prioritized alongside strategies to improve adaptive capacity through home weatherization and updated building codes in affordable housing developments to require efficient centralized systems.

Meanwhile, much has to be done to ensure grid reliability and stability during major heat events. Variable-speed heat pumps remain the most viable option to provide necessary cooling to households while limiting grid impacts. As such, policies to lower the upfront cost of investing in and expanding access to heat pumps should be crafted to prioritize low-income and other sensitive groups to heat.

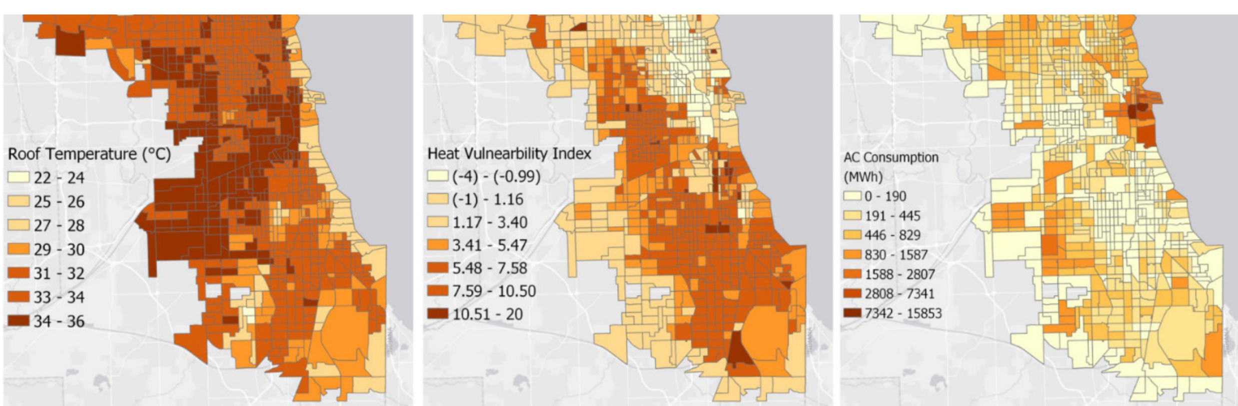


Figure 2. Spatial comparison of roof temperature, heat vulnerability, and air-conditioning consumption in Chicago in August 2013

Source: (Sharma et al. 2018)

This report uses temperature forecasts that are long-term projections from recent, typical weather. They show average temperature changes in the climate zones under consideration in the year 2050. Yet we know that as global temperatures increase, a rise in heat wave occurrence, intensity, and length has already been documented (IPCC 2021). Among weather-related incidents, deaths from heat are a large and rising contributor, and may even be under reported given the array of illnesses exacerbated by heat stress (Gerrard 2018). Heat waves are particularly impactful in urban areas that experience "urban heat island" effects from hardscapes that trap heat and fewer trees that provide cooling effects (see Figure 28). Effects on overnight lows are particularly pronounced, with urban areas showing a 1–7°F differential with outlying areas during the daytime but as much as a 22°F difference at night (Donegan 2016; EPA 2021).

Heat waves are anticipated to be a driver of growing cooling demand. As shown in this report, using air-source heat pumps, particularly variable-speed and variable-refrigerant-flow (VRF), to meet both growing cooling and continued heating demand offers significant carbon emissions reductions against a business-as-usual scenario.

Overview of Analysis and Recommendation

The sections below describe our methods for projecting future climate conditions in the northern tier of the U.S. and examine the anticipated market potential for key technical approaches to cooling. Barriers to technology adoption are discussed in detail, followed by consideration of behavioral and distributional equity factors.

Our approach in developing the report was to first analyze how energy use and emissions would change if today's typical heating and cooling systems continued to be used in a future with hotter average temperatures. We then reviewed a set of mitigation strategies for both building energy use and refrigerant emissions that achieve better GHG emissions outcomes for their level of impact, leading up to a near "best-case" scenario. The mitigation strategies include use of efficient dual heating and cooling solutions (e.g., air-source heat pumps, VRF), weatherization, improved lighting efficiency and plug load controls, refrigerant leak mitigation and end-of-life refrigerant management, and the use of climate-friendly refrigerants. These findings are presented in the context of current market and technology conditions as well as insights into ways current conditions are likely to change in the coming years, including a more renewable grid.

To develop recommendations for how to equitably implement the examined emissions mitigation strategies, we identified key barriers—industry, technology and affordability—that could prevent those outcomes and identified actionable policies and programs to achieve affordable, efficient clean cooling and heating.

Changing Cooling and Heating Demand in a Warming Climate

Projected Growth in Cooling Demand

A main resource on projected changes in the U.S. energy use for cooling comes from the Energy Information Administration (EIA), which published a set of 2050 projections in March 2020. The EIA points to energy use for air-conditioning as the end use with the largest projected increases, due to an increase in cooling degree days. The EIA analysis assesses heating degree days and cooling degree days on a population-weighted basis, and the increase in cooling degree days is amplified by expected population shifts away from cooler climate zones and into warmer climate zones as an aging demographic seeks comfort. Although the EIA 2050 projections show the increase in energy use for cooling being more than offset by a reduction in heating energy use, adding in projections for other building energy use (water heating, etc.) leads to a net increase in the building sector's overall energy use by 2050. These projections are based on a reference case that includes some increase in building efficiency based on already enacted standards but does not account for future policy changes.

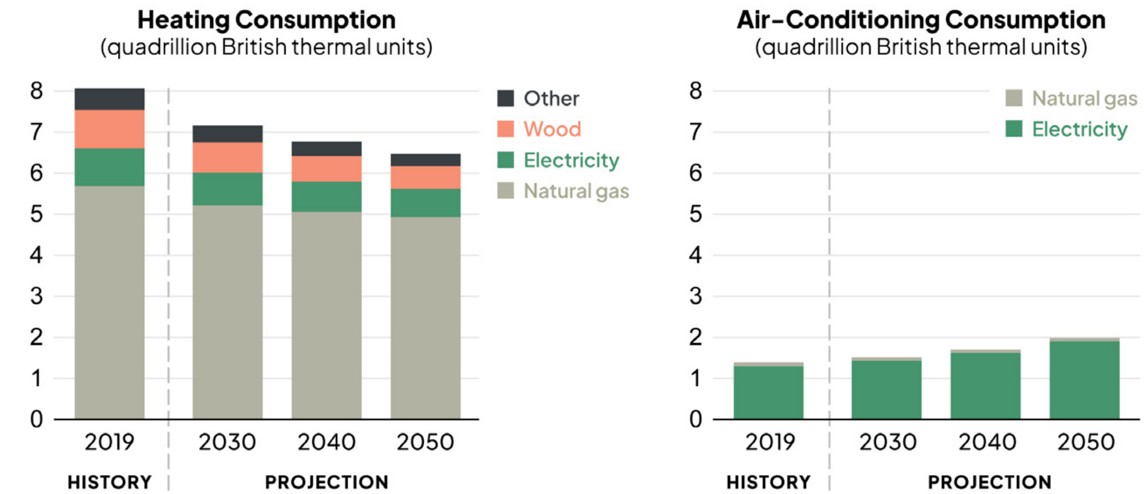


Figure 3. EIA reference case for the buildings sector delivered heating and air-conditioning consumption (2019-2050)
Source: (EIA 2020)

The EIA data is broken down by building type, with air-conditioning use in single family homes dominating in the residential sector, and the largest share of air-conditioning demand in the commercial sector coming from office buildings.[1] Our analysis resulted in similar trends for the building types and the cool and temperate climate zones included in this study.

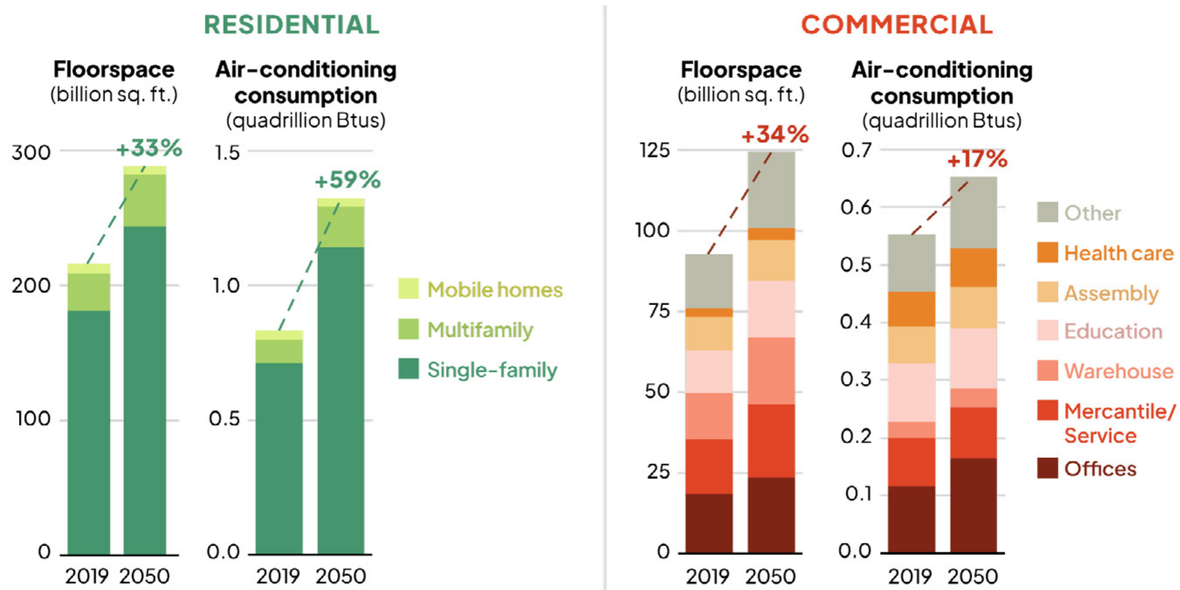


Figure 4. Buildings sector floorspace and air-conditioning consumption (2019, 2050)
Source: (EIA 2020)

Energy Modeling and Analysis

Approach and Methodology for Energy Use Analysis

The project team conducted an energy modeling exercise to evaluate the energy use of prototypical buildings using a variety of design options to meet increased cooling demand. The analysis investigated 'Business as Usual' (BAU) and 'Interventions Analysis' scenarios to explore the impact of predicted climate conditions in 2050 on building energy use.

For this analysis, the project team used EnergyPlus prototype building models that the U.S. Department of Energy (DOE) and Pacific Northwest National Laboratory (PNNL) develop and maintain Prototype Building Models as part of the Building Energy Codes Program. PNNL generates a new set of reference models, or prototypes, to reflect each version of the International Energy Conservation Code (IECC). The prototypes have typical design features that are tailored for each climate zone and are minimally compliant with energy code. We selected vintage prototypes for the analysis so the results would provide an indication of energy use of the building stock in 2050. Specifically, we used the 2012 IECC commercial reference buildings and 2015 IECC residential reference buildings.

1 EIA projections did not take into account the impact of the COVID-19 pandemic, which had near-term impacts on building energy use in the residential and commercial sectors and has the potential to influence long-term commercial square footage projections.

We used the following prototypical buildings for the BAU analysis including investigating impacts of modifying weather without making changes to the prototypes themselves:

- large office
- medium office
- strip mall
- secondary school
- warehouse (non-refrigerated)
- full-service restaurant
- mid-rise apartment
- single family detached

For the Intervention Analysis, we evaluated the impact of modifying the designs of a subset of these prototypes to explore the energy savings potential of passive and active design interventions.

According to data from the most recent Commercial Buildings Energy Consumption Survey (CBECS) the commercial prototypes represent 77% of the existing commercial building stock by floor area (EIA 2021).

The project team analyzed impacts in eight American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) climate zones—those above the red line in Figure 5. These eight climate zones were chosen based on the future expectations of:

- Air-conditioning added where there is currently no air-conditioning.
- Central air-conditioning added where there is currently a high saturation of "under cooling" (e.g., window units that do not serve the entire home).
- Highest potential savings benefit from replacing heating (+ cooling) with heat pumps.

The climate zones in the grayed-out region of Figure 5 were excluded from the assessment due to the high prevalence of air-conditioning and higher shares of heat pump adoption in parts of the region.

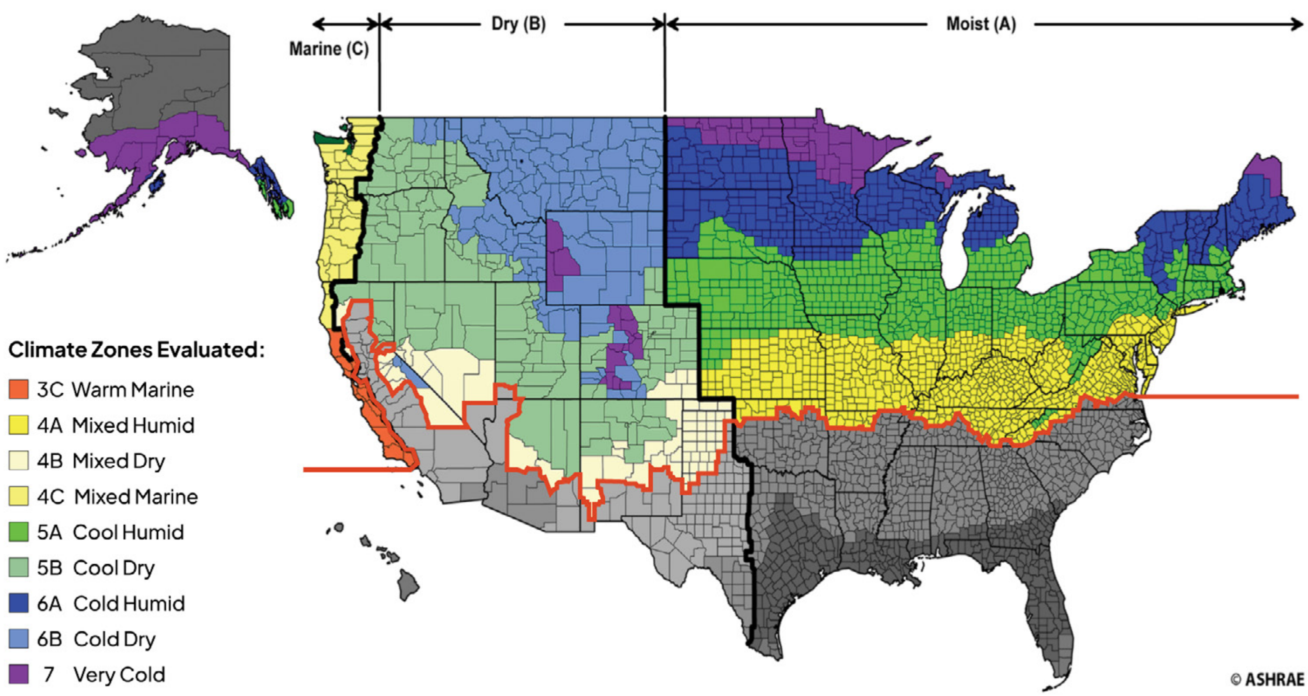
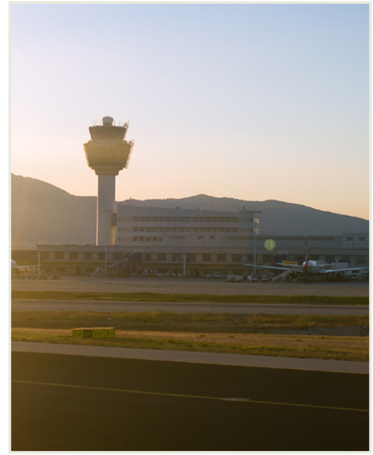


Figure 5. Climate zones analyzed in energy simulations
Source: (ASHRAE 2021)

Each prototypical model was simulated using two sets of weather files: historical weather (Typical Meteorological Year X, TMYX) and future-shifted weather (WeatherShift™). TMYX weather data is derived from actual weather in the 2004–2018 period. Throughout the report, weather and emissions values using TMYX weather data are referred to as “recent average” values. WeatherShift adjusts historical weather files from locations globally to project future weather based on results of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report with options available to adjust based on Representative Concentration Pathways (RCP 4.5 or 8.5), warming percentile bin, and future years. We used weather based on RCP 8.5 for year 2050 at a 50th percent warming bin.



Data from the following weather stations was used for both the historical and future-shifted weather scenarios:

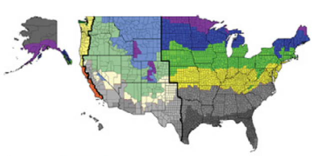
- 3C: San Francisco International Airport. San Francisco, CA
- 4A: John F Kennedy International Airport, NYC, NY
- 4C: Seattle Tacoma International Airport, Seattle, WA
- 5A: Buffalo Niagara International Airport, Buffalo, NY
- 5B: Denver Aurora Buckley AFB, Denver, CO
- 6A: Rochester International Airport, Rochester, NY
- 6B: Great Falls International Airport, Great Falls, MT
- 7: Falls International Airport, International Falls, MN

The HVAC systems used in the analysis are described under Current Practices in Section 3.

Changes in Weather

A review of weather files indicates the warming trend will continue. Extreme heat and cold events are quantified using the metrics of number of days above 90°F and number of hours below 5°F, respectively. Measuring extreme cold events (hours below 5°F) is particularly relevant for this study because heat pump efficiency decreases as temperatures fall and electric-resistance mode or other back-up systems may be necessary to maintain temperature setpoints.[2] While the general warming trend holds across climate zones, the degree of change varies among climate zones, as shown in Table 1.

Table 1: Projected Annual Changes in Typical Weather by Climate Zone



	Annual Days > 90°F			Annual Hours < 5°F		
Climate Zone	Recent Average	2050 Projection	Percent Change	Recent Average	2050 Projection	Percent Change
3C – Marine Warm	1	2	100%	0	0	–
4A – Mixed Humid	7	36	414%	0	0	–
4C – Mixed Marine	0	7	–	0	0	–
5A – Cool Humid	0	16	–	32	1	- 97%
5B – Cool Dry	32	77	141%	158	89	- 44%
6A – Cold Humid	2	21	950%	648	425	- 34%
6B – Cold Dry	16	32	100%	528	437	- 17%
7 – Very Cold	1	13	1,200%	1224	786	- 36%

2 Products that meet the Northeast Energy Efficiency Partnership’s Cold Climate Air-Source Heat Pump specification (v3.1, effective August 1, 2021), must function at a COP of 1.75 or greater at 5° F.

For extreme heat days, marine Climate Zones (3C, 4C) see modest increases from already low baselines, while humid climate zones (4A, 5A, and 6A) see relatively sizeable increases in days over 90°F from low baselines. Most notably, Climate Zone 5B, which already experiences more than a month's worth of days over 90°F, sees that number more than double, with an additional 45 days above 90°F expected by 2050. Bearing in mind that heat waves can occur in any of these climate zones, the change in typical weather is an indicator of heat stress on people and increasing cooling loads for buildings. In any given year, areas can experience extreme heat events beyond the "typical" values used for modeling purposes. For example, in 2021 Seattle saw three consecutive days above 100°F (Meyer 2021), far exceeding the recent average of zero days above 90°F which is typical for Climate Zone 4C.

For extreme cold, three Climate Zones in the study region (3A, 4A, 4C) are not projected to have any extreme cold events, with no hours below 5°F using typical weather today nor in the 2050 projection. For the cool humid Climate Zone 5A, the expected increase in warming will nearly eliminate hours below 5°F. The remaining four climate zones are projected to see significant decreases in hours below 5°F, with the percent reduction relative to recent average ranging from 17% to 44%.

Business as Usual Analysis Results

The BAU analysis considers the impact of projected changes in weather if the typical building systems in use today persist into 2050. It does not incorporate any changes in the type of heating or cooling systems used, nor other weatherization, efficiency, or energy conservation improvements. It also does not account for upstream emissions from methane leakage or refrigerant leaks from cooling systems in the historic or 2050 scenario. The analysis is based on 2019 grid emissions factors from the U.S. Environmental Protection Agency (EPA).

Analyzing the impact of the warming trend from recent average weather to projected 2050 weather on energy use and GHG emissions across the eight prototypical buildings and the eight climate zones shows a relatively insignificant decrease in overall energy use and emissions for heating and cooling. This net decrease comes despite an increase in both energy use and emissions for cooling and is driven by an even larger decrease in energy use and emissions for heating. Emissions from these eight building types in these eight climate zones continue to represent a significant share of U.S. buildings sector emissions, with the projected 2050 emissions representing approximately 14% of residential and commercial emissions in 2020.

As shown in Figure 6, overall emissions decrease 5%, the net result of a 34% increase in cooling emissions and a 26% decrease in heating emissions. Although focused on a narrower geography than the EIA data presented above in the Projected Growth in Cooling Demand section above, this analysis of cool and temperate climate zones shows a similar pattern to the EIA projections.

