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Heat pumps for all? Distributions of the costs and benefits of residential air-source heat pumps in the United States

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Summary

Electrification of fossil-fuel combustion in buildings is a key component of achieving global greenhouse gas emissions targets. We use physics simulations of 550,000 statistically representative households to analyze distributions of the costs and benefits of three air-to-air heat pump performance levels, with and without insulation upgrades, across the diversity of the U.S. housing stock. We find positive greenhouse gas reductions in every U.S. state for all performance levels across five 2022–2038 electric grid scenarios, with full adoption reducing national emissions by 5–9%. We find that air-to-air heat pumps could be cost-effective without subsidies in 59% of households (65 million). However, efficiency is key: whereas minimum-efficiency equipment could increase energy bills in 39% of households, this fraction is only 19% when also upgrading insulation or 5% when using higher-efficiency equipment, though both of these strategies have higher upfront costs. Such affordability challenges could be addressed through supportive incentives, policy, and innovation.

Context & scale

There are many types and models of heat pumps available on the market. Even for a specific model, the performance and return on investment can vary depending on the climate, building characteristics, operation, and energy prices. Thus, the costs and benefits of heat pumps are more accurately represented as distributions rather than single values.

We evaluate distributions of costs and benefits of three air-to-air heat pumps—the dominant technology in North America, Asia, Australia, and parts of Europe—across the diversity of the U.S. housing stock. We find that there is no one-size-fits-all solution and identify the factors affecting costs and benefits in the U.S. context. In the global context, these findings demonstrate the importance of assessing distributions of costs and benefits and can inform program design by showing how the local climate, housing stock, energy prices, and equipment characteristics can be considered in order to maximize impact while avoiding unintended consequences.

Highlights

- Electrification with heat pumps reduces lifetime GHG emissions in every U.S. state.
- Air-to-air heat pumps are cost-effective without subsidies in 65 million U.S. homes.
- Cold-climate heat pumps avoid most bill increases, but at a higher upfront cost.
- Envelope upgrades can save thousands of dollars on the upfront cost of heat pumps.

eTOC blurb

We evaluate distributions of costs and benefits of three air-to-air heat pumps across the diversity of the U.S. housing stock. We find that while the economics of heat pumps are extremely varied, they reduce lifetime GHG emissions in every U.S. state and are cost-effective without subsidies in an estimated 65 million U.S. homes. High-efficiency cold-climate heat pumps avoid most potential bill increases, but come a higher upfront cost that can be addressed through supportive incentives, policy, and innovation.

Keywords: Electrification, heat pump, decarbonization, residential buildings, energy efficiency, building stock modeling

1. Introduction

As an efficient method of heating that can be powered with renewable electricity, air-to-air and air-to-water air-source heat pumps (ASHPs) are being promoted in many countries as a method for decarbonizing buildings and increasing energy independence.[1] However, economy-wide decarbonization studies frequently do not discuss the barriers to building electrification with ASHPs.[2,3,4] Scenarios of buildings sector emissions reductions often exogenously assume rates of electrification with heat pumps regardless of their economic performance.[5,6,7,8] The economic barriers for heat pump adoption have been discussed qualitatively[9,10,1,11] and, to a lesser extent, quantitatively.[12,13,9 14,15] However, there is not a comprehensive picture of where ASHP adoption is cost-effective across climates, housing stock segments, and ASHP performance levels. Thus, the national-scale potential for economic ASHP adoption in the United States is not well understood.

More broadly, decarbonization pathways modeling frequently ignores distributional impacts, despite a renewed interest in quantifying distributional consequences of policy and a history of fossil fuel combustion harming some groups—such as people of color—more than others.[16,17] This study quantifies the costs and benefits of ASHP adoption across the diversity of climates, housing stock, and fuel prices in the United States—while addressing common shortcomings of ASHP modeling—to develop a comprehensive picture of the distributions of costs and economic benefits to households and discuss the implications for programs that promote this technology. This study does not attempt to evaluate impacts to vulnerable groups or to predict the likelihood of adoption patterns, which may be determined by both economic and non-economic factors.[18] Subsequent work can build on such distributions to correlate the energy burden impacts to specific income or demographic groups (e.g., Brossman et al.[19]) or to predict adoption based on both economic and socio-demographic factors.

This study focuses on *air-to-air* heat pumps, which deliver heated or cooled air to ductwork or directly to a room. In contrast, *air-to-water* heat pumps deliver heated water to radiators. Air-to-water heat pumps are seen as a key solution to replace boilers in countries such as Germany and Poland, and saw record sales growth of 49% in Europe in 2022.[20] While air-to-air heat pumps have lower sales growth rates, they are the dominant type of heat pump in North America, China, Japan, Australia and New Zealand, as well as Nordic, Baltic, and southern European countries.[20] Each type of heat pump has distinct barriers to adoption. Unlike air-to-water heat pumps, air-to-air heat pumps do not have integrated thermal mass or storage, which makes system sizing, the potential need for backup heat, and peak electricity demand particularly important challenges. However, they are reversible so that they provide air conditioning, which typically makes their incremental cost over legacy furnace and air conditioner equipment more favorable than if they were only replacing a fuel boiler.

A primary deficiency of studies that address the economic costs and benefits of ASHPs is that they only consider an average or prototypical consumer.[21,22,23,24,25] However, heterogeneity—in climate, housing characteristics, occupant behavior, and fuel prices—means that even if an *average* household saves money on their energy bills, there may be a wide distribution such that some households see large bill increases.

A second shortcoming of ASHP analyses is lack of detail in performance modeling. Some studies use a single coefficient of performance (COP) value to represent efficiency regardless of weather conditions.[26,27] Several studies improve upon this by using a COP vs. outdoor temperature curve to represent how performance changes with weather,[14,24,25] but even this can miss out on other aspects of performance, many of which are particularly important for high-efficiency variable-capacity equipment. Our modeling incorporates many of these aspects empirically, including: the COP vs. compressor speed (and thus heating load) relationship, fan power, defrost, cycling, the capacity vs. outdoor temperature relationship, and the relationship between sizing, capacity retention, and supplemental heat use; though it does not try to represent manufacturer-specific refrigeration cycle controls.

Deetjen et al. evaluate distributions of costs and benefits of ASHPs using a detailed physics-based model, but do so only for minimum efficiency single-speed ASHPs that have primarily been used in warmer climates, and perform quite differently from ASHPs designed for cold climates.[28] Technical advances in thermostatic expansion valves, variable-speed blowers, improved coil design, and improved electric motor and compressor designs have contributed to improved efficiency and cold-climate performance of ASHPs.[29] There are now over 25,000 products listed in the Northeast Energy Efficiency Partnerships (NEEP) cold-climate ASHP (ccASHP) list that have a COP of 2 or greater while running at maximum capacity at -15°C (5°F).[30] However, ccASHPs are more expensive and it is not well understood in which climates they should be recommended. Nadel and Fadali model a ccASHP and a traditional ASHP in various locations and conclude that life-cycle costs can be minimized by popularizing ccASHPs in climates with more than 4,000 heating degree days (base 65°F), but their analysis did not use dynamic hourly modeling to account for the performance aspects listed above.[21]

Equipment installation costs are the third area where we advance understanding. Although wholesale ASHP prices are only $200 to $500 more than equivalently sized