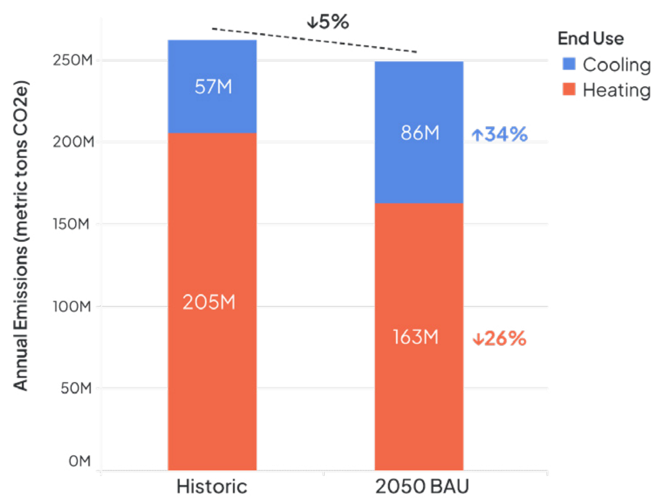
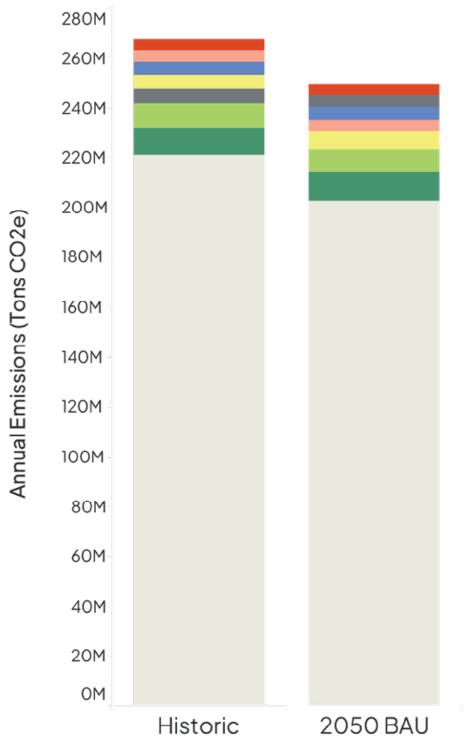


Figure 6. Recent average and projected 2050 BAU annual emissions for prototypical baseline buildings and HVAC systems in the study region with weather-driven changes in heating and cooling demand with 2019 grid emissions factors, and no refrigerant emissions

Looking at the same total emissions by prototypical building rather than by heating and cooling end use shows that single family homes dominate under both the recent average and projected 2050 weather. As shown in Figure 7 below, single family homes constitute more than 80% of the projected total emissions in each scenario. Single family homes are 71% of the extrapolated building area.



Building Type	Historic (%)	2050 (%)
Office - Large	1.6%	1.8%
Office - Medium	1.7%	2.0%
Retail Strip Mall	1.9%	2.0%
Secondary School	2.2%	2.8%
Warehouse	2.3%	1.8%
Sit Down Restaurant	3.6%	3.7%
Apartment	4.1%	4.6%
Single Family Home	82.6%	81.2%

Figure 7. Recent average and projected 2050 BAU annual emissions by prototypical baseline buildings and HVAC systems in the 8-zone study region with weather-driven changes in heating and cooling demand with 2019 grid emissions factors, and no refrigerant emissions

Interventions Analysis

The interventions analysis assessed the potential energy savings that could be achieved in a future warmer climate using both active and passive energy conservation measures. We used the following prototypes for the Interventions Analysis:

- medium office
- strip mall
- mid-rise apartment
- single family detached house

We chose these prototypes because medium office and strip mall represent the largest shares of commercial spaces by floor area with significant cooling loads and air-source heat pump potential.

Mid-rise apartment and single family detached houses were selected to provide a mix of single and multifamily housing, which have a strong impact on the equity analysis and policy recommendations. The baseline HVAC systems for each of the protype buildings are the baseline systems in the PNNL prototypes and apply to all of the historic and BAU scenarios of that prototype.

The Intervention Analysis scenarios were simulated using future-shifted, 2050 weather only. We did not run simulations with historic weather files.

The primary active energy conservation measures implemented in the modeling was the replacement of prototype baseline HVAC system with a highly efficient and/or all-electric system (see Table 2 below for the two scenarios).

Table 2: HVAC Systems Simulated in the Intervention Analysis

Prototype	Baseline Cooling and Heating System(s) (Historic and 2050 BAU)	Mitigation System 1 (2050)	Mitigation System 2 (2050)
Strip Mall and Medium Office	Packaged air-conditioning direct expansion (DX) system with furnace	Packaged system Air-to-Air Heat Pump (single-speed)	Variable Refrigerant Flow (VRF)
Residential (mid-rise apartment and single family)	Single-zone air-conditioning (DX) with furnace	Packaged Single-Zone Heat Pump (single-speed)	Packaged Single-Zone Reversible Heat Pump (VRF modeled as proxy for variable-speed)

Additional active energy conservation measures are as follows, herein referred to as "lighting efficiency and plug load controls" or "lighting and plug load energy conservation measures."

- Increase efficiency of lighting by 30% as defined by lighting power density.
- Add controls to eliminate nighttime use of all plug loads (done for commercial prototypes only).

The passive energy conservation measures implemented in the prototype models are as follows, herein referred to as "weatherization."

- Reduced infiltration by 25%.
- Improved envelope performance by adding R-10 to overall opaque envelope components.
- Shading improvements by adding internal automated blinds (tuned to respond to glare).
- Mixed-mode ventilation, which opens windows and shuts off HVAC systems when conditions are favorable.

Results of the Intervention Analysis are presented in a subsection of Section 3 titled "Heat Pump Technology + Passive Cooling."

Recognizing that the existing building stock includes a wider range of baseline systems than the prototypical designs, we expanded the analysis to investigate the implications of other common (though not predominant) baseline systems. The project team investigated two variations on the baseline HVAC system for single family and multifamily buildings. On the cooling side, we evaluated a scenario with a share of homes having no air condition today and a mitigation scenario with 100% of homes having air-conditioning in 2050. Based on 2020 preliminary data from Residential Energy Consumption Survey (RECS), approximately 12.8% of households in the study area[3] reported not using air-conditioning equipment. However, based on recent trends, most buildings will have cooling by 2050. On the heating side, we evaluated a scenario with a share of homes having electric-resistance heating; 2020 RECS data indicates 21.6% of households in the study area report having an electric baseline heating system (EIA 2022).

3 The climate regions used in RECS are not equivalent to the eight climate zones in this study. We used data from the Very-cold/Cold, Mixed-Humid, and Marine climate regions in RECS to approximate the share of households with the alternative baseline conditions in this report's study area.

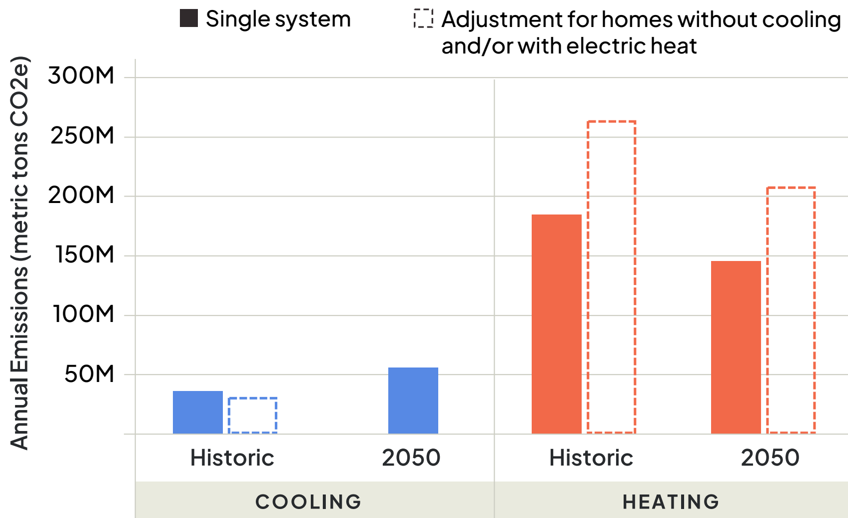


Figure 8. Residential cooling and heating emissions assuming a single system across all buildings, and adjusted for homes without cooling, and/or with electric heating

As shown in Figure 8, when looking at the impact of our alternative residential baseline HVAC systems, reducing the share of residential households—both single family and multifamily—with existing cooling systems reduces the total emissions from these prototypes by 13% compared to the single system per prototype scenario of 100% of households having central air-conditioning. The 2050 cooling scenario shown above reflects the residential sector cooling emissions under the projected 2050 weather. For heating, including a share of households with electric-resistance heating increases residential heating emissions compared to the single system per prototype scenario of 100% of households using natural gas furnaces by 43%. These analyses are based on the 2019 grid emissions factors.

Additional discussion of the impact of electric resistance in the 2050 BAU scenario for heating presented in the subsection on Technical Solutions in Section 3.

03

Technology and Markets

The traditional technologies that currently provide heating in most U.S. buildings rely heavily on fossil fuels, while separate air-conditioning systems use electricity. Together, cooling and heating needs consume over half of residential energy use. The majority of commercial floorspace is served by packaged heating and air-conditioning units. Heat pumps provide an electric-powered alternative that can take advantage of decarbonization throughout the grid while serving both needs. However, heat pump technology relies on refrigerants, just as air-conditioning does. Direct emissions from refrigerants must be taken into consideration when assessing the climate impacts of heating and cooling options.

A wide variety of heat pump solutions exist, with different capabilities and constraints, so opportunities for retrofits also vary in terms of costs and requirements. Heat pump systems share common components, design and installation requirements with traditional air-conditioning systems. This has led to wider adoption in residential settings for air-conditioning alone, as opposed to dual use, though this is changing particularly in new construction.

Current Practices

Summary of Heat Pump Technologies

In the U.S., space cooling and heating in residential buildings is most often delivered through a combination of mechanical ductwork and separate furnace and air-conditioning systems. The air conditioner is typically a split system consisting of an outdoor condensing unit and an indoor evaporator unit—or coil, which is located inside the metal ductwork near the furnace. The furnace, either natural gas, electric or oil fired, is comprised of a combustion chamber and an air handler and fan which forces the heated air through the ductwork.

Heat pumps are a leading alternative clean cooling and heating technology that are classified by their source (e.g., ground, water or air) and their transfer medium (e.g., water/hydronic, air or refrigerants). Common residential heat pump systems are either ducted heat pumps (similar to the furnaces and air conditioners described above) or ductless—also known as mini splits or multi splits. Ducted and ductless heat pumps are similar to the split air conditioner design with an outdoor condensing unit and an indoor air handler unit or units with an evaporator coil. In addition to higher efficiency compared to a traditional air conditioner, the heat pump also has a reversing valve, which allows it to switch the operation of the system from capturing heat from the home and transferring to the outdoors, to capturing heat from the outdoors and transferring it indoors—thereby cooling or heating the space based on demand. In addition to meeting the air-conditioning load, the heat pump can either displace a portion of the heat provided by the main heating system (e.g., furnace) or with proper design and technical capabilities, replace the traditional heating system. Figure 9 depicts typical residential heating and cooling system configurations.

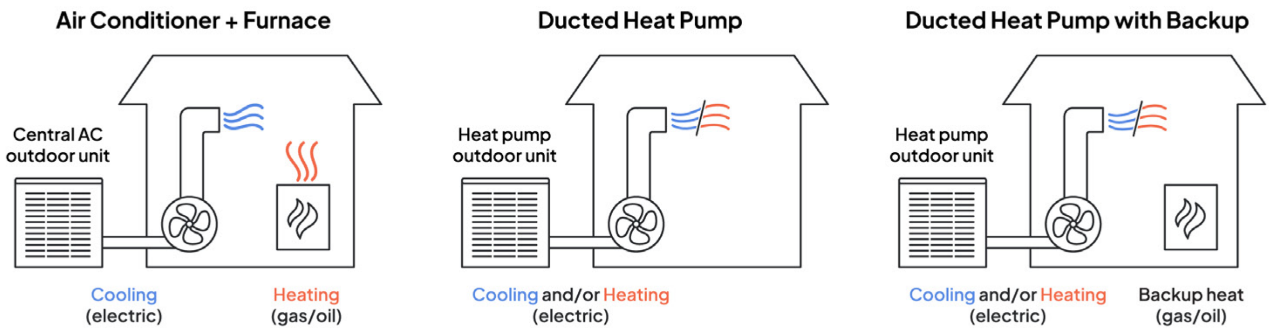


Figure 9. Residential heating and cooling system configurations

For homes or businesses with existing mechanically ducted furnace and split air conditioners, ducted heat pumps can be a cost effective and relatively simple retrofit solution. However, in new construction or as a retrofit, ductless heat pumps can eliminate additional costs of ductwork and use refrigerants to deliver heating or cooling more efficiently to individual spaces. These ductless systems and some ducted systems are variable-speed (describing the speed of the compressor fan), which offers greater efficiency and more consistent comfort when compared to traditional single-speed or even dual-speed systems, as they are more responsive to the heating and cooling loads.

For larger homes or commercial applications, VRF heat pumps provide increased control by, in addition to varying the compressor speed, also varying the flow or volume of refrigerant to different zones to better match specific heating or cooling loads in those spaces.[4] In these larger system settings, VRF systems are capable of higher performance compared to conventional systems in part because they pair well with heat recovery. Heat recovery can be easily applied to either the dedicated ventilation system through exhaust air heat recovery, or the VRF systems can be designed with heat recovery capabilities whereby heat from warmer zones is transferred to cooler zones and vice-versa rather than being lost to the outdoor condensing unit.

In a residential setting, heat pumps can be paired with smart thermostats that allow for easy adjustments to operating schedules and setpoints. This allows building occupants to minimize costs by heating and cooling at times when electricity is least expensive (for those on time-of-use rates). It also offers the opportunity to participate in load management incentive programs (e.g., automated demand response programs). Additionally, variable-speed equipment offers additional benefits over single-speed or dual-speed systems because of the ability to incrementally shed load while maintaining core system functions.

4 An additional difference between residential-duty heat pumps and VRF heat pumps is the threshold of capacity. VRFs have capacities of 65 kBtu/h and higher and require three-phase electrical power.

Summary of Costs of Heat Pumps

- **Residential installation costs of ducted systems:** Recent data shows national average cost savings from installation of ducted heat pumps compared to both air conditioners and furnaces: approximately 40% in new construction (RMI 2018) and 25% in retrofits (LBNL 2021; RMI 2018).
- **Residential installation costs of ductless systems:** Ductless, variable-speed mini-split systems in residential applications show an additional increase of 20% per ton compared to ducted systems (LBNL 2021), though these costs don't fully account for on-average higher efficiency and benefit of these smaller sized systems (i.e., fewer tons needed), particularly in multifamily buildings.
- **Incremental cost of higher efficiency heat pumps:** Ducted variable-speed heat pumps are approximately a 20% cost increase per ton from dual-speed (NEEA 2022; LBNL 2021) and 50% increase compared to single-speed heat pumps (LBNL 2021). TECH Clean California (2022) data shows a 16% increase per ton between groupings of 14–17 SEER and 17–20 SEER rated heat pumps.
- **Future cost declines:** Air-source heat pump costs are projected to decline by 20–38% by 2050 (NREL 2018).
- **Operation data gap:** Comprehensive, real-world operational cost comparison data is limited, though forthcoming data from TECH Clean California will show the bill impacts of shifting to residential heat pumps in California.
- **Data gap for commercial incremental installation costs of variable-refrigerant-flow systems:** While some state-specific cost data exists for commercial buildings in both retrofit—e.g., eTRM (2022)—and new construction—e.g., CEC (2021)—comprehensive national analysis incorporating the costs of both air-conditioning and furnace baselines comparing variable-refrigerant-flow systems is needed.

Residential Space Cooling

The U.S. has one of the highest rates of air-conditioning in the world with a reported 109 million or 88% of existing single family and multifamily housing with active cooling. However, the prevalence of central air-conditioning ranges from a high of 83% in single family detached homes to a low of 49% of two-to-four unit apartment buildings, 46% of which use window or wall air conditioners (EIA 2022). The same EIA survey reported that over 40% of central air-conditioning systems in residential homes were more than 10 years old and offer potential opportunities for early replacement prior to failure.

Although cold and very cold climate regions report similar prevalence of air-conditioning, households in colder regions with historically low cooling demands have a higher reported use of window and wall air conditioners (see Figure 10).

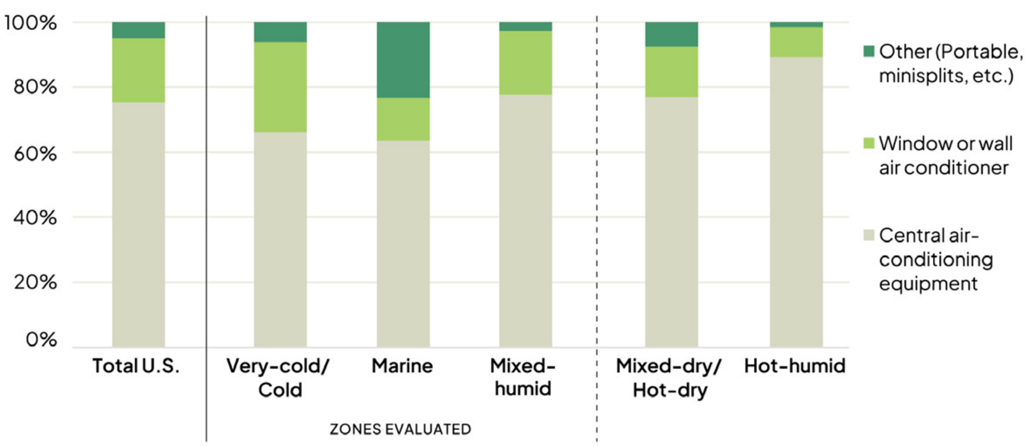


Figure 10. Main cooling equipment choice by climate region, 2020
Source: (EIA 2022)

Residential Space Heating

In 2015, heating and cooling represented over 50% of residential home energy use with the highest share in single family homes (Figure 11). Single family homes represent approximately 67% of the over 130 million homes in the U.S. with an additional 27% multifamily and 6% manufactured housing units (EIA 2015).

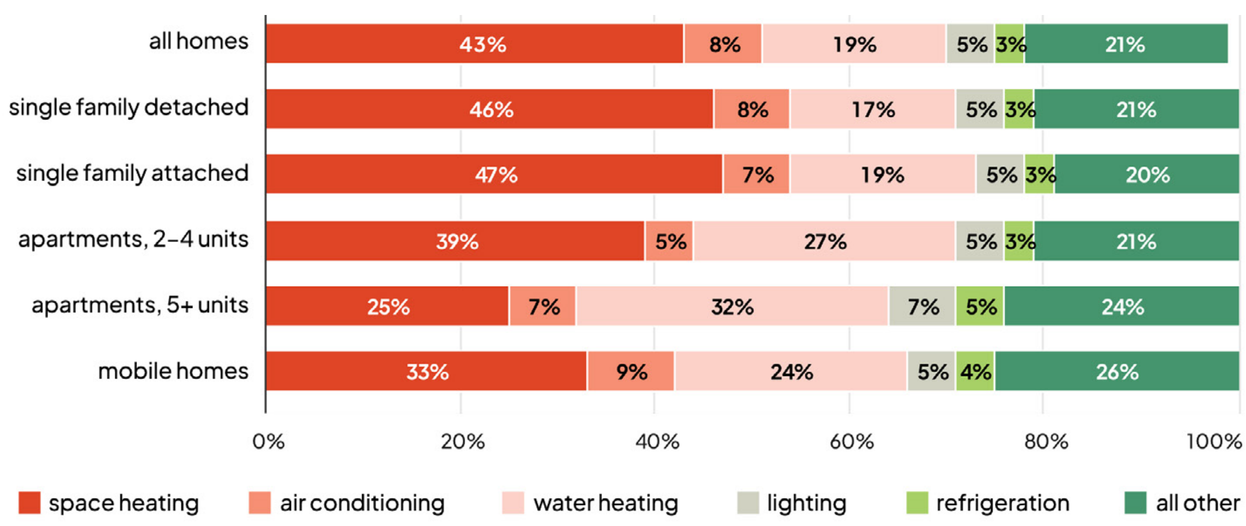


Figure 11. End-use energy consumption shares by types of U.S. homes
Source: (EIA 2015)

Most of the residential heating and cooling in the U.S. historically has been centralized HVAC equipment delivered through mechanical ductwork. For heating systems, in 2020 61% of U.S. homes had central warm-air furnaces; with the highest rate in detached single family (69%) and a lower rate of central systems in multifamily (46% in 2–4 unit and 41% in buildings with 5 or more units) (EIA 2020).

In Figure 12, residential heating systems and fuel types were summarized based on U.S. climate regions, highlighting the significant diversity of heating systems, but that in cold or very cold climates approximately 70% were central furnaces primarily supplied by natural gas. In the same EIA survey, it was reported that over 50% of space heating systems in residential homes were over 10 years old and have potential opportunities for early replacement prior to failure.

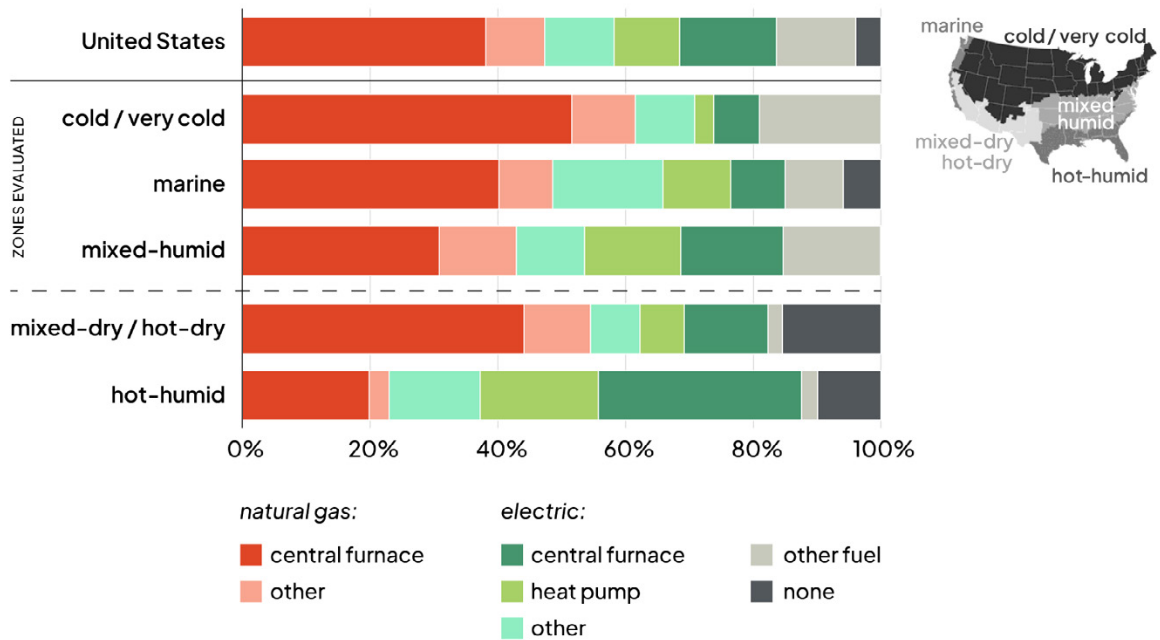


Figure 12. Main heating equipment choice by climate region, 2015.
Source: (EIA 2015)

These older, fossil fuel-burning space heating units in residential homes introduce combustion-related pollutants. A recent report highlighted that the "pollutants resulting from fossil fuel combustion — including nitrogen oxides (NOx), carbon monoxide (CO), fine particulate matter (PM2.5), ultrafine particles (UFPs), and formaldehyde (CH_2O)—are linked to a variety of adverse health impacts" including asthma, neurological disorders and cancers (RMI 2021).

Commercial Space Heating and Cooling

Heating and cooling solutions for commercial buildings range considerably in technology and in capacity to serve larger areas. According to the 2018 Commercial Buildings Energy Consumption Survey, in the U.S., packaged heating units are the leading heating solution, serving 37% of buildings and representing 50% of commercial floorspace (EIA 2021). Packaged units can be small designs that heat or cool a single room to larger rooftop units that can serve an entire commercial building.

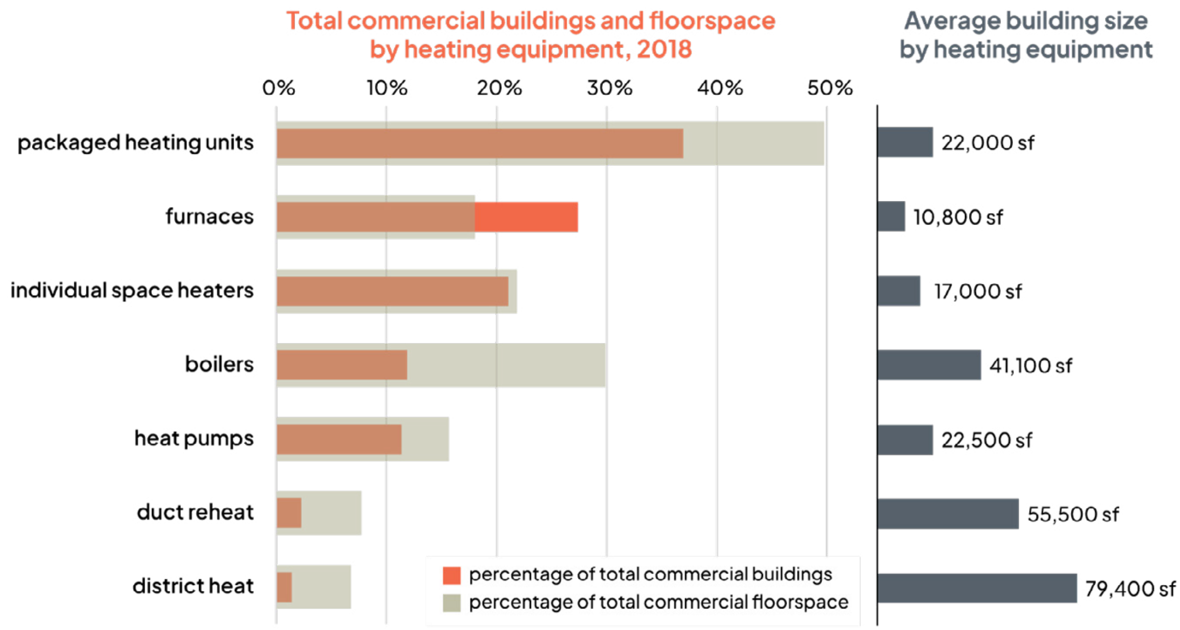


Figure 13. Number of commercial buildings by heating equipment and floorspace
Source: (EIA 2021)

In 2018 approximately 11% of buildings and 16% of commercial floorspace space heating needs were served by heat pumps and although this is similar to the number of buildings served by boilers, boilers served nearly double the floorspace—second only to packaged units.

Similarly, packaged air-conditioning dominated cooling in commercial buildings with 43% of buildings served and representing 58% of total floorspace. Residential-style central air conditioners have the second highest share of building cooling equipment, in large part to applications in small commercial buildings as highlighted by the relatively low percentage of floorspace.

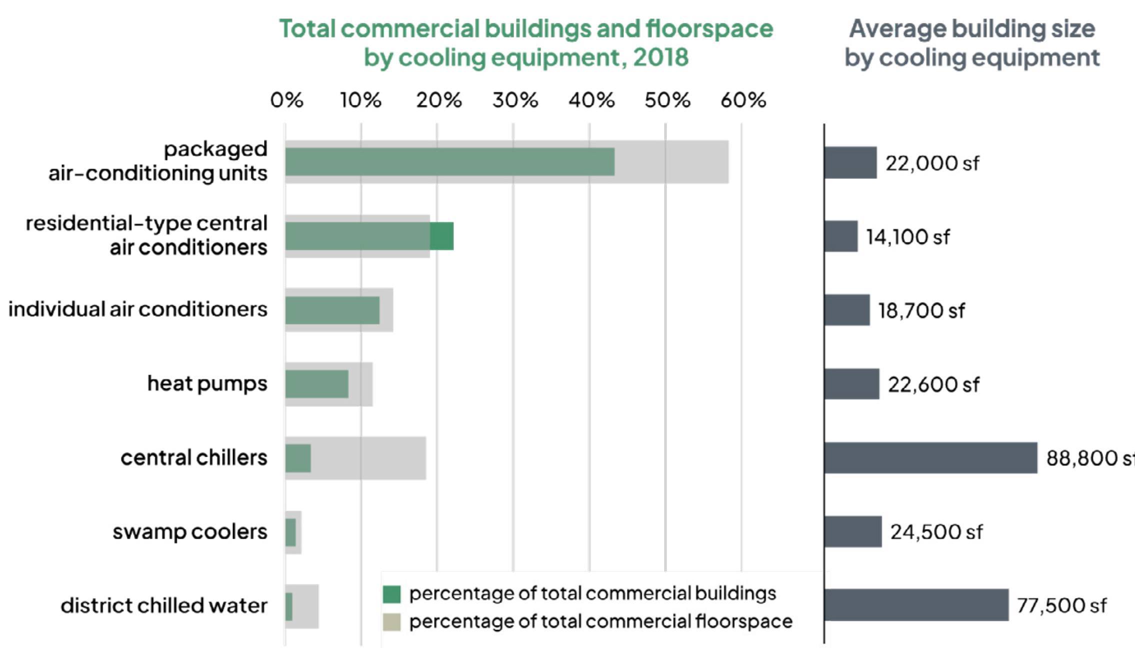


Figure 14. Number of commercial buildings with air-conditioning by cooling equipment type and floorspace
Source: (EIA 2021)

The Role of Refrigerants

Refrigerants are everywhere. We depend on refrigerant-based equipment and systems to keep our food cold and make our indoor air comfortable. Traditional refrigeration systems use manufactured refrigerant chemicals such as hydrofluorocarbons (HFCs), which were the primary replacement for prior-generation refrigerants such as hydrochlorofluorocarbons (HCFCs) and chlorofluorocarbons (CFCs), which were phased out in the Montreal Protocol (1987) for their ozone-depleting properties. CFCs also have greater Global Warming Potential (GWP) than HFCs, and their phase down has helped to mitigate the global warming impact of refrigerants. Yet despite their have lower impacts on ozone and relatively improved greenhouse gas emissions impact, HFCs are still potent greenhouse gases with high GWP. HFCs have an estimated 1,000 to 9,000 times greater GWP than carbon dioxide and are the fastest growing source of emissions in the U.S. (New York State Department of Environmental Conservation 2022).[5] The impact of these chemicals is of concern because all heating, ventilation, air-conditioning, refrigeration (HVACR) systems that use refrigerants have a high likelihood of incurring leaks over the equipment lifetime, releasing these potent GHGs directly into the atmosphere. Because most refrigerants have no color or odor, leaks can be difficult to identify and fix. The general market approach is to ignore leaks until a significant issue arises.

Officials from 170 countries negotiated an amendment in Rwanda (2016) to the Montreal Protocol, proposing a global phasedown of HFCs, with a schedule for eliminating 85 percent of HFC emissions by 2050. The synthetic refrigerants adopted in place of HFCs have lower GWP, and some ultra-low GWP refrigerants have negligible impact on the environment and are available for most commercial and industrial applications. Although other countries embraced this "Kigali Amendment," the United States has been slow to shift away from HFCs, despite the serious GHG threat these refrigerants pose to the climate. Table 3 shows the refrigerant options the industry has developed with the goal of reducing environmental impact and tradeoffs.

Table 3: Refrigerant Types and Attributes

Refrigerant Type	Global Warming Potential[6]	Ozone Depletion	ASHRAE Refrigerant Safety Group Classification	HFC / CFC / HCFC/ HC [a]
CO_2	1	0	A1	N/A – inorganic compound
R-290	3	0	A3	HC
R-152a	0	124	A2	HFC
R-454A	240	0	A2L	HFC
R-454B	475	0	A2L	HFC
R-32	675	0	A2L	HFC
R-22	1,810	.055	A1	HCFC
R-410A	2,090	0	A1	HFC
R-11	4,750	1	A1	CFC
R-12	10,900	1.0	A1	CFC
R-23	14,800	0	A1	HFC

Source: (EPA 2022)

Table note: a.) HFC = hydrofluorocarbon, CFC = chlorofluorocarbon, HCFC = hydrochlorofluorocarbon, and HC = hydrocarbon.

5 GWP is a scale that allows comparisons of the global warming impacts of different gases. It is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period (usually 100 years), relative to the emissions of 1 ton of carbon dioxide (CO_2). See the U.S. Environmental Protection Agency fact sheet on GHGs and GWP: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.

6 EPA generally relies on GWP values within the Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4): https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

Although the Kigali Amendment to the Montreal Protocol entered into force in 2019, following its adoption in 2016 by the Parties to the Montreal Protocol, the U.S. set in motion relevant legislation, the American Innovation and Manufacturing (AIM) Act of 2020, to align with the Kigali Amendment's phasedown timeline.[7] The AIM Act directs the EPA to address approximately 20 HFCs in three ways: (1) phasing down the production and consumption of listed HFCs; (2) managing the HFCs and their substitutes; and (3) facilitating the transition to advanced, next-generation technologies.

The EPA estimates the rule would eliminate the equivalent of 4.7 billion metric tons of carbon dioxide from 2022 to 2050 — about equal to three years of U.S. power sector pollution. Major U.S. equipment and refrigerant manufacturers support the principles behind the Kigali Amendment and are working to accelerate the transition to environmentally friendly refrigerants that are both cost effective and energy efficient. The AIM Act does not address or require any efficiency improvements that can be made in conjunction with the transition to less harmful refrigerants.

It is important to note that neither federal nor state HFC phasedown requirements address the hundreds of thousands of existing HVACR systems. There are neither requirements nor incentives for end-users to stop using existing refrigerants. Existing equipment might leak high-GWP refrigerants, causing significant GHG emissions. Existing systems—because of their age, wear and tear, and deferred maintenance—also tend to consume much more electricity than new systems. The expected life of a single refrigeration system or packed rooftop unit is up to 30 years. The slow replacement rate of HVACR systems is due in part to the nature of the technology and the general low adoption rate of new technologies where well-established technology already exists.

It is also important to note that while natural and synthetic low-GWP refrigerants are commercially available in large refrigeration systems and chillers, the split-system HVAC low-GWP refrigerant landscape has historically lagged behind. The technical and market challenges are discussed in the Barriers section. Recent advancements in technology and safety standards have opened up the HVAC market to low-GWP refrigerant options, with a general target GWP at or below 750. The GWP ceiling of 750 for the HVAC sector is driven by the California Air Resources Board (CARB)'s HFC phasedown legislation, which is more aggressive than the currently proposed federal regulations under the American Innovation in Manufacturing (AIM) Act. U.S. refrigerant manufacturers are actively developing nontoxic, nonflammable (A1 per ASHRAE classification) chemical blends that can meet the 750 GWP limit, but the most widely available option today is R-32, a mildly flammable (A2L per ASHRAE classification) refrigerant that has been installed in European and Asian HVAC equipment for years. R-32 has a 100-year GWP of 675 and was used in this report as a proxy for any synthetic refrigerant with a similar GWP that may be developed by 2050.[8]

Technical Solutions

A 2021 building electrification roadmap developed an opportunity analysis of heat pumps for displacing fossil fuel-based heating systems. Heat pumps were identified as a preferred technical solution due to their diverse applicability and relative product maturity as a commercialized technology, as well as offering significant emissions reductions and energy savings over conventional natural gas technologies. The report assessed heat pumps for residential and commercial buildings based on technology readiness, building type and applications—new construction and retrofit, among other criteria (New Buildings Institute 2021).

7 In addition, President Joseph Biden signed an executive order on January 27, 2021, directing his administration to send to the Senate, for ratification, the Kigali Amendment's phasedown of HFCs.

8 IPCC's Fourth Assessment Report (AR4)

As an example of the impact from heat pump adoption, the 2021 Building Electrification Technology Roadmap compared the direct energy and emissions benefits of a heat pump and premium heat pump with low GWP refrigerants to a high-efficiency condensing gas furnace in a residential home. In this analysis, the premium heat pump refers to inverter-driven, variable-speed models with higher heating performance in cold climates and offers a 36% energy reduction in equivalent MMBtu per year and 71% reduction in metric ton carbon equivalent emissions per year.

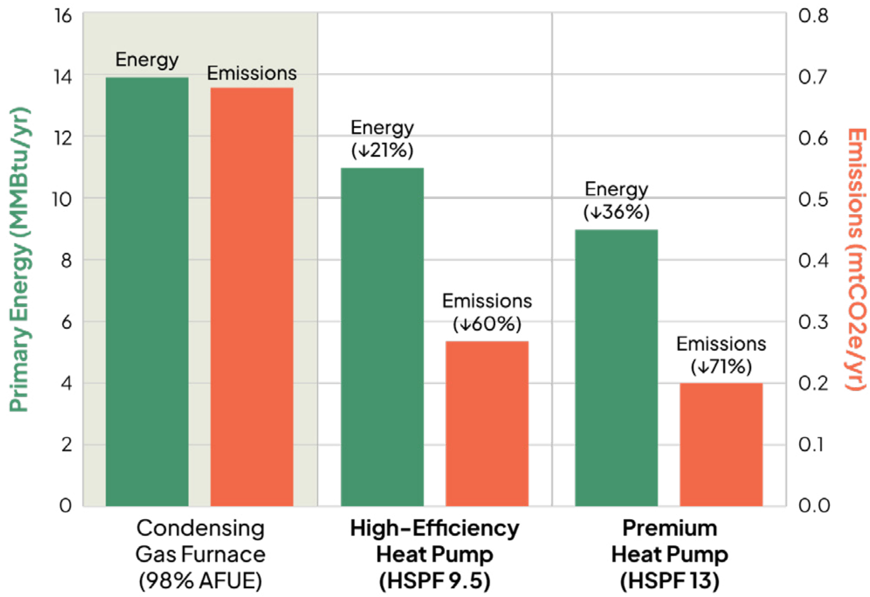
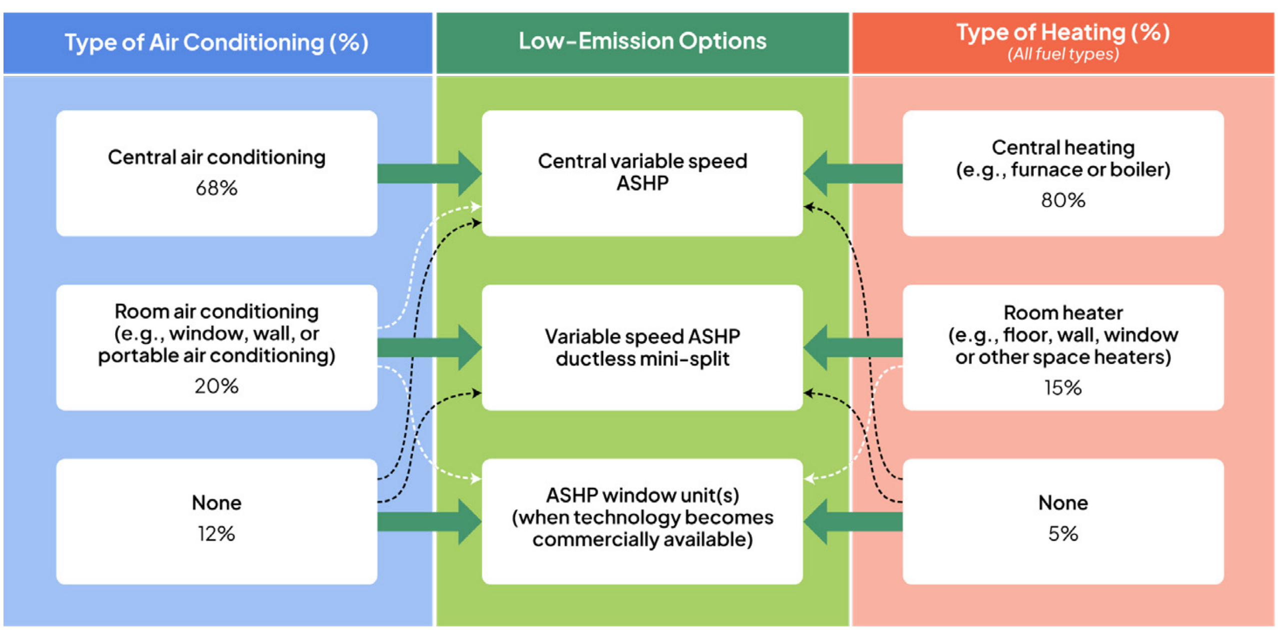


Figure 15. Energy and emissions comparison of gas furnaces and high-efficiency heat pumps

Source: (New Buildings Institute 2021)

As highlighted by the EIA RECS 2020 survey of residential space cooling and heating data, central air-conditioning and central natural gas furnaces are the single largest opportunity for clean cooling and heating heat pump solutions. Table 4 below is a summary of the targeted residential baseline cooling and heating systems and the corresponding general primary and secondary low-emissions solutions.

Table 4: Residential Baseline Systems and Low-Emission Options for Cooling and Heating



Source: (EIA 2022)

As commercial buildings range in scale from small residential-scale businesses to large commercial offices with significant and often simultaneous needs for heating and cooling, the heat pump solutions scale to the applications. For the smaller buildings, the residential-style packaged and split, inverter-driven heat pumps offer a comprehensive heating and cooling solution that varies capacity to meet building loads—even in predominantly cool/cold climate regions. However, for larger commercial applications, VRF heat pumps offer a more centralized and economical solution to smaller packaged and split heat pumps and capability to provide simultaneous heating and cooling to multiple and diversely loaded zones (NEEP 2019).

Table 5: Commercial Baseline Systems and Low-Emission Options for Cooling and Heating

Type of Air Conditioning (%)	Low-Emission Options	Type of Heating (%) *(All fuel types)*
Packaged air conditioning 66%	VRF or air-to-air heat pump	Packaged heating units 42%
Residential-type central air conditioning 21%	VRF or central variable speed ASHP (based on floorspace cooled)	Central heating (e.g., furnace or boiler) 40%
Room air conditioning (e.g., window, wall, or portable AC) 13%	ASHP window unit or ductless mini-split	Room heater (e.g., floor, wall, window, or other space heaters) 18%

Source: (EIA 2021)

Analysis is based on a subset of CBECS data representing prevalent primary space heating/cooling types.

The technical analysis supporting this study focused on air-source heat pumps and VRF heat pump technologies available on the market today. However, rapid innovations in technology expanding performance in cold climates, utilization of low GWP refrigerants, as well as the diversity of design solutions including ductless, ducted, air to water and future window-installed heat pumps, will continue to increase levels of performance, range of applications and integration with building and grid needs.

One notable new, emerging heat pump technology is the development of window-installed heat pump products, a focus of the New York "Clean Heat for All Challenge" which launched an industry competition in 2021 to retrofit 50,000 affordable housing multifamily apartments over 10 years. The New York City Housing authority has committed to purchasing 25,000 units of the winner of the Challenge deploying them in six of their housing developments over five years.

Heat Pump Technology + Passive Cooling

The extrapolated interventions modeled included an analysis of baseline emissions plus six different mitigation scenarios. Each mitigation scenario assumes fully electrified heating, with a reversible air-source heat pump utilizing electric-resistance back-up as weather conditions require. The mitigation scenarios address two different types of heat pumps, single-speed and variable-speed ("VRF/ccASHP"), each examined with the cumulative impact of a heat-pump only retrofit, a heat-pump plus weatherization retrofit, and a heat pump plus weatherization, lighting efficiency, and plug load controls. The analysis was run for two different grid emissions factor scenarios: 2019 emissions factors using EPA Emissions Factors for Greenhouse Gas Inventories (18% renewable) and an NREL Cambium scenario with a 95% decarbonized grid in 2050 compared to 2005 levels (80% renewable). The EPA emissions factors are based on historic actuals and include peak emissions in their averages. The Cambium data set is a simulation of the whole power system, including peak emissions.

Figure 16 below presents the results based on the 2050 grid emissions factors. These emissions do not account for upstream methane leakage in the baseline gas furnace scenario. These emissions totals address the four prototypical buildings and eight climate zones included in the mitigation analysis.

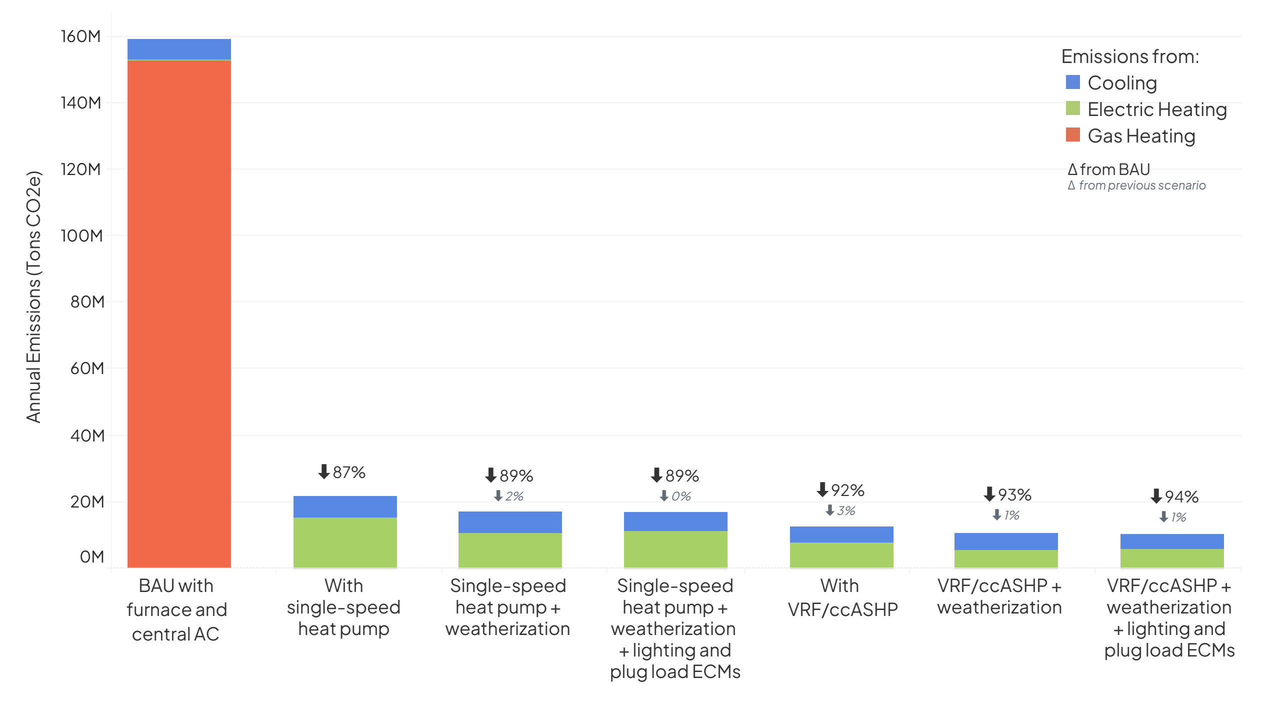


Figure 16. 2050 BAU and mitigation scenario emissions for four prototypical buildings in the study region using 2050 grid emissions factors (80% renewable)

The results of the analysis show that the greatest emissions reduction potential for the prototypical buildings lies in the heat pump retrofit, with weatherization, and lighting efficiency and plug load controls (referred to as "energy conservation measures" or "ECMs") yielding incremental additional savings. Assuming an 80% renewable grid in 2050, a single-speed heat pump would generate carbon savings of 89% against combination furnace and air-conditioning that is typical today. The importance of efficiency levels within the choice of heat pump systems is evident from the even greater savings from a variable-speed (VRF or cold climate) heat pump—94% against the baseline or an additional 5% beyond a single-speed heat pump.

As noted above, this analysis is based on prototypical buildings that include a single baseline heating system. To explore the implications of more varied baseline conditions in the building stock, the project team analyzed the impact of including a share of single family and multifamily households having electric-resistance heating in the BAU scenario. While the residential sector shows a 96% reduction in heating emissions against the single system per prototype scenario, the heating emissions reduction goes down to 95% when adjusting the BAU scenario for some electric-resistance heating.

Even considering the emissions factors of the 2019 grid, variable-speed heat pumps continue to show a strong potential for savings against the BAU scenario. However, in most building types and climate zones analyzed, single-speed heat pumps would need to be replacing a worse-than-average baseline system or be combined with weatherization to achieve carbon reductions with the 2019 grid emissions factors. It is important to note that the 2019 emissions factors are based on national averages, and emissions factors within certain regions could be sufficient to deliver emissions reductions in the single-speed heat pump scenario. Figure 17 below illustrates the impact of the 80% renewable 2050 grid compared to the 18% renewable 2019 grid for the current, typical building systems and each of the seven mitigation scenarios.

The analysis in Figure 17 was completed using the 2050 projected weather data. In addition to showing the impact of the improved grid, it also makes clear that although the improved grid and warmer weather will drive down overall building emissions in 2050 from where they are today, significantly greater savings are possible through heat pump deployment, weatherization, lighting efficiency and plug load controls. In the BAU with furnace and central air-conditioning scenario, grid improvements lead to an approximately 37% annual emissions reduction, whereas the best-case scenario of variable-speed heat pump, weatherization, other energy conservation measures yields an emissions reduction greater than 80%.

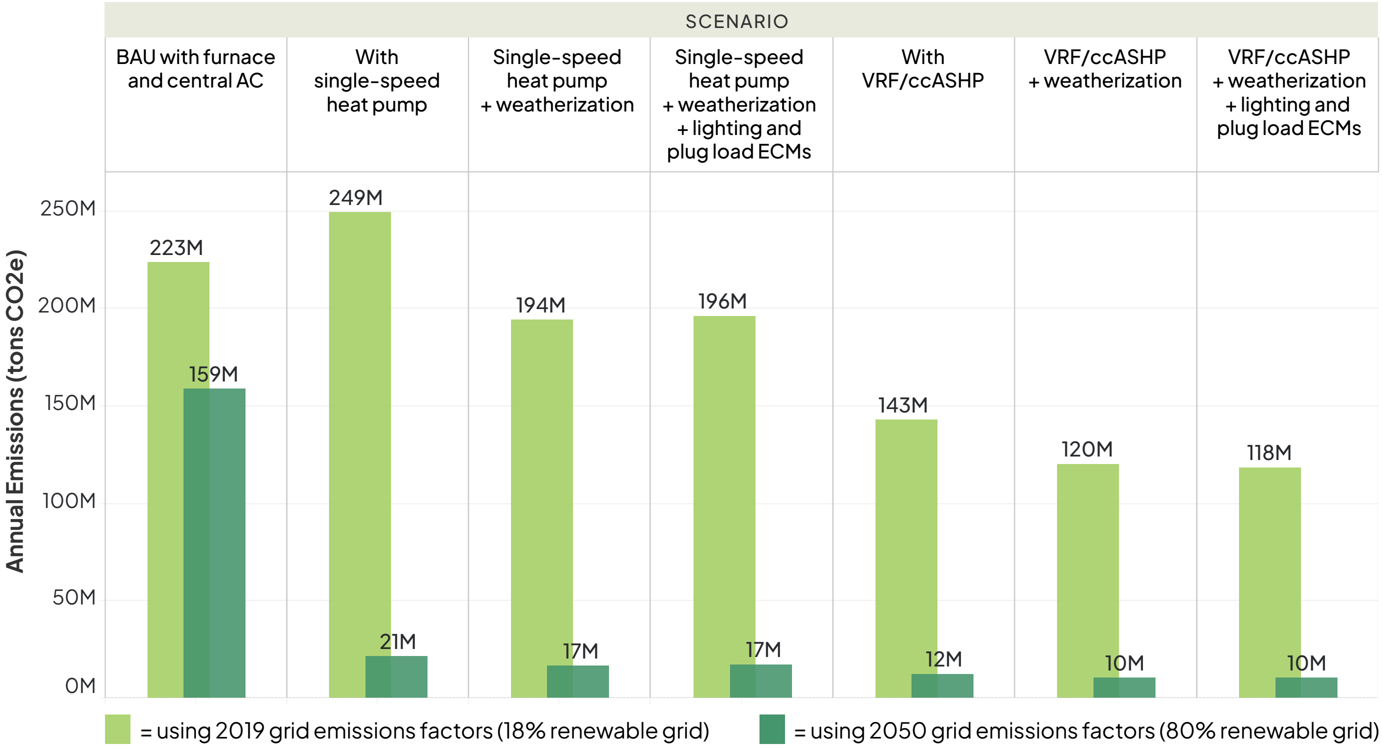


Figure 17. Comparative 2050 annual scenario emissions for four prototypical buildings in the study region using 2019 and 2050 grid emissions factors

While the figures above make clear that variable-speed heat pumps show a significant energy and emissions reduction compared to single-speed options, the impact is even more dramatic when looking at peak electricity demand. Figure 18 below represents the per building summer and winter peak electricity demand for a single family home in Climate Zone 4A (Mixed Humid) with either a single-speed or variable-speed cold climate air-source heat pump (ccASHP). These electric demand figures were calculated using the projected 2050 weather data (BAU scenario).

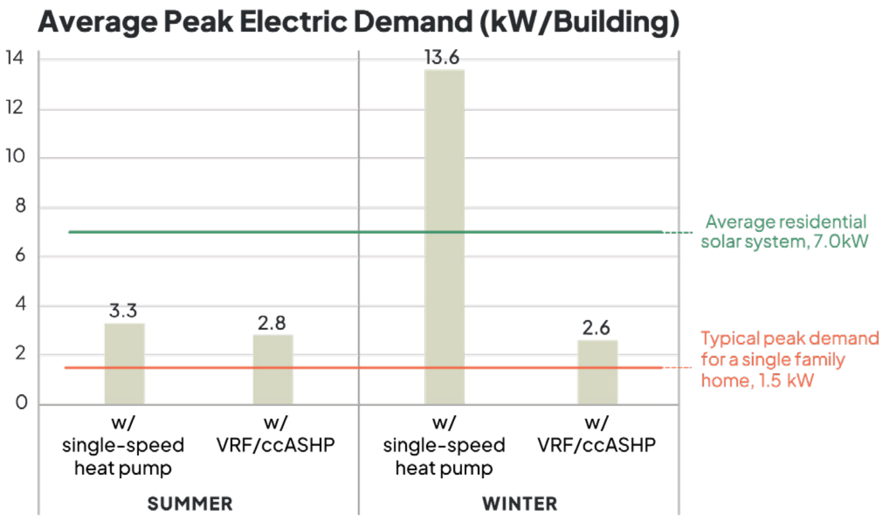


Figure 18. Average 2050 winter and summer peak electric demand for single family home in climate zone 4A with single- or variable-speed heat pump

The variable-speed heat pump reduced peak demand by 15% for summer peaks and 80% for winter peaks. Importantly, this analysis also shows that the variable-speed heat pump can keep winter peak demand below the standard heat pump's summer peak. This demonstrates the potential of high-performance heat pumps to alleviate concerns that electrification will lead to winter peaking grids when less solar production is available to meet peak demand. Single family homes in Climate Zone 4A provide a dramatic example of this trend due to their high winter peak demand with a single-speed heat pump. However, the pattern that variable-speed heat pumps have lower per-building winter peak demand than single-speed heat pumps' summer peak demand is consistent across building type and climate zones.

Refrigerant GHG Mitigation

While buildings' energy use is a core driver of emissions, direct emissions from refrigerants are another consideration when assessing the climate impacts of different heating and cooling options. This study analyzed refrigerant emissions for the baseline heating and cooling equipment (furnace and central air-conditioning) and a heat pump scenario without any strategies to mitigate emissions from refrigerants. Both scenarios were analyzed based on R-410A refrigerants due to its current market share for air-conditioning systems in the U.S. We also looked at five refrigerant GHG mitigation scenarios:

1. A shift to low-GWP refrigerants (R-32 or similar)
2. Leak-tight installations for 80% of installs and end-of-life recovery for 80% of systems
3. A shift to a mix of low-GWP and ultra-low GWP refrigerants (50% R-32, 50% R-290)
4. The 50/50 low and ultra-low GWP refrigerant blend plus leak-tight installation and end-of-life recovery for 80% of systems
5. Shift to R-290 or other refrigerant with negligible environmental impact (100% adoption)

Figure 19 shows the results of the 2050 refrigerant analysis combined with the heating and cooling emissions from variable-speed heat pumps using 2050 grid emissions factors. The analysis includes two "baseline" scenarios for refrigerants, one with the gas furnace and central air-conditioning systems using BAU building energy use emissions, and one with heat pumps. Refrigeration mitigation scenarios are compared to these two baseline systems. The analysis shows that although emissions from refrigerants alone increase from the baseline scenario with furnace and central air-conditioning to a heat pump scenario without refrigerant GHG mitigation, the total building emissions in that scenario is more than 70% lower due to the large reduction in emissions from heating energy use. Furthermore, a switch to low-GWP refrigerants would drive refrigerant emissions below the baseline with furnace and central air-conditioning scenario, with further incremental reductions in refrigerant emissions possible through additional mitigation measures. The best-case scenario analyzed, 100% ultra-low GWP refrigerants, delivers 99.99% lower refrigerant emissions than the baseline with furnace and air-conditioning and 94.5% lower overall emissions.

A similar pattern holds when looking at refrigerant emissions with heating and cooling emissions from variable-speed heat pumps using 2019 grid emissions factors (Figure 20). The refrigerant emissions do not change, and the reduction in heating and cooling emissions is sufficient to offset the increase in refrigerant emissions from the larger refrigerant load sizes associated with using heat pumps for heating and cooling. With 2019 grid emissions factors, the baseline heat pump scenario has 35% lower overall emissions, and the best-case scenario shows a 53% emissions reduction across energy use and refrigerants.

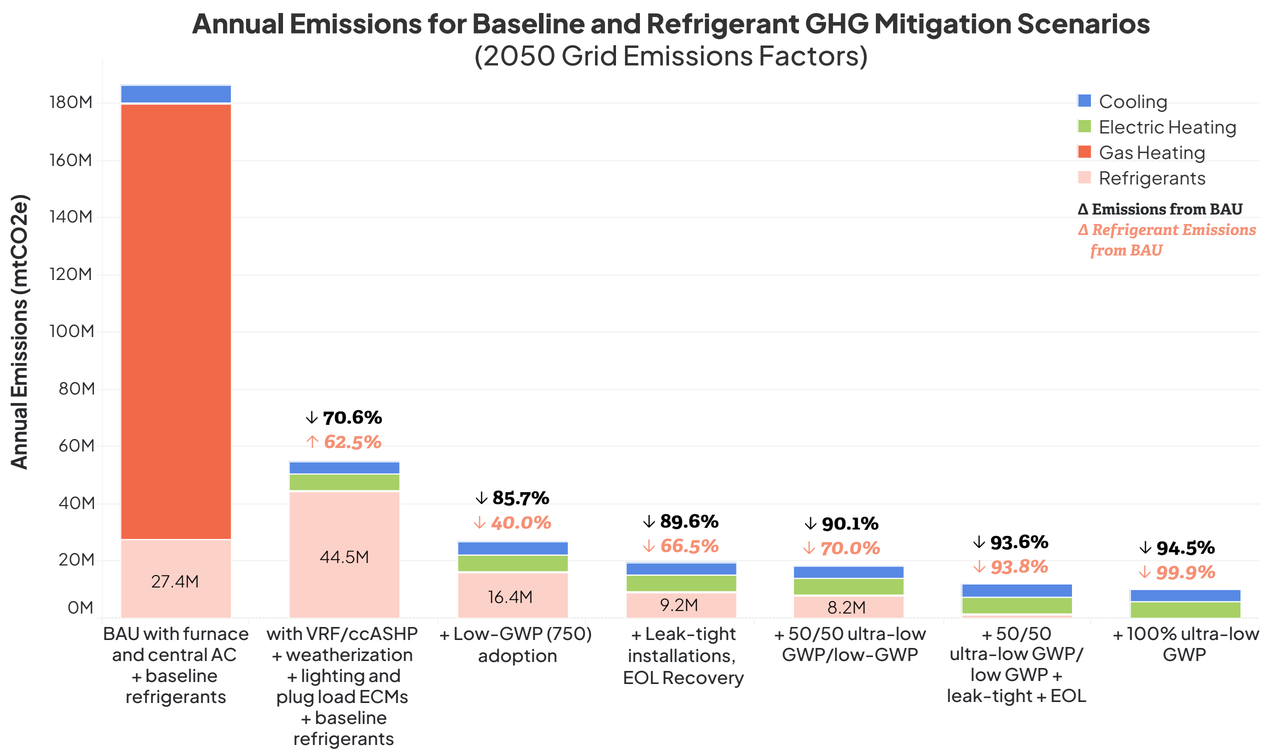


Figure 19. 2050 energy use and refrigerant GHG emissions for two scenarios with no refrigerant mitigation and five refrigerant GHG mitigation scenarios using 2050 emissions factors (80% renewable)

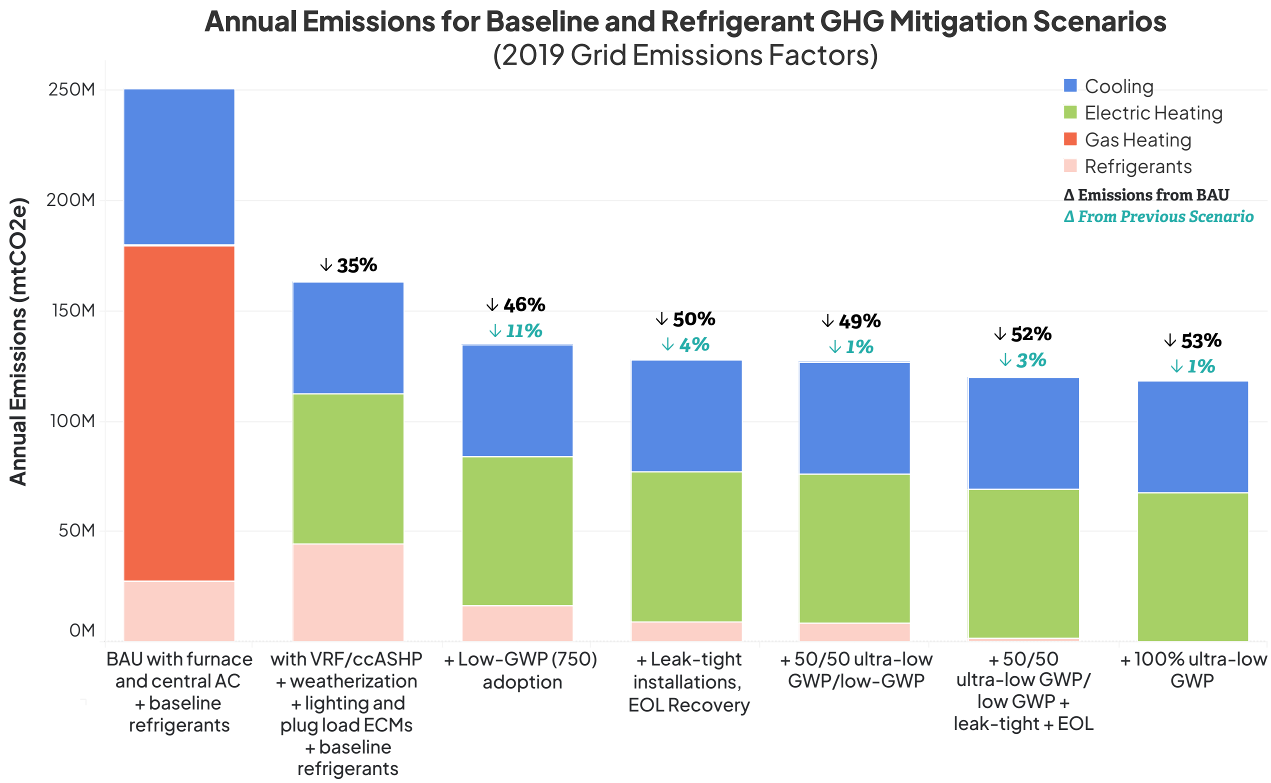


Figure 20. 2050 energy use and refrigerant GHG emissions for two scenarios with no refrigerant mitigation and five refrigerant GHG mitigation scenarios using 2019 grid emissions factors (18% renewable)

Heat Pump Market Potential

Heat pump adoption and future potential in the U.S. varies widely based on application—space heating and cooling, market opportunity—new construction and retrofit, as well as by building type—residential and commercial and application (see Figure 21).

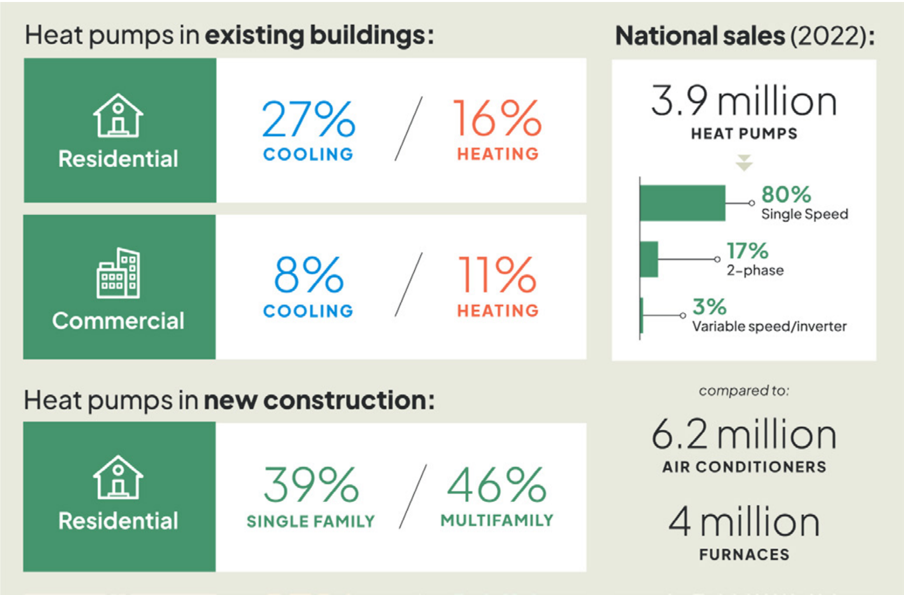


Figure 21. Current heat pump adoption in the U.S.

Sources: (EIA 2015/2020/2021; AHRI 2021; DOE 2020; NAHB 2020; Industry Interviews 2021)

Heat Pumps in Residential and Commercial Space Heating and Cooling Applications

In existing residential buildings, heat pumps represent 27% of central air-conditioning (EIA 2015) and 16% of heating systems (EIA 2021). This higher rate of adoption in air-conditioning systems reflects the common components, design and installation requirements that heat pump systems share with traditional air-conditioning systems.

Commercial building adoption of heat pumps lags residential with approximately 8% cooling and 11% heating, though serving a higher representative share of total commercial buildings floorspace, 11% and 16% respectively (EIA 2018).

In 2021 shipments of over 4 million gas furnaces and over 6 million air conditioners were reported compared to nearly 4 million heat pumps. Reported heat pump shipments in 2021 were predominantly (97%) smaller residential-scale models between 1–5 ton capacity (AHRI 2021).

Typically, air-conditioning first-time purchases and emergency replacements occur at the peak of summer. For first-time purchases, decisions and installations often need to be made quickly during heat waves. For replacements, the timing for repair, equipment availability and unplanned costs lead customers to a "like-for-like" replacement. The CLASP 2021 analysis proposed displacing the market for unidirectional conventional air-conditioning technologies with bi-directional or reversible heat pump solutions that offer a relatively low incremental cost—especially if discounted upstream at the manufacturer-level. In cooler and cold climate regions, this solution would allow for additional offset of existing central furnace load—especially in shoulder seasons—at no additional cost.

Growing Market Share of High-Performance Heat Pumps

Based on guidance from industry an estimated 80% of today's heat pumps in the U.S. are single-speed, 17% are dual-speed, and 3% are variable-speed, inverter driven models (Industry Interviews 2021). Federal efficiency standards will increase in 2023, raising the minimum standard cooling and heating efficiency of residential air conditioners and heat pumps. Increased standards continue to put upward pressure on traditional air-conditioning equipment, forcing design improvements to achieve efficiency levels more easily met by heat pumps.

Federal minimum standards, and voluntary utility and ENERGY STAR® specifications, measure heat pump performance based on two metrics: Seasonal Energy Efficiency Rating (SEER) and Heating Seasonal

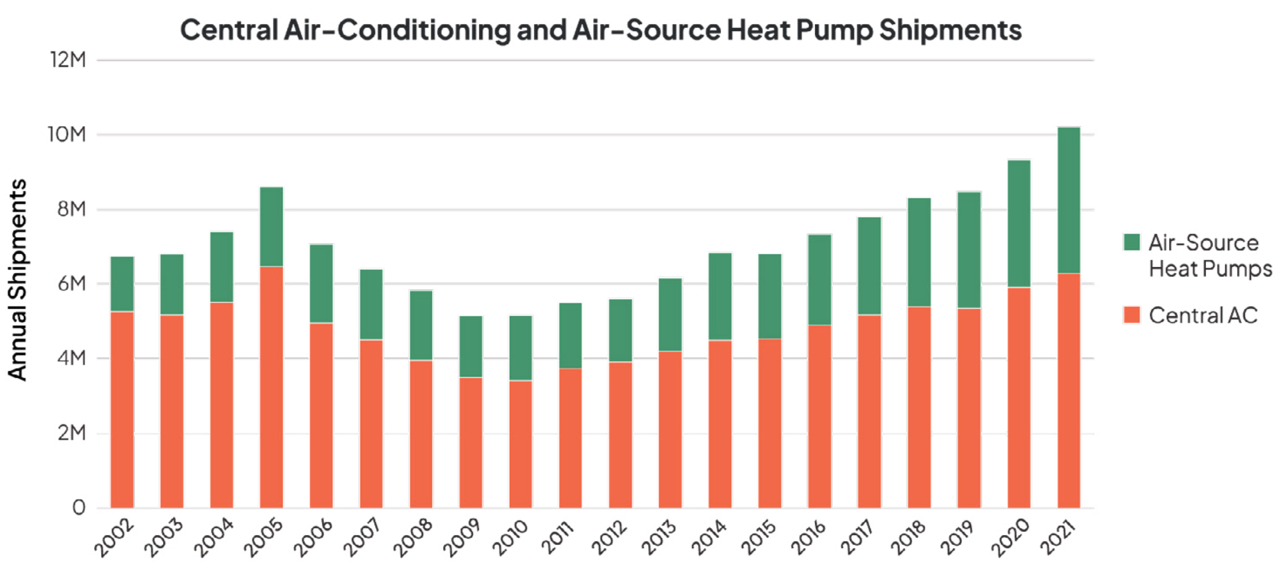


Figure 22. Central air-conditioning and air-source heat pump shipments between 2002 – 2022

Source: (AHRI 2021)

Performance Factor (HSPF). SEER applies to the cooling season efficiency of air conditioners and heat pumps, whereas HSPF is applicable only to heat pumps due to their ability to reverse operation during the heating season. The Southwest region has a federal minimum energy efficiency ratio (EER) as well for air conditioners, but not for heat pumps, representative of performance for temperatures higher than 95°F.

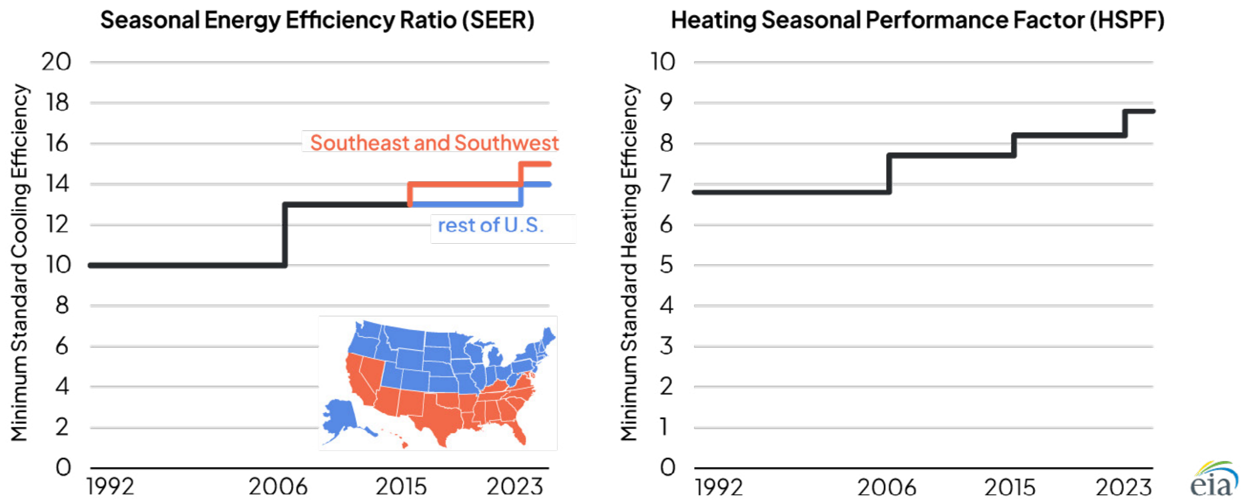


Figure 23. Increasing federal minimum efficiency standards for residential air-conditioning and heat pumps
Source: (EIA 2019)

Increasing use of heat pumps for heating applications—especially in cold climates—is accelerating the development and sales of variable-capacity, inverter-driven heat pumps. Regional energy efficiency organizations in the Northeast and Northwest have developed ccASHP requirements and specifications "designed to identify air-source heat pumps that are best suited to heat efficiently in cold climates (IECC Climate Zone 4 and higher)" (NEEP 2022). The ccASHP specification requires eligible models to be variable-capacity and achieve a coefficient of performance (COP) greater than 1.75 at 5°F at maximum capacity operation, a SEER greater than 15, and HSPF greater than 9 or 10 for ducted and ductless models respectively. Although the Northwest uses the NEEP ccASHP product list, only ductless heat pump models and those meeting or exceeding 80% of nominal capacity at 5°F are eligible. Meeting the Northwest minimum cold climate capacity requirements effectively can only be achieved by continuously variable-capacity, inverter-driven heat pump models, which achieve high SEER levels exceeding 17 in the NEEP ccASHP qualified product list. While there is some correlation between variable-speed capacity and efficiency, there isn't certainty; there is an opportunity for compressor type to be shared more widely as a field in AHRI's public database.

Higher Opportunities for Heat Pumps in New Construction

Residential new construction represents a significant area of growth with 38% of buildings with heat pump air-conditioning and 39% of single family and 46% of multifamily with heat pump heating systems (U.S. Census Bureau 2020). However, as shown in Figure 24, geographically the market share of heat pumps used for space heat in new homes ranges significantly in 2020 with a high of 77% in the east south central region and lower adoption levels from 3% to 20% in northern colder climate regions (NAHB 2020).

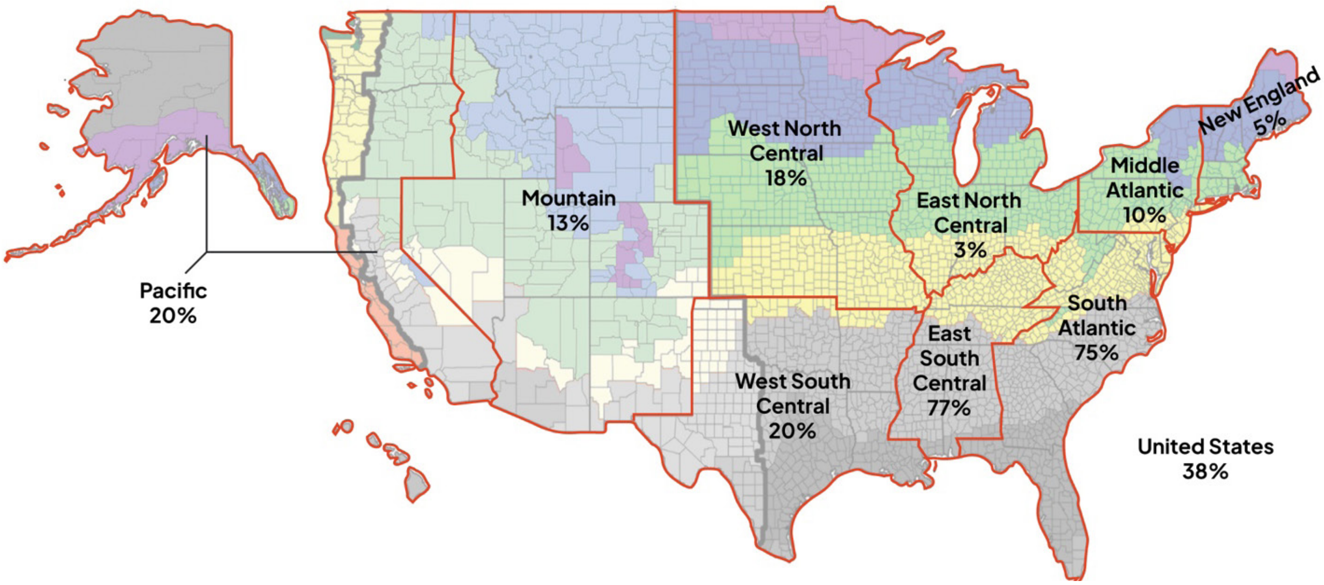


Figure 24. Share of new homes in 2020 with air or ground source heat pumps for space heating with overlay of study region

Source: (NAHB 2021)

New construction has a significantly higher adoption of heat pumps due to increasing requirements of building codes, equipment standards, engineered whole-building designs and other valued non-energy benefits (e.g., increased usable space and lower system costs). As highlighted previously, increased stringency of new federal minimum efficiency standards will reduce the incremental cost barriers to higher-efficiency heat pumps, as conventional technologies face new development hurdles, increased costs and performance limitations.

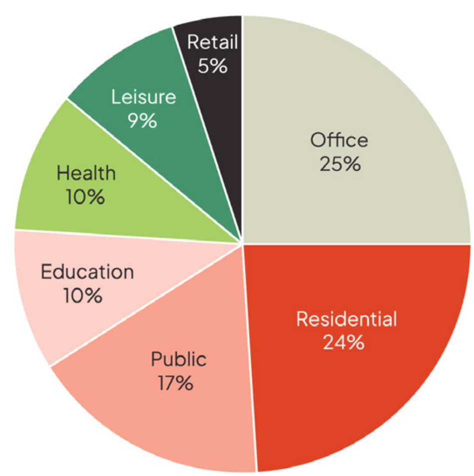


Figure 25. U.S. VRF applications in 2020

Source: (ASHRAE 2021a)

VRF heat pump systems historically have captured a larger proportional share of new construction in light and medium commercial applications. As shown in Figure 25, more recently, residential applications of mini-VRF have grown to 24% of VRF installations (ASHRAE 2021a). Commercial applications of VRF are led by offices (25%), which are often seen as an ideal application of VRF to maximize the benefits of the variable capacity to meet individual space loads and occupancy, elimination of ductwork, as well as heat recovery capability to provide simultaneous heating and cooling with a single outdoor unit instead of redundant systems.

Key Barriers to Heat Pump Deployment

We identified specific barriers to widespread adoption of heat pump heating and cooling solutions based on a review of market and technology studies, direct interviews with key industry stakeholders, and engagement during project stakeholder meetings. These barriers were segmented into three categories: **technology**, **industry**, and **affordability**. Technology and industry are covered in this section; affordability is covered in the *Achieving Distributional Equity* section.

Technology barriers

EMERGENCY PURCHASES

One barrier to increasing market share is the common case of emergency purchases, both replacements and additions of new cooling systems due to rapid changes in climate and prolonged heat waves. A recent report estimated that 85% of HVAC system replacements are done on an emergency basis (Pantano et al. 2021). Typically, distributor stocking, contractor proficiency, upfront costs, and existing site design based on conventional air-conditioning and heating systems will limit opportunities for heat pump conversions and additions. Overcoming this status quo in the HVAC industry is critical to advancing the adoption rate of high-efficiency heat pump alternatives.

Increasing federal minimum efficiency standards continue to raise the floor for all equipment replacements and new purchases. However federal standards and the applicable test procedures do not adequately capitalize on the advantages of heat pumps, particularly variable-speed heat pumps.

LACK OF PRODUCT AWARENESS AND CONFIDENCE

Heat pump manufacturers identified a lack of awareness of heat pump technologies and the benefits they offer (increased comfort, higher efficiency, and in some cases operational cost savings) as a significant barrier to increased market adoption.

Early heat pump designs suffered from performance issues. As a result, increasing contractor and building owner confidence is a critical element to drive adoption in northern climates in the U.S. Recently developed cold-climate specifications place specific emphasis on variable-capacity and advanced inverter-driven heat pumps able to operate at full capacity in cold climates. These specifications include requiring manufacturers to report on performance at cold temperatures for heat pumps to be included in qualified product lists that are used for incentive programs and code compliance in northern climates.

LACK OF REALIZED VALUE FROM VARIABLE SPEED AND REFRIGERANT FLOW

Variable-speed and variable-refrigerant-flow systems offer a clear value to customers and the grid at-large, yet due to the sophistication of the technology, the ecosystem has not yet caught up to realize these benefits, ranging from modeling software to test procedure to lack of automated connectivity.

LACK OF LOW- AND NO-GWP REFRIGERANT OPTIONS

The U.S. HVAC market has historically been restricted by various technical challenges in its attempts to identify a lower GWP refrigerant to replace R-410A. Unlike the commercial refrigeration market, which has developed multiple ultra-low GWP refrigerant solutions for most applications, there is not currently a clear path to an ultra-low GWP refrigerant solution for HVAC systems, particularly split systems such as heat pumps. The main ultra-low GWP refrigerant options—propane (R-290), ammonia (R-717), and carbon dioxide (CO_2, R-744)—all present significant barriers to widespread market adoption. Refrigerant-grade CO_2 has high operating pressures and if equipment were to fail inside a home or office building, there could be serious injuries. Additionally, the thermodynamic properties of refrigerant-grade CO_2 cause its efficiency to suffer significantly in warm ambient conditions, potentially offsetting HFC emissions savings by increasing energy consumption during space cooling. Ammonia, which has remained popular in large industrial plants, is toxic at relatively low parts per million (ppm) concentrations, though is being explored some for more expansive HVAC applications. Propane is the most promising ultra-low GWP refrigerant option, due to its thermodynamic efficiency which is unaffected by ambient conditions. However, international and national restrictions on A3 (highly flammable per ASHRAE classification) refrigerants such as propane have prevented any products utilizing these refrigerants from entering the U.S. HVAC market. The International Electrotechnical Commission (IEC), the international body responsible for the safety standards that apply to household appliances like window air conditioners and heat pumps, recently voted to increase the maximum allowable charge for A3 refrigerants. However, the process to update U.S. safety standards to reflect the international charge increases is uncertain.

Even most synthetic refrigerant blends that would be appropriate replacements for R-410A (similar efficiency and capacity) are struggling to keep both flammability and GWP low. To meet the 750 GWP limit in place in California, new refrigerants often include one or more flammable components, such as a hydrocarbon like propane, or an HFO. This results in an ASHRAE classification of A2L, or mildly flammable. Charge restrictions exist for A2L refrigerants, but the maximum allowable charges are typically higher than for A3 refrigerants. R-32 is an A2L refrigerant that has been widely adopted for space cooling in the European and Asian markets; manufacturers are working to develop an A1 (nontoxic, nonflammable) refrigerant that can compete with R-32 in the U.S. HVAC market. The biggest barrier the market faces is identifying a refrigerant blend that has similar capacity and efficiency to R-410A, but carries a significantly lower GWP without introducing flammable components.

Industry Barriers

WORKFORCE KNOWLEDGE AND CAPACITY

The centralized heating and cooling solutions using metal ductwork, which have historically dominated the U.S. HVAC market, require mechanical engineering application knowledge. However, introduction of heat pumps and new refrigerants as clean alternatives increases the need to make expanded training available to contractors as well as distributors in the HVAC industry.

Additionally, increasing rates of workforce retirement and transitions to other occupations—deemed a "Gray Tsunami" in HVAC and refrigeration industry (Turpin 2022) continues to place significant strain on contractors' ability to build out the necessary skilled workforce for a rapid clean heating and cooling technology transition.

LACK OF INSTALLER VALUE PROPOSITION

Heat pumps offer a higher-efficiency HVAC solution for residential and commercial buildings. But the value proposition for installers to promote new heating and cooling solutions is limited by contractor experience with the technology and customer awareness, as well as contractor capacity. As highlighted by the status quo of emergency first-time purchases and replacements, the immediate need to provide heating and cooling at an affordable price to customers often constrains contractors' upselling of heat pump technology despite the lasting benefits.

Incentivizing and strengthening the value proposition for the entire HVAC industry to proactively promote and sell clean heating and cooling solutions is essential to increase adoption. This includes addressing some higher costs (e.g., when comparing a heat pump to just a furnace or air conditioner, or incremental cost of variable-speed) and complexity of installations. Increased customer awareness of product benefits may raise demand for early replacement of aging equipment, and thus offer more sales opportunities for installers.

SUPPLY CHAIN PRODUCT AVAILABILITY AND PRICE HIKES

Supply chain product availability is not a new barrier for heat pumps. However, the COVID-19 pandemic disruptions to the overall supply chain have amplified impacts to product availability, especially for heat pump products or components manufactured overseas. These impacts have not only reduced the availability, but also increased the cost of core materials and components in heating and cooling systems, requiring manufacturers to prioritize specific product construction. The increases in costs and volatility create barriers to heat pumps, especially for businesses or households with limited budgets for building improvements, even those that offer longer term operational savings.

President Biden recently invoked the Defense Production Act and specifically identified support for heat pump manufacturing as one of the sectors that will be targeted for increased federal support. The intent is to mitigate supply chain disruptions and recent price hikes associated with the pandemic and accelerate the clean energy economy in the U.S. (Aton 2022).

04

Behavior and Efficient Cooling

What goes into customer's decision-making process behind space-conditioning—when it is added, what systems are considered, and how it is used? A keen understanding of the cognitive processes that drive these factors is imperative for promoting technology, designing programs and intervention strategies, and crafting policies that influence people toward selecting efficient systems and operating them in an optimized manner.

Behavioral Context

Tolerance of warmer temperatures is influenced by culture, social norms, and repeated experiences. The high prevalence of air-conditioning in the United States building stock suggests the dominant culture is geared toward technical solutions to cooling. While many homes have both air-conditioning and ceilings fans for indoor climate control, air-conditioning systems are used far more frequently as a response to higher temperatures (EIA 2015). Related research has explored the inter-dependencies between humans and technologies and how this relationship shapes preferred temperature ranges. Here, a strong culture supporting technology to regulate indoor temperatures can insinuate that air-conditioning is the only way to achieve comfort (Mazzone and Khosla 2021). These preferences for a human-engineered environment may disrupt decarbonization goals in countries where this mentality is culturally dominant. Yet, many cultures in warmer climates still have low levels of adoption despite being technologically advanced (Biardeau et al. 2020). Instead, these areas have adopted behaviors to maintain comfort without technology, such as adjusting sleeping and work patterns to more ideal times of day. While efficient cooling technologies will be more popular in cultures similar to that of the U.S., alternatives that do not require energy should still be marketed as a viable option to maintaining comfort.

Strategies to Influence Consumer Heat Pump Selection

There are multiple value propositions that can make the case for heat pumps as a cooling solution for consumers. While situational factors such as operational cost remain barriers to be addressed through policy and regulatory considerations, behavior-specific influences can further promote heat pumps as a source of efficient cooling and heating.

To gain support for policies or incentives, messages should be framed in concrete terms that describe the tangible benefits to the individual, such as immediate bill savings for households or payback periods. Consequences of inaction, too, should be covered in terms of the local context and how wasteful products can be detrimental to residents' communities. Connecting impacts to local landmarks, institutions, or otherwise valued places that individuals can relate to expands behavioral motivation to a personal level. This is especially true for audiences that may not identify strongly with environmental values. For others, the opposite may be true; abstract framing and normative appeals can activate environmental and prosocial value orientations to motivate behavior. Examples may include framing benefits in terms of consideration for others or bringing attention to actions of a relevant reference group. Understanding the audience when framing messages is an important consideration to influence product selection and may guide behavior in an oppositional manner if done incorrectly.

While some level of product knowledge is necessary while shopping for a new appliance, expertise should not be required to select efficient products. Effortless access to relevant information to inform decisions is critical. Adequate labeling is essential for consumers to make informed decisions about their purchases. Allowing for fair comparisons between efficiency, GHG emissions (including refrigerants), and lifetime costs will drive consumers toward selecting a system that better fits their needs, which are often aligned with efficient technology.

Specific programs offered by utilities may also benefit the consumer economics. Offering incentives for efficient equipment, time-of-use rates, or rebates for utility control over the system improves the affordability for both up-front and long-term cost propositions. Common behavioral program offerings, such as Home Energy Reports, can also lead to household energy savings. These kinds of interventions compare energy usage to households of similar characteristics and demographics to display how energy efficient a home is compared to relevant peers while offering suggestions on how to save more. Innovative behavior-based energy efficiency programs have presented significant savings opportunities, with some finding up to 30% reductions in energy consumption (Sussman and Chikumbo 2016). These programs should be supported by external agencies in partnership with utilities to continue evolving this space.

Pairing a comparative energy insight label with subsidies or rebates can be an effective way to motivate purchasing decisions. DTE Energy, for example, operates an online marketplace that connects product energy rating scores with lifetime product costs and savings to offer consumers greater insights to their purchasing (DTE 2022). Similarly, Efficiency Vermont offers consumers expert-vetted efficient product choices and guidance for how to redeem rebates on eligible products (Efficiency Vermont 2022). This lowers the bar of entry by simplifying research on products and rebates by consumers. These program offerings are common for many utilities, though marketplace development varies widely. Support for standardizing these approaches should be pursued in partnership with utilities, regulators, consumer advocates, and behavioral scientists.

Users can see the timeline and magnitude of payback from an efficient option. The label also includes relevant comparisons to other models that may be considered, condensed into an energy score.

Presentations and simplifications of options guide consumers to purchase more efficient products. Marketing research has suggested that for goods like air-conditioning systems, consumers will spend more time per page reading the information about the product, but search through fewer pages overall (Huang, Lurie and Mitra 2009). Websites such as the DTE Energy and Efficiency Vermont marketplaces take advantage of this behavioral pattern by first showing the most efficient and expert-recommended options.

The amount of information provided for each product is vast but is characterized in such a way that the most important variables are most salient. This eliminates the legwork done by consumers by providing a trusted source of research and advice. Further, the estimated savings and a referential price comparison to other similar products is provided. These characteristics provide consumers with the information they seek out when looking for new equipment, without overwhelming them with detail. Additionally, color coding the efficiency score can guide consumers to select the most efficient products more often. Research in nudge theory has found simple changes in environmental signals, such as color coding, influences behavioral decisions to a significant degree (Campbell-Arvai, Arvai and Kalof 2014).

Purchasing of Efficient Product—Economic Factors

Cost is a priority concern when choosing residential and commercial systems. Even if efficient technologies can pay off in the long run, economics may present insurmountable barriers that prevent widespread adoption. In instances where upfront capital is not a barrier, future savings are often discounted; saving money now on a less expensive appliance is prioritized over the future potential of saving money, even if that value is greater (Tversky and Kahneman 1992; Griffioeon, Handgraaf and Antonides 2019). In this case, willingness-to-pay for energy efficient technology is superseded by immediate savings from a less efficient technology with a lower upfront capital cost. However, as public concern in climate change increases, this equation may be influenced by a willingness to adopt efficiency as a means of lowering personal contribution to climate impacts.

Studies have shown this dichotomy is already prevalent: individuals place a high importance on minimizing costs, yet some also greatly value emission reduction strategies that would increase costs (Bessette and Arvai 2018). While literature on willingness-to-pay for efficient home technologies is limited, Bessette and Arvai (2018) found a set of university students willing to pay an additional $44–$65 per month to eliminate GHG and air particulate emissions from the energy mix that is delivered to their home. Notably as well, participants rated energy generation portfolios that rely on efficiency improvements the highest of all options presented in the study.

Conveying the emission reductions of energy efficiency could then significantly bolster the adoption of more expensive and efficient technology in demographics that do not have substantial cost barriers, though financial savings should not be messaged as strongly if this approach is pursued (Griffioeon, Handgraaf and Antonides 2019). Financial and environmental considerations operate on different levels of cognition; finances can be viewed in concrete terms, while environmental values are often abstract. Research on energy conservation has found that individuals will act on information differently depending on how personally distant it feels (Brügger, Morton and Dessai 2016; Trope and Liberman 2010). As distance from an event or object increases, individuals have greater intentions to behave according to values rather than situational factors. Since energy conservation is a less tangible concept for some consumers, designing interventions to increase adoption of efficient cooling technology should focus on outcomes of efficiency measures, such as lifetime emissions savings. Alternatively, if supportive situational factors exist, structuring messages in concrete and personalized terms would be a better approach. Particular attention must be paid to how messages are framed to garner broader support for opportunities that are concrete (e.g., policy, incentives) or abstract (e.g., energy conserving behaviors).

Risk perception, too, plays an important role in discounting future savings. Savings from cooling technologies are sometimes difficult to ascertain due to variations in seasonal weather, changes in use, or whether it is the first product of its kind installed in a household. Such uncertainty increases the perception of risk associated with the decision to purchase a more efficient product.

When faced with a decision that may result in future savings, individuals become more risk-averse and prefer alternatives of higher certainty, even despite lower value (Tversky and Kahneman 1992). As such, the upfront premium paid for energy efficient technology may be seen as too risky compared to familiar options such as window units. Actions to reduce consumer's perceived risk include innovative lending strategies for energy efficiency upgrades or other mitigating measures such as extended warranties, replacements, or returns (Haw and Weiss 2018). These types of performance guarantees or savings insurance policies can help address the uncertainty consumers may have in their ability to achieve savings from efficient technologies, but at a cost.

Labeling is another important factor when conveying the potential savings of efficient cooling technology, though its effectiveness is highly dependent on how information is being conveyed to consumers (Campbell-Arvai, Arvai and Kalof 2014). For example, many products with efficiency labels are only about 10–30% better than the worst-performing products, despite the availability of technologies that are as much as 70% more efficient (Delmastro et al. 2021). In studying the effect efficiency labels have on variable- versus single-speed air conditioners, researchers found that information complexity causes discrepancies in purchasing decisions and consumer values (Zhou and Bokenya 2016). When information became comparable between models, willingness-to-pay for the more efficient model increased by 20%.

In other words, when presented with a choice between two products on a retail shelf, consumers indicated they would spend more to opt for a better performing model when labels accurately reflected performance indicators in digestible terms. While lower income respondents were understandably constrained in *ability* to pay for the more expensive technology, middle- and upper-income participants had no significant differences in preferences. To understand technical benefits a product may offer, expert knowledge is unnecessary. If cost barriers are not prohibitive, guiding the purchase of efficient technology can readily be done through simple comparative labels.

Purchasing of Cooling Equipment—in Response to Heat Waves

Little research exists on purchases responding to heat waves, yet retailer shelves are often depleted shortly after local weather stations announce an impending period of hot weather. Ascertaining the occurrence of weather-responsive buying is occurring is challenging, without exploring retail sales of air conditioners and how they may align with heat waves. Undoubtedly, some households purchase air conditioners as a response to heat waves. How many, and if the response is before, during, or after experiencing a heat wave remains to be answered through the literature, so further research is needed.

One possible explanation of why shelves empty during heat waves may relate to normative influences and marketing tactics. Local news agencies, officials, and health experts often will urge to residents to stay cool during the coming days. This may influence purchasing decisions even without explicitly advocating for buying a new air conditioner. Trusted sources and authority figures appeal to normative influences and may activate different value orientations. As personal thermal comfort is highly valued in U.S. culture and the presence of air conditioners is so ubiquitous, solutions to maintaining comfort are often geared toward the technical side rather than passive opportunities such as shutting blinds and reducing energy inputs. In other words, if asked how to stay cool in the summer, the most common answer likely would be to run the air-conditioning. Similarly, implied scarcity also activates normative influences to guide behavior toward obtaining the scarce item and making rapid purchasing decisions (Peterson, Kim and Jeong 2020; Elisa, Fakhri and Pradana 2022). Items that have limited or unpredictable supply have inherently more value and imply that others are also purchasing the item.

While research is lacking in direct observations of purchasing decisions during heat waves, data suggests that the population that would be considering an emergency purchase is declining as central air-conditioning prevalence increases. The Energy Information Administration's Residential Energy Consumption Survey provides information on the share of households using air-conditioning and whether they are using individual air-conditioning systems (e.g., window and wall air conditioners) versus central. Looking at RECs data over time allows us to identify trends. In 2015, over 102 million households in cold and very cold climates reported having air-conditioning equipment installed, which increased to 109 million by 2020 (EIA 2015; EIA 2022). No climate zone experienced a decline in presence of air conditioners during this time frame, and the increase was largely concentrated in central air-conditioning systems and heat pump system installations. During the 5-year period, households that used individual air-conditioning unit cooling decreased from 14.3 million to 11.9 million in cold and very cold climates. Across the U.S., too, declines were experienced as fewer households reported using one or more individual air-conditioning units.

While households without air-conditioning may purchasing inefficient air-conditioning units in response to heat waves, this does not yet seem to have affected the overall direction of cooling technology prevalence.

Indoor Thermal Preferences

OVERCOOLING

The culture around air-conditioning in the U.S. has influenced behavioral choices to the extent that over-cooling buildings has become a challenge to responsible energy management. For technologies other than variable-speed heat pumps, reducing energy consumption from space-conditioning without affecting comfort can be challenging as needs of occupants' range widely while building design often offers uniform temperature controls for an office space. As such, conditions are often set at temperature thresholds lower than necessary to maintain thermal comfort for most occupants.

Each year, this excess cooling costs as much as $10 billion, consumes more than 100,000 GWh, and is responsible for approximately 57,000 kilotons of CO_2e (Derrible and Reeder 2015; Parkinson et al. 2021). Overcooling alone accounts for approximately 8% of total cooling energy use, emissions, and financial cost that could be avoided if setpoints were increased to more comfortable temperatures. Notably, complaints about cold office temperatures increase alongside warmer outdoor temperatures and overcooling is most common in warmer climates. Behavioral interventions can aid in alleviating this problem, but the design of these strategies must be informed by understanding the range of individuals' thermal needs and comfort levels.

TEMPERATURE NORMS

An understanding of typical temperature set points can inform approaches to influence behavior. Strategies such as education and outreach campaigns, decisions on default temperature setpoints in thermostats and HVAC controls systems, and incentive programs can be designed to motivate behavior toward more efficient energy use.

Choices for indoor temperature setpoints differ across demographics, geographies, environmental conditions, and activities. Still, the range of setpoints households choose is only separated by a few degrees with most households specifying temperature setpoints in the mid-70's year-round (EIA 2015). In commercial settings, studies seeking to better understand human performance in office settings have found optimal temperatures to fall between 71.6 – 78.8°F, while temperatures exceeding 84°F negatively impacted performance (Cui et al. 2013). Notably, improvements in thermal comfort (e.g., going from uncomfortably warm to warm), increased motivation and work performance above baselines taken at identical temperatures. In other words, starting the workday at higher temperatures that gradually decrease over time improves employee performance over a flat, cooler temperature. Humidity also factors in significantly with thermal preferences, where relative humidity exceeding 70% can drive individuals to overcool homes or buildings rather than dehumidify the space (Iweka et al. 2019).

Behavior varies across socioeconomic groups as well, with different studies documenting multiple trends. The 2020 EIA RECS data document seasonal air-conditioning and heating setpoints by time of day. These data indicate that for both cooling and heating, lower-income households are more likely to keep a set temperature at all times of day, while middle- and upper-income households tend to adjust thermostats at night (EIA 2015). It also indicates that most households keep temperatures between 70–76°F in the summertime when the house is occupied. For both air-conditioning and heating setpoints, households across income brackets opt for cooler temperatures at night compared to set points in the day.

Between income brackets, the EIA data shows a trend across income brackets of air-conditioning setpoints increasing as incomes rise and heating setpoints decreasing. This runs counter to other reports that found low-income households to conserve energy to a greater degree than other households (Eisenberg 2014). While this is the case on an aggregate basis, other data suggests low-income households consume more energy for space-conditioning per square foot than other comparable homes (Rose and Hawkins 2020), a trend consistent with similar energy use being spread over smaller living environments. While more research is needed in this area, the differences between energy consumption for space-conditioning and lower temperature set points can likely be attributed to weatherization and technological discrepancies between homes. Homes that are well insulated and equipped with a central space-conditioning system can maintain comfortable temperatures at more efficient set points, while other households may face a need to set lower temperatures to remain marginally comfortable. The need to select less efficient set points to maintain comfortable temperatures results in low-income households bearing a disproportionate energy burden relative to income across the country and cites a need for bolstered weatherization and efficiency programs (Drehobl, Ross and Ayala 2020).

Using environmental controls to maintain comfort is more extreme in the United States than other parts of the world, as evident by the high penetration of homes with air conditioners and significant portion of energy use attributed to space-conditioning (IEA 2021). Many cultures in warmer climates still have low levels of adoption despite being technologically advanced (Biardeau et al. 2020). Instead, these areas have adopted behaviors to maintain comfort without technology, such as adjusting sleeping and work patterns to more ideal times of day. While efficient cooling technologies will be more popular in cultures similar to that of the U.S., alternatives that do not require energy should still be marketed as a viable option to maintaining comfort.

Notably, however, occupants do not have to be present in the building to negatively impact energy performance. A study investigating commercial building energy consumption in hot and dry climates discovered up to 56% of total energy was consumed during non-working hours, likely due to occupants forgetting to shut off lights and adjust HVAC setpoints when leaving the building (Masoso and Grobler 2010). This suggests that simple behavioral interventions paired with control mechanisms could rapidly diminish energy consumption in many commercial buildings.

As illustrated in Figure 26, social and personal parameters are a key component of residential cooling behaviors. As contextual factors such as climate, policy and building design are less fluid, understanding these parameters can inform interventions and program design to reduce energy use in a timely and comparatively cost-effective manner. Researchers note that comprehending behavioral influences on building energy use requires a collaborative effort between social scientists, energy modelers, and engineers (Delzendeh et al. 2017). In particular, efforts are needed to conduct qualitative sociological research to assess what drives occupants' energy behaviors.

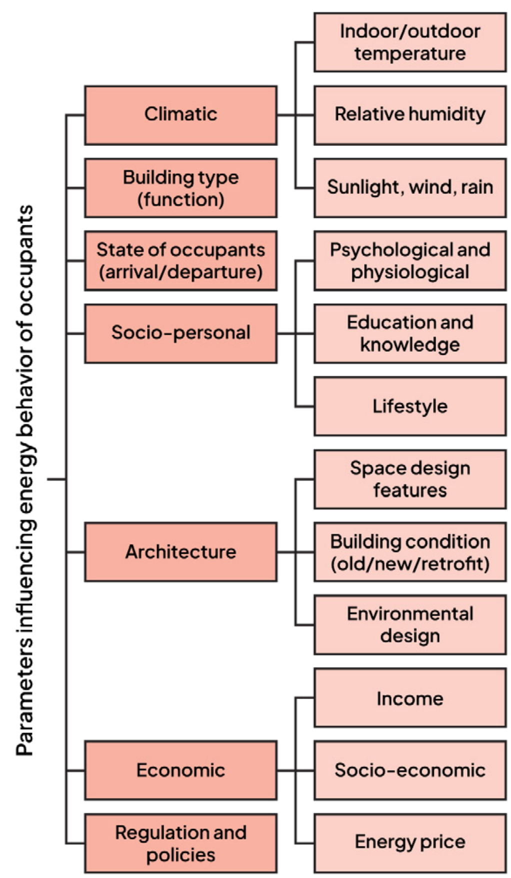


Figure 26. Factors and sub-factors influencing energy behavior of occupants

Source: (Delzendeh et al. 2017)

OVERUSE OF TECHNOLOGY

Researchers also argue that the broad adoption of air-conditioning has resulted in scarce use of passive techniques to craft a comfortable environment (Wilhite 2009; Lundgren-Kownacki et al. 2018). While passive cooling techniques, humidity control, or fan use are viable options for regulating comfortable indoor temperatures, in recent decades they have become overlooked as options comparable to air-conditioning. Other research suggests that frequent exposure to air-conditioning, along with cultural norms that favor cooler temperatures, narrows the range of acceptable indoor temperatures for thermal comfort comfort (Lundgren-Kownacki et al. 2018).

Impacting Behavior Across Income Brackets

Economic considerations are imperative for driving clean technologies forward, though are not solely reliant on incentives to reduce upfront costs. Adequate and comparable labeling plays a similarly vital role in guiding consumer product choices. This alleviates the burden of having expansive knowledge of HVAC energy consumption and instead packages the necessary information in a manageable form. Access to clean cooling systems is not equally spread across income levels, however. Lower-income individuals are more likely to rent rather than own a home, limiting opportunities to select a product. As a strategy to address this challenge, communities can enact building codes for commercial multifamily properties to include space-conditioning for new development. Differences are found across income brackets in operation of air conditioners, too. Using income to define a specific target audience can aid in crafting interventions as described above, as well as in addressing distributional equity, as discussed in the *Achieving Distributional Equity* section below.

05

Achieving Distributional Equity

Defining Distribution Equity

Forging a pathway to a future with low GHG emissions requires high heat pump adoption and requires attention to not only general market dynamics but also to the specific circumstances of historically disadvantaged populations most at risk to climate hazards. Energy equity entails many aspects and is frequently categorized along four dimensions: structural, procedural, distributional, and inter-generational (ACEEE 2021). This section explores distributional equity considerations with a focus on the residential sector. Distributional equity addresses how policies and programs can encourage an equitable distribution of burdens and benefits. We approach this topic from the perspective of upfront and operating cost burdens as well as health and comfort benefits from access to affordable cooling.

A key factor that influences each of these considerations with respect to equitable cooling is the lower prevalence of air-conditioning generally among lower income households and lower prevalence of central air-conditioning as well (Figure 27, EIA 2022).

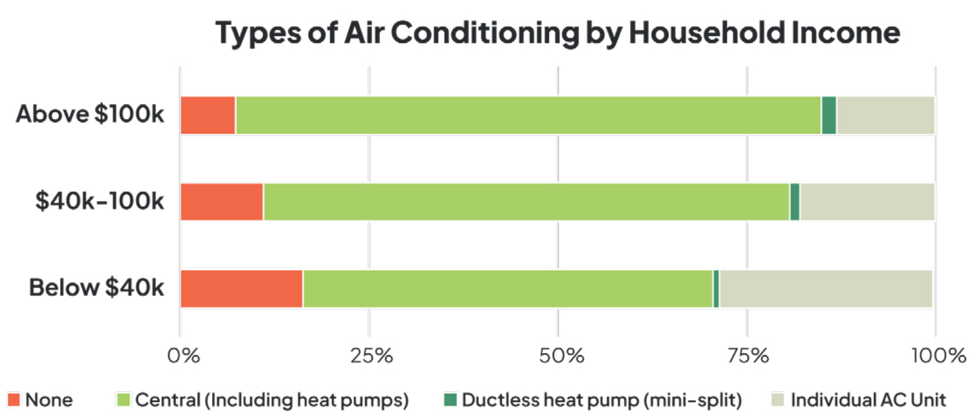


Figure 27. Prevalence of air-conditioning by household income level
Source: (EIA 2022)

Even among those households with access to cooling equipment, some research points to an equity gap, with lower-income households enduring more heat in summer months. They turn on air-conditioning at higher outdoor temperatures and choose higher set points for their air-conditioning systems (Carroll 2022). This points to the potential that, after high-efficiency equipment is installed, lower-income households might opt to use more air-conditioning (i.e., rebound effects) with attendant impacts on both operating cost and emissions. This same dynamic could take place in any household but is more likely to occur in households where there is evidence that set points are currently based on economic constraints rather than thermal preference. That households may be considered underserved for cooling also points to the importance of delivering greater distributional equity in affordable cooling.

Additionally, housing conditions such as mold and moisture issues or needed roof repairs have proven to be barriers to weatherization in the past and will also affect low-income households' access to both active and passive cooling strategies. Passive cooling strategies directly affect the upfront and operating cost impacts of electrification and deliver health and comfort benefits in addition to the efficient cooling benefits of heat pumps.

Affordability Barriers

Upfront Costs

While upfront (equipment and installation) and operating (energy use and maintenance) costs are important factors for the overall heat pump market, these considerations loom especially large for households with limited economic means. These households are also disproportionately people of color (Creamer 2020). Upfront costs affect households' ability to afford a heat pump in the first place, particularly considering that heat pump retrofits are most cost effective when replacing both a heating and cooling system at the same time (E3 2019). They also have nuanced and upstream effects on equipment choice and pre-electrification measures. For one, upfront costs can constrain a household's choice of heat pump, limiting adoption of models with higher efficiency and greater grid connectivity among low-income households. As the research presented here shows, variable-speed heat pumps result in significantly better emissions and peak electricity outcomes, but these models come at a premium. Delivering the benefits of higher-efficiency heat pumps that offer both heating and cooling for their broad social impact and in a manner that supports distributional equity means developing policies and programs that prioritize access to higher efficiency models across the income spectrum.

Existing Building Conditions

Upfront costs also may limit the adoption of complementary weatherization measures that deliver health and comfort benefits and may reduce HVAC sizing requirements and operating costs. While the research presented here shows only marginal energy use and emission reductions from weatherization and additional efficiency measures, this is based on housing that meets the 2015 IECC residential code. Lower income households in the U.S. occupy a larger share of older homes with greater repair needs (Li 2021). Older homes are more likely than homes that meet the 2015 IECC residential code to realize greater reductions in energy use, emissions, and cost. They also are more likely to see additional benefits from weatherization measures, which are associated with a wide range of health and comfort benefits that have been documented through direct survey work (Tonn et al. 2014) as well as literature reviews (Vermont Department of Health 2018). In addition to its comfort benefits, lowering heating and cooling loads through weatherization also can mean lower-capacity heat pump requirements, lower cost installations due to the greater ability to reuse existing ductwork, and lower ongoing operating costs (Aldrich 2021).

Older homes also are more likely to require electrical system upgrades that support electrification readiness—measures such as extending wiring, upgrading circuit panels, or upgrading service lines or transformers. These measures can add expense and delay and, without appropriate funding and streamlined processes, can prove to be a barrier to high-efficiency heat pump installation.

Going even further upstream from weatherization measures, a segment of the housing stock requires health and safety or building durability repairs such as roof repair/replacement, mold and moisture remediation, and/or unsafe wiring replacement. Experience from the Weatherization Assistance Program shows that many households that qualify for federal assistance are deferred from the program due to a lack of funds to address these measures (Benshoff 2022). Comprehensive programs that go upstream from heat pump installation and create the conditions for greater health, safety, and comfort as well as optimized HVAC installations are critical to distributional equity in heat pump deployment.

Operating Costs

While upfront costs of heat pumps and related home upgrade measures pose a barrier to efficient, affordable, clean cooling and heating, consideration of ongoing operating cost in the form of energy bills is another critical consideration for distributional equity. While bidirectional heat pumps are typically a cost-effective solution for replacing old, inefficient central air-conditioning systems, they have a more mixed cost impact when replacing gas furnaces (Walker, Less and Casquero-Modrego 2022), and certainly have the potential to increase energy burdens when adding air-conditioning, a needed energy service, to households that go from un- or under-served for cooling to having and using an appliance for cooling.

The importance of delivering comprehensive retrofits, noted above in relation to upfront costs, is also a critical factor in driving down operating costs, as combining electrification with additional cost saving measures can result in bill savings even in cases when the heat pump measure alone would increase operating costs. However, it is not the only tool in the toolbox, and other strategies to directly decrease utility bills for low-income households are needed for scenarios (e.g., replacement on failure opportunities) when comprehensive retrofits prove infeasible. Three examples are community solar, bill assistance programs, and rate design.

An additional consideration with respect to operating costs comes into play with multifamily rental housing. Depending on the building's pre- and post-retrofit heating and cooling system types and metering configurations, energy services (e.g., space or water heating) that had been included in rent may change to being paid for on tenants' utility accounts. This can occur when moving from central to in-unit systems or when retrofitting in-unit systems from an owner-paid gas account to a tenant-paid electric account. In these cases, regardless of the change in overall, property-wide energy costs, individual households can face increased utility costs. These dynamics are at play in all multifamily rental housing. For subsidized housing programs that incorporate utility allowances (e.g., Low-Income Housing Tax Credit properties, Section 8, public housing, et al.), the cost shift is mitigated to some degree through the utility allowance. In other cases, consumer protections are needed to facilitate a fair allocation of energy costs and rents.

Heat Wave Considerations

As noted earlier, the temperature forecasts that underlying this report's analysis are a long-term projection from recent, typical weather that shows average temperature changes in the climate zones under consideration in the year 2050. Yet we know that as global temperatures increase, a rise in heat wave occurrence, intensity, and length has already been documented (IPCC 2021).

Extreme heat disproportionately impacts low-income communities and communities of color, as these communities have encountered a long history of disinvestment that has resulted in less access to green space, street trees, and adequate housing (Benz and Burney 2021). Looking at geographic distributions, the average person of color lives in a Census tract with higher surface heat island intensity (summarized in Figure 28) in all but 6 of the 175 most populated urban areas across all climate zones in the U.S. (Chakraborty et al. 2021). This trend of increased exposure is reflected as income drops below the poverty line as well. Research continues to support the finding that populations with the greatest risk of heat-related illness and lowest adaptive capacity often face the greatest exposure to heat (Voelkel et al. 2018; Hoffman, Shandas and Pendleton 2020; Wilson 2020).

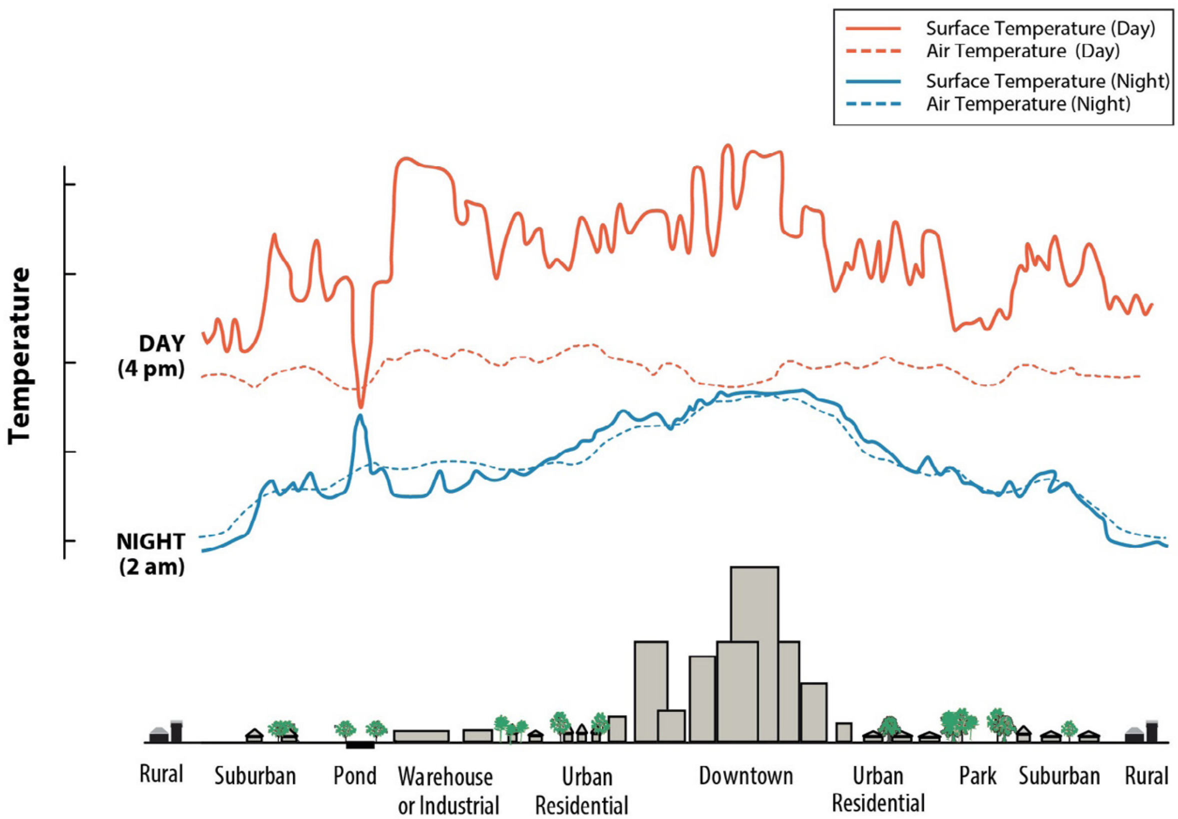


Figure 28. Diagram of the urban heat island effect
Source: (EPA 2021)

There is a correlation between population demographics and negative health outcomes during extreme heat events. In particular, individuals over 65 or under 5 years old, low-income households, and those living alone have significantly increased risks of morbidity and mortality from heat-related illnesses. Systemic issues play a role in the geographic dispersal of racial and ethnic groups, of which minority populations are more often housed in areas with greater exposure to heat. The relationship between these sociodemographic factors and increased exposure has been documented in nearly all of the most populated urban areas in the United States.

This indicates cities must take a proactive approach in planning for equitable adaptation to heat waves. Extreme heat causes more illness and death than any other naturally occurring event and, as global emissions exceed thresholds, adaptive strategies must be considered alongside mitigatory actions. Such strategies include replacing dark and impermeable surfaces with porous and reflective materials. Green space significantly decreases the urban heat island effect and should be integrated immediately into city planning efforts (Sarangi et al. 2021).

Efforts to reduce outdoor temperatures also have the benefit of reducing indoor temperatures. This reduces the need for indoor cooling, allowing less use of air-conditioning which reduces cooling emissions and puts less strain on the energy grid. Additionally, expanded access to passive cooling strategies alleviates energy costs—an especially valuable benefit for those struggling with energy burdens. Urban greenery can lower ambient air temperatures in the immediate vicinity by several degrees, with the cooling power of large parks extending nearly a quarter mile beyond its borders. These spaces offer an area of respite from heat outside of the home while also reducing heat impacts on households surrounding the greenery.

While decarbonizing buildings and driving toward efficient cooling systems are core strategies for mitigating heat morbidity and mortality, it is also crucial that the transition be implemented in a way that encompasses and benefits those of greatest risk and limited adaptive capacity. Cities should prioritize sociodemographic factors and spatial distributions of vulnerable groups in consideration for heat preparedness planning and response. Such planning occurs through data-informed approaches to identify overlaps between highly vulnerable and exposed populations. Additionally, considerations must be made for local contexts and unique challenges faced by these groups. As such, coproduction of urban environmental policies with local stakeholders and residents is imperative to meet their specific needs.

As noted earlier, both Chicago and Portland, Oregon, experienced devastating impacts from such events, exacerbated by urban heat island (UHI) conditions. These cities have responded with localized strategies and concern for vulnerable populations. As extreme heat events become more frequent, it will be important for all municipalities to monitor and adapt planning efforts to new contexts to best protect at-risk populations.

06

Call to Action

Heat Pumps Provide Efficient Cooling and Heating and Reduce GHG Emissions

Heat pumps' ability to provide efficient heating and cooling and use electricity from a heavily decarbonized grid creates a tremendous opportunity to reduce GHG emissions in cold and temperate climate zones in the U.S. This is especially true when employing high-efficiency, variable-speed heat pumps. The best-case scenario includes moving to variable-speed and VRF heat pumps with additional weatherization, lighting efficiency, and plug load controls on an 80% renewable grid, plus 100% ultra-low GWP refrigerants. As depicted in Figure 29, this combination of interventions would achieve a 95% reduction over continued use of natural-gas furnaces with central air-conditioning systems.

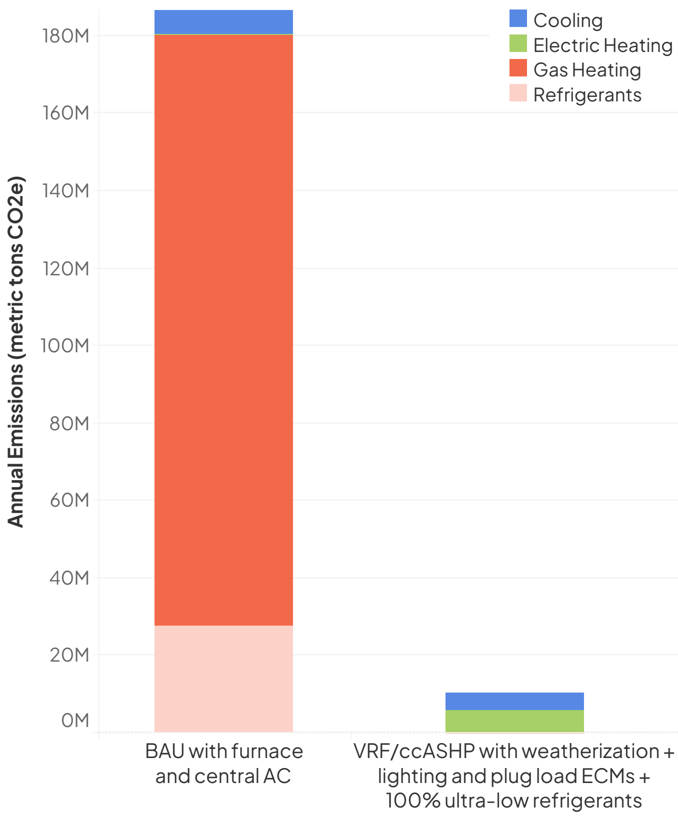


Figure 29. 2050 emissions comparison between BAU and best-case scenarios of interventions with an 80% renewable grid

30 Actions for Heat Pump Adoption

With a holistic market transformation approach, we have identified **30 policy and programmatic recommended actions** to increase adoption of high-efficiency heat pumps for both cooling and heating, organized by barrier—Industry, Technology and Affordability—and then alphabetically by key groups involved. Some actions will likely involve multiple groups, in which case the primary group is listed first. The groups are:

- **Federal regulatory agencies + Congress**
- **Manufacturers**
- **Philanthropy community**
- **Policy advocates** *(should consider all recommendations)*
- **State regulatory agencies + state legislatures**
- **Utilities + utility commissions**

Actions for Industry Barriers

Action Reference	Who	Barrier - Detail	Action Description	Action Type	Time Horizon	Scale
A	Manufacturers Philanthropic Community	Workforce knowledge and capacity	**National education / re-branding campaign** (e.g., heat cool pumps).	Program	Intermediate: 1–3 years	National
B	Utilities (+ Regional Energy Efficiency Organizations)	Workforce knowledge and capacity	Develop a "**Heat pump Nation**": a National Heat pump installer network, education and training hour requirements of training gateway to incentives, expanding the number of contractors who have familiarity and trust in heat pumps as a solution for their customers' needs. Incorporate basic building science education on envelope improvement and system sizing to increase HVAC efficiency.	Program	Intermediate: 1–3 years	National
C	Utilities	Lack of installer value proposition	Integrate **grid flexibility enablement programs** at time of installation and/or through repair, maintenance contractors.	Program	Intermediate: 1–3 years	State Regional

Actions for Technology Barriers

Action Reference	Who	Barrier - Detail	Action	Action Type	Time Horizon	Scale
D	Federal Regulatory Agencies (DOE*)	Emergency purchases	Require **reversing valves** on all air conditioners, thereby making them reversible heat pumps (DOE standard).	Policy	Intermediate: 1–3 years	National
E	Federal Regulatory Agencies (DOE)	Emergency purchases	Explore opportunities for **regional heat pump standards** to optimize for climatic difference beyond the existing single, national heat pump standard.	Policy	Intermediate: 1–3 years	National
F	Federal Regulatory Agencies (DOE)	Lack of realized value from variable speed	Modify the Standards Test Procedure to ensure **repeatability and reproducibility below 5°F**.	Policy	Intermediate: 1–3 years	National
G	Federal Regulatory Agencies (DOE)	Lack of realized value from variable speed	Modify the Standards Test Procedure to include **manufacturer-recommended controls** to help ensure equipment + controls are optimized to meet the performance rating.	Policy	Intermediate: 1–3 years	National
H	Federal Regulatory Agencies (EPA*)	Lack of low- and no-GWP refrigerant options	Make currently optional provisions specified for **refrigerant charge verification** in ENERGY STAR© version 6.1 for air conditioners and heat pumps a requirement in the next specification.	Policy/ Program	Intermediate: 1–3 years	National
I	Federal Regulatory Agencies (EPA)	Lack of low- and no-GWP refrigerant options	**Expand the new refrigerant-based filter** to the product finder pages for ENERGY STAR© certified Central Air Conditioner and Heat Pump Equipment.	Policy/ Program	Intermediate: 1–3 years	National
J	Manufacturers(AHRI) Federal Regulatory Agencies (EPA)	Lack of realized value from variable speed	Make the compressor type field visible in databases, or make requirement in AHRI and ENERGY STAR© to make **whether a product is variable-speed** easily findable.	Other	Short: less than 1 year	National
K	Philanthropic Community Federal Regulatory Agencies (DOE)	Emergency purchases	**Spur market transformation among manufacturers**—through technology prizes/competitions to inspire technology innovation and replace inefficient incumbent technologies for window units, particularly for multifamily renters.	Program/ Other	Intermediate: 1–3 years	National
L	State Regulatory Agencies (Building Code) State Legislatures (+IAPMO's Uniform Mechanical Technical Committee)	Lack of low- and no-GWP refrigerant options	**Change the mechanical codes to allow lower-GWP refrigerants**, including updates to certain mechanical codes (e.g., Uniform Mechanical Code) and supporting state adoption. Certain states, through both legislative and regulatory actions, are already in the process of addressing state-specific building code updates to allow the use of equipment containing low-GWP alternative refrigerants.	Policy	Short: Less than 1 year	National State

*DOE = Department of Energy EPA = Environmental Protection Agency

Actions for Technology Barriers, continued

Action Reference	Who	Barrier - Detail	Action	Action Type	Time Horizon	Scale
M	State Regulatory Agencies	Emergency purchases	Explore opportunity for **NOx standards through air quality** regulators (example: California Air Quality Management District to adopt with 14 n/j rule to align with South Coast for interim reductions).	Policy	Intermediate: 1–3 years	State
N	State Regulatory Agencies	Lack of realized value from variable speed	Require **tests of capacity and total static pressure** to within original equipment manufacturer specs on install.	Policy	Intermediate: 1–3 years	National State
O	State Regulatory Agencies (California Air Resource Board, Regional Greenhouse Gas Initiative) Federal Regulatory Agencies (EPA) Congress	Lack of low- and no-GWP refrigerant options	**Include refrigerants in existing carbon markets and create federal carbon market** for reclamation and destruction of high-GWP refrigerants.	Policy	Intermediate: 1–3 years	National State Regional
P	State Regulatory Agencies (Appliance Standards and Building Code Agencies) State Legislatures	Lack of realized value from variable speed	**Adopt grid flexibility standards** to develop the market for grid flexible HVAC solutions (enable the full benefits of variable-speed technology to be captured).	Policy	Intermediate: 1–3 years	State
Q	Utilities (+ Local governments)	Emergency purchases	Implement programs for **new temporary heating/cooling units** that can serve as emergency purchases while heat pumps are sized, installed, etc.	Programs	Intermediate: 1–3 years	State Regional Local
R	Utilities Manufacturers (+ Software developers)	Lack of realized value from variable speed	**Improve modeling** of variable-speed heat pumps in standard modeling software to account for accurate gains in efficiency.	Other	Intermediate: 1–3 years	National
S	Utilities Philanthropic Community	Lack of realized value from variable speed	Invest in **third party test lab capacity** for cold climate heat pumps.	Program/ Other	Intermediate: 1–3 years	National
T	Utilities (+ Regional Energy Efficiency Organizations)	Lack of realized value from variable speed	Develop **contractor training** on how to use published data to properly size heat pump equipment in colder climates.	Program	Intermediate: 1–3 years	State National

Actions for Affordability Barriers

Action Reference	Who	Barrier - Detail	Action	Action Type	Time Horizon	Scale
U	Federal Regulatory Agencies (The Federal Housing Finance Agency)	High upfront costs	Incorporate **heat pump replacement costs** in **green mortgage and refinancing**.	Policy	Intermediate: 1–3 years	National
V	Philanthropic Community	High upfront and operational costs	**Develop roadmap to address cost barriers** —What investment? Who pays? How do we unlock it? (e.g., unlock includes health and safety value from NOx reductions).	Other	Short: Less than 1 year	National
W	Utilities Federal Regulatory Agencies (DOE)	High upfront costs	**Establish national or regional upstream incentive program** featuring: • Extra incentives for variable-speed systems • Limitation-free installation qualification • Free-installs for industry participants • Extra incentives for Low-GWP refrigerants and leak-tight installation verification • Exclude EER requirements which make it less difficult for variable-speed / inverter technology or include a tradeoff between EER and grid connectivity.	Program	Intermediate: 1–3 years	National
Y	State Regulatory Agencies Utilities	High upfront costs	Coordinate **group purchasing power** of heat pumps.	Program / Other	Intermediate: 1–3 years	State Regional Local
Y	Utility Commissions	High operational costs	Enable **deep energy rate reform** (e.g., reducing the electricity rate base, marginal cost rates), essential to pull in private capital and build an industry, like the rooftop solar industry.	Policy	Intermediate: 1–3 years	State
Z	Utility Commissions	High upfront costs	Expand **Tariff On-bill Financing**.	Policy	Intermediate: 1–3 years	State

Action Reference	Who	Barrier - Detail	Action	Action Type	Time Horizon	Scale
AA	Utility Commissions State Regulatory Agencies	High upfront and operational costs	Properly **evaluate, quantify and unlock non-energy benefits** of heat pumps into state/utility policy (e.g., cap + trade funds, cost-effectiveness tests, health + safety funding mechanisms). Ensure those metrics are included in policy decision-making.	Policy	Intermediate: 1–3 years	State
BB	Utility Commissions Federal Regulatory Agencies (Department of Health and Human Services)	High upfront and operational costs	**Modify energy assistance programs** offered by utilities as well as the **federal Low-Income Home Energy Assistance Program** (LIHEAP) to incentivize electrification and cover cooling costs.	Policy / Programs	Intermediate: 1–3 years	National
CC	Utility Commissions	High upfront costs and operational costs	**Promote fuel switching for low-income households** through comprehensive programs that address health and safety measures as well as weatherization and appliance efficiency measures.	Programs	Intermediate: 1–3 years	National
DD	Utility Commissions State Legislatures	High upfront costs	**Modify incentive policy to eliminate barriers to stacking and braiding of federal funding**, including for electrification and heat pump deployment.	Policy	Intermediate: 1–3 years	State

Appendix A: Research Methodology

The methodology for conducting this research encompassed three components:

1. A **Literature Review** documented prior on background assumptions for the study, such as the U.S.'s expected share of global cooling emissions, the availability of cooling emissions data for cool and temperate climate zones in the U.S., refrigerants' role in cooling emissions, and equity factors related to the distribution of costs and benefits of increased demand for cooling.
2. We used **Stakeholder Meetings and Interviews** to vet the project's scope and focus, the modeling methodology, and initial findings as well as to gather insights into prior research and promising approaches to equitable clean cooling and decarbonization.
    a. In the course of conducting the modeling, research, and analysis, we held three stakeholder meetings to gather input and vet findings. In **December 2021**, we convened a group of stakeholders representing energy and equity advocates and researchers, efficiency and refrigerant experts, and philanthropy. In the meeting, we presented on the research focus, literature review results, high-level modeling methodology, and draft outline. Through breakout sessions, we gathered participants' input on additional considerations relevant to the research, current policy and program leaders for heat pump deployment and equitable cooling solutions, and ways the project intersected with their work today. Key takeaways included an affirmation of the focus on weatherization and efficiency in addition to heat pump adoption, interest in analysis and solutions related to heat waves response, and several leads on promising programs and additional people to engage in the report review.
    b. In **January 2022** we held a session reviewing a more detailed version of the modeling methodology. Discussion topics included how the research will engage with extreme weather and heat waves, heat pump performance in cold climates, ways that back-up systems and hybrid heating solutions may be used during the transition to full adoption of heat pumps, and the specifications used for weatherization and efficiency measures. Based on stakeholder feedback, the modeling team increased the level of increased lighting efficiency and modified the approach to single family insulation.
    c. In **May 2022** we presented preliminary findings from the modeling along with ways that the broader market and technology context informs our understanding and interpretation of those findings. We also laid out the barriers framework and evaluation criteria used to develop recommendations and solicited input on policy and program recommendations overcome barriers and drive toward the low emissions scenarios modeled.

    In addition to the broader stakeholder meetings, we also conducted one-on-one interviews with three categories of stakeholders: industry representatives, and equity researchers and advocates. From discussion with leading heat pump manufacturers, we uncovered insights into the current heat pump market and expected changes to both the market and available technologies. From interviews with stakeholders from the housing sector who focus on energy equity, we gained insights into promising program models and key barriers for renters.
3. The analysis presented centers on **Energy Modeling with Future-shifted Weather Files** that quantifies the expected emissions impacts of warming weather and a set of mitigation strategies. The following section describes this in more detail.

Appendix B: Modeling Methodology

Energy Modeling with Future-shifted Weather Files

Summary of tools

The main tools used for this study are EnergyPlus™ and WeatherShift™.

EnergyPlus is a whole building energy modeling program that models both annual energy consumption and water use in buildings. EnergyPlus is free and open-source software funded by the U.S. Department of Energy (DOE).

Annual energy simulations in EnergyPlus require EPW weather files[9] for simulating building energy requirements, including variables such as temperature, humidity, and solar irradiance. EPW files contain hourly values of key weather variables for a typical meteorological year. To date, EPW files developed for building energy modeling have relied on historical averages of weather data (temperature, humidity, etc.). However, buildings and infrastructure built today will experience significantly different weather patterns in the future than were seen historically due to the impact of climate change.

To evaluate the impact that future weather will have on the buildings in this study, the WeatherShift tool was utilized to develop EPW files for typical future meteorological year. WeatherShift uses data from global climate change modeling to produce EPW weather files that are adjusted for changing climate conditions. The adjustment process alters all climatological variables traditionally used by thermal building analysis tools, including:

- dry bulb temperature
- dew point temperature
- relative humidity
- pressure
- solar radiation
- sky cover
- wind speed
- wind direction

By using these shifted EPW files, building energy modelers can more accurately estimate the impact that changing weather will have on building energy and thermal flows. Note that WeatherShift adjusts for typical variables over the course of the year but does not adjust for a changed frequency of extreme events, such as increased number of heat waves, hurricanes, or storms.

9 EPW is a file extension designating a standardized data formatting used for EnergyPlus weather files

Energy use results per building were used to calculate emissions associated with heating, cooling, and refrigerants. A future electric grid is almost certain to be cleaner. To investigate that change, and to be able to isolate its effects from the other interventions modeled, the team used two different electric emissions factors (the numbers below are kilograms of carbon dioxide equivalent per megawatt hour):

- 2019, U.S. Average: 401.91 [10]
- • 2050, 95% reduction in power sector emissions compared to 2005 levels by 2050 scenario: 34.6 [11]

The 2019 value is historic data while the 2050 values are both projections from NREL's Cambium model of electricity futures. Cambium offers generation and emissions factors by hour, but the team used the annual average because the weather used for NREL's electricity modeling was not the same as that in the WeatherShift™ files for the energy modeling, so the two cannot be matched by date and time. The uncertainty in projecting the electricity generation mix 28 years in the future is surely greater than the loss of precision from using annual numbers.

The EnergyPlus results were extrapolated based on National New Construction Weighting Factors developed by PNNL for the period 2003 – 2018.[12] New construction in that time period aligns well with our intention to model the population of buildings that will be around in 2050. Buildings built 2003 – 2018 will be about 40 years old then. The PNNL weighting factors combine with commercial building area projections from the EIA Annual Energy Outlook 2021 to give the 2050 floor area by building type and climate zone.

Building Level Changes – Business as Usual (BAU)

Description of methodology and assumptions for future-shifted weather analysis

The purpose of the BAU study was to determine the impact of predicted changes to the climate in 2050 on current building energy use, without any interventions to improve the performance of or electrify existing buildings.

Simulations were run for each of the prototypes listed above in each of the climate zones identified for this study. Weather data for each climate zone is represented by several EPW weather files representing the following:

- **TMY3.** Current/historic weather representing a typical meteorological year
- **Weathershift™ 2050, RCP 8.5, with 10%, 50% & 90% scenario "bins."** Three warming percentile future climate scenarios following representative concentration pathway (RCP) 8.5 and a 2050 future target date.

The Weathershift EPW files are created using over 30 global circulation models (GCMs) from research institutions around the world. Since predicting climate change impact is an inherently uncertain and variable process, using a variety of models, this study used the 10th, 50th, and 90th percentile EPW files for modeling to evaluate outcomes within a range of potential future weather. This allows boundary-setting of the future modeling outputs.

In addition to the uncertainty range, each GCM can be initialized with different levels of greenhouse gas (GHG) emissions. These levels are referred to as representative concentration pathways (RCPs). RCP 8.5 represents a BAU global carbon emissions scenario, based on current global outputs and estimations of large countries such as the United States and China. This was selected for this analysis to evaluate a conservative future in the absence of significant changes in immediate climate action.

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10 EPA eGRID2019, February 2021, USA average,

11 Gagnon, Pieter; Hale, Elaine; Cole, Wesley (2022): Long-run Marginal Emission Rates for Electricity - Workbooks for 2021 Cambium Data. National Renewable Energy Laboratory. 10.7799/1838370. aer_load_co2e

12 www.pnnl.gov/main/publications/external/technical_reports/PNNL-29787.pdf

Weathershift creates EPW files for a range of future dates and time periods. The 2050 date represents the middle-to-end of a typical building system's expected lifespan assuming construction completion in 2025.

Building Prototype System Efficiencies

Prototype	Iteration	System	Cooling efficiency (COP)	Heating efficiency (COP or %) *
Medium Office	Baseline	Packaged AC (DX) system with furnace	3	0.8
	Mitigation sys 1	Packaged AC (DX) system with HP	3	2.75
	Mitigation sys 2	VRF	3	3.25
Strip Mall	Baseline	Packaged AC (DX) system with furnace	3	0.8
	Mitigation sys 1	Packaged AC (DX) system with HP	3	2.75
	Mitigation sys 2	VRF	3	3.25
Residential (Apartment & Single family)	Baseline (Weathershift study)	Packaged Terminal Units with furnace	3	0.8
	Mitigation sys 1	Packaged Terminal Units with HP	3	2.75
	Mitigation sys 2	VRF	3	3.25
Restaurant	Weathershift study only	Packaged AC (DX) system with furnace	Requirements in codes or standards. Minimum equipment efficiency for packaged heat pumps	Requirements in codes or standards Minimum equipment efficiency for packaged heat pumps and warm air furnaces
Warehouse	Weathershift study only	Packaged AC (DX) system with furnace	Requirements in codes or standards. Minimum equipment efficiency for Air Conditioners and Condensing Units	Requirements in codes or standards. Minimum equipment efficiency for Warm Air Furnaces
School	Weathershift study only	Packaged VAV system with furnace	Requirements in codes or standards. Minimum equipment efficiency for Air Conditioners and Condensing Units. Minimum equipment efficiency for Air-cooled Chillers	Requirements in codes or standards. Minimum equipment efficiency for Warm Air Furnaces. Minimum equipment efficiency for Gas and Oil-fired Boilers

*Heat pumps: Minimum outdoor heating temp is -8C (17.6F) and electric resistance covers remaining load

VRF (proxy for variable-speed HP): Minimum outdoor heating temp is -20C (-4F) and electric resistance covers remaining load

Direct GHG Emissions from Refrigerants Methodology

To calculate the estimated direct greenhouse gas emissions associated with refrigerant leakage during equipment lifetime and end-of-life losses, the following equation was utilized:

Individual system annual GHG emissions = [leakage rate] * [system charge] * [GWP of refrigerant]

Where:

- ***Leakage rate*** is the percentage of total charge that leaks from the system on an annual basis. End-of-life (EOL) loss of refrigerant is incorporated into annual leakage rate based on equipment lifetime
- ***System charge*** represents the amount of refrigerant the equipment is designed to contain based on system size
- ***GWP*** (global warming potential) of refrigerant is the GHG impact of a refrigerant chemical or blend of chemicals relative to carbon dioxide

LEAKAGE RATE

Leakage rates were calculated based on data from the California Air Resources Board (CARB) Emissions Factor Reporting, which is the most comprehensive refrigerant leakage estimation resource in the U.S. due to their statewide Refrigerant Management Program (RMP). The RMP requires all systems containing over 50 pounds of refrigerant to maintain records documenting refrigerant added to the system over time, which is used to calculate an annualized leak rate. Leakage rate estimates for HVAC equipment vary widely depending on system configuration, direct exchange piping runs, age, and the proportion of factory-sealed components to field-installed components. While studies have been conducted on the leakage rates of residential air-source heat pumps, there is little data on leakage rates of commercial air-source heat pump systems. To be conservative, the same leakage rate was applied to both heat pump systems and unitary air-conditioning systems.

SYSTEM CHARGE

System charge was calculated based on the following factors: building prototype, maximum cooling load, and equipment type. Maximum cooling loads for each featured building prototype were modeled for both present day conditions and 2050 conditions. Equipment is sized for "design day condition" i.e., maximum loads. System charge will vary significantly between packaged/unitary HVAC equipment and direct-exchange (DX) heat pump systems.

GWP (GLOBAL WARMING POTENTIAL)

These emissions calculations used GWP_{100}* values, which are a measure of the climate change impact associated with emissions of one substance as compared to the climate change impact associated with emissions of carbon dioxide over a time horizon of 100 years. GWP values are based on the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 6. Specific values can be found in Climate Change 2021, the Physical Science Basis Chapter 7.SM. The GWP values of refrigerant blends were calculated as a weighted average of GWP values of the components.

**There is debate on whether to use GWP_{100} value or GWP_{20} value, which is a comparison over a time horizon of 20 years. As most hydrofluorocarbon (HFC) chemicals that make up refrigerants have a relatively short atmospheric lifetime, there is a growing movement to account for their global warming impact over a shorter time period. As of the publishing of this report, leading institutions such as the California Air Resources Board (CARB) and the Environmental Protection Agency (EPA) use GWP_{100} values. To maintain consistency and comparison accuracy, GWP_{100} values were used in this analysis.*

Baseline Scenario Assumptions

The baseline scenarios assume a fossil-fuel heating system and a packaged/unitary cooling system for all building prototypes except for single family residential. The modeling outputs were used to determine the system charge size based on maximum cooling load per building prototype, climate zone, and industry averages for pounds of refrigerant/ton of cooling. The 2050 emissions estimates reflect the increase in both cooling degree days and peak cooling demand, which in turn increased equipment charge sizes. Leakage rates and refrigerant GWP remained constant between present day and 2050 emissions.

Heat Pump Scenario Assumptions:

The heat pump scenarios assume that both the heating and cooling loads will be handled by an air-source heat pump. Therefore, to determine the maximum load that the equipment would need to be sized for, which dictates system charge, heating and cooling loads were both evaluated. As in the baseline scenario, the maximum heating/cooling load was determined through modeling for each building prototype and climate zone. Industry averages were used to determine heat pump/DX-specific estimates for pounds of refrigerant/ton of cooling or heating. The 2050 emissions estimates reflect the shift in certain climate zones of heat pump sizing being dictated by the heating load, to being dictated by the cooling load. Leakage rates and refrigerant GWP remained constant between present day and 2050 emissions.

Appendix C: Literature Review

The warming global climate poses a certain conundrum: warming temperatures will drive increased demand for cooling, and increased use of air conditioners could in turn drive greater warming. The cooling conundrum has been the focus of a number of global and U.S.-centered reports, and this report builds on that work to explore ways of meeting increased cooling demand while driving down greenhouse gas emissions and increasing access to cooling for historically disadvantaged populations. Existing research covers a range of geographic scales, market segments, emissions sources (energy use and refrigerants), and time periods. This report fills a particular niche by focusing on cold and temperate climates in the U.S., commercial and residential buildings, and emissions from both energy use and refrigerants, projecting out to the year 2050.

GLOBAL AND MULTI-NATIONAL RESOURCES

Multiple studies affirm that we expect to see a significant increased demand for cooling in the coming decades globally, and that a large share of that increase will take place in the United States. The 2018 International Energy Agency (IEA) report, *The Future of Cooling*, is a core resource on expected global changes in cooling demand as well as its main drivers and mitigation potential. The expected growth in cooling demand is dramatic. The energy used for cooling already has tripled from 1990 to 2016, and the report projects demand to again triple by 2050 in its Baseline Scenario. It points to increasing temperatures, demographic factors, and economic growth and affordability as drivers of increased cooling demand, while noting equipment efficiency, decarbonized electricity generation, building design, and demand side management as mitigating factors. Although the report documents that the U.S. has seen relatively flat increases in demand for cooling in recent years, it projects both residential and commercial space-cooling capacity will grow, with the U.S. growth in commercial demand expected to be the second greatest in the world, behind only China. The report also analyzes an Efficient Cooling Scenario, under which the increase in energy use for cooling increase by only half as much as the Baseline Scenario. The prospect for significant efficiency improvements is documented through analysis of minimum, standard, and best available efficiencies for HVAC equipment in different countries and for different equipment types. This analysis points to the potential for significant efficiency gains in the U.S. even without new technology development.

Additional studies complement the IEA report in affirming the scale and direction of anticipated impacts at the global level. Dreyfus et al. (2020) builds on *The Future of Cooling* to detail emissions from energy use for cooling and supplements it with a discussion of emissions from refrigerants and their mitigation potential. It documents global HFC use for refrigeration and air-conditioning and estimates the impact of the Kigali Amendment to the Montreal Protocol on refrigerant emissions. A Navigant Consulting report from 2016 for the U.S. Department of Energy, *The Future of Air-conditioning Use in Buildings*, also provides a global analysis of projected cooling emissions from air-conditioning and refrigerants, and includes analyses of cost and technology outlook.

Many studies of changes in demand for cooling take into account multiple drivers of increased cooling demand without quantifying the relative impact of the different factors, while others address particular drivers. Deroubaix et al. (2021) evaluates the extent to which changes in the climate are driving the increased energy demand for heating and cooling, finding that the climate's role has increased over the past few decades compared to the proceeding decades. It finds that increases in cooling demand have swamped decreases in heating demand while at the same time pointing out that changes in cooling demand have been highly variable, pointing to a need for further research. Woods et al. (2022) disaggregates multiple sources of cooling emissions (temperature load, humidity load, embodied, and refrigerants). It finds that emissions from dehumidification account for nearly a third of cooling-related emissions, and that this share increases under their 2050 weather projections with more efficient buildings and higher ventilation rates. *Solving the Global Cooling Challenge* (Campbell et al. 2018) examines the growth trajectory for a particular HVAC system, Room Air Conditioners (RACs), and also looks at the impacts of refrigerant leakage. It finds that energy use from RACs is expected to increase more than threefold globally, from 2,300 to 7,700 TWh between in 2016 and 2050. Expected growth in the U.S. is more of a marginal change given the high prevalence of existing air-conditioning, growing from 600 to 820 TWh within the same period. A 2019 report from The Economist Intelligence Unit, *The Cooling Imperative*, forecasts sales of cooling equipment through 2030 in six countries, including the U.S. It addresses a wider range of cooling end uses, encompassing four types each of Air-conditioning and refrigeration applications. And a 2021 guide from the United Nation's Environment Program's Cool Coalition is a resource for global cities on how to develop a cooling action plan.

U.S.-SPECIFIC RESOURCES

Climate Central (2021) looks at historical (1970 to 2020) changes in cooling degree days in multiple U.S. cities and documents a consistent increase. It also looks at the share of homes being built with central air-conditioning from 1973 to 2020 by census region. This data indicates that cool and temperate climates have lower central air-conditioning prevalence overall but steeper increases over time, getting closer to 100% saturation by 2020 across all regions.

Montgomery (2019) and Jenkins (2021) also point to high levels of air-conditioning adoption within the U.S., with some additional detail on how adoption levels vary by geography and household income level.

Petri and Caldeira (2015) compares historical heating and cooling degree days in the U.S. to a projected future state (2080–2099). Other U.S.-specific studies focus on particular issues related to increased cooling demand. Auffhammer et al. (2017) details changes in U.S. peak electricity demand due to heat waves and increased cooling loads, showing that with today's building systems and electricity markets, heat waves will drive increasingly intense and frequent peak events. Obringer et al. (2022) models household-level residential air-conditioning demand in six regions of the U.S. under two warming scenarios (1.5°C and 2.0°C). It finds that the projected increases could lead to an increased number of household days without air-conditioning if electricity supply is unable to meet the increased residential cooling demand. Pantano et al. (2021) explores the mitigation potential and cost implications of a heat pump deployment strategy focused on replacing air-conditioning systems with heat pumps and maintaining hybrid home heating. The Great Plains Institute (2021) has focused not on cooling but on building decarbonization, exploring heat pump deployment potential in the midcontinent of the U.S in detail.

Other literature on cooling and heat pump deployment points to the importance of additional aspects that are addressed in this report. The International Energy Agency (2021) has documented the important role behavioral approaches play in optimizing energy efficiency. Benz and Burney (2021) point to the uneven impacts of extreme heat across race and class divisions within the U.S., and points to the importance of incorporating equity considerations into cooling programs and policies.

In the course of laying out the challenges of meeting increased cooling demand without further exacerbating global climate change, several sources offer recommendations on policies and programs to decrease cooling-related emissions. Many of these resources are focused on the global scale. The Future of Cooling (EIA 2018) offers policy recommendations focused on reducing building energy use. Similarly, Dreyfus et al. (2020) provides policy recommendations related to both energy use and refrigerants. Also applying a global perspective, The Cooling Imperative (EIU 2019) sets forth a Reduce, Shift, Improve, Protect framework for policy solutions to the growing demand for air-conditioning. Focusing in on room air conditioners, *Solving the Global Cooling Challenge* (Campbell et al. 2018) evaluates conventional strategies and proposes a high-efficiency, low global warming potential technology solution. In *Beating the Heat*, Campbell et al. offer a set of climate-friendly cooling solutions for city governments. Woods et al. (2022) call for more research and development into more efficient humidity management technologies than the cold surface condensation technique widely used today. Examples include liquid desiccants, membrane-based water vapor compressors, or electrochemical or electric field-driven moisture removal. Looking specifically at the U.S., the Great Plains Institute's 2021 *Roadmap* offers recommendations for building decarbonization but without a specific emphasis on cooling, and the 3H Hybrid Heat Homes proposal (Pantano et al. 2021) provides a detailed rationale for a specific solution to medium-term heat pump deployment. While many of the recommendations set forth in both the globally-focused and U.S.-specific resources will be applicable to residential and commercial buildings in the temperate and cool climate zones of the U.S., none are geared toward addressing the particular policy contexts and solutions for this market segment.

Taken together, this body of literature affirms the value of new research focused on cold and temperate climates in the U.S. that addresses emissions from energy-use and refrigerants in both commercial and residential buildings with consideration for behavioral approaches and equity impacts.

Categorization of Resources

Author	Title	Geography	Market Segment	Emissions Source(s)	Time Period
Auffhammer et al.	Climate change impacts on U.S. electricity demand	U.S. - national	-	-	2100
Benz and Burney	Widespread race and class disparities in surface urban heat extremes across the United States	U.S. - national	Residential buildings	-	-
Campbell et al.	Solving the Global Cooling Challenge: How to Counter the Climate Threat from Room Air Conditioners	Global - some U.S. specific data	Residential buildings	Energy use and refrigerants	2050
Climate Central	Cooling Degree Days	U.S. - cities/census regions	Residential buildings	-	1970–2020
Deroubaix et al.	Large uncertainties in trends of energy demand for heating and cooling under climate change	Global	Buildings	Energy use	2030
Dreyfus et al.	Assessment of climate and development benefits of efficient and climate-friendly cooling	Global	Building and Transportation	Energy use and refrigerants	2100
Economist Intelligence Unit	The Cooling Imperative	Multinational	Building and Transportation	Energy use and refrigerants	2030
EIA	EIA projects air-conditioning energy use to grow faster than any other use in buildings	U.S. - national	Buildings	Energy use	2050
Great Plains Institute	A Road Map to Decarbonization in the Midcontinent: Buildings	U.S. - midcontinent	Buildings	Energy use	2050
IEA (2018)	The Future of Cooling: Opportunities for energy-efficient air-conditioning	Global - some U.S. specific data	Buildings	Energy use	2050
IEA (2021)	The Potential of Behavioural Interventions for Optimising Energy Use at Home.	Global	Buildings and Transportation	Energy use	-
Jenkins	Warming Has Made Air-conditioning a 'Huge Growth Industry.'	U.S.	Residential buildings	-	2021
Montgomery	8 Charts on How Americans Use Air-conditioning	U.S.	Residential buildings	-	2015
Navigant Consulting	The Future of Air-conditioning for Buildings	Global - some U.S. specific data	Buildings	Energy use and refrigerants	2050
Pantano et al.	3H 'Hybrid Heat Homes' An Incentive Program to Electrify Space Heating and Reduce Energy Bills in American Homes	U.S.	Residential buildings	Energy use	2032
Petri and Caldeira	Impacts of global warming on residential heating and cooling degree-days in the United States	U.S.	-	-	2099
UNEP	Beating the Heat: A Sustainable Cooling Handbook for Cities	Global - cities	Buildings	-	2050

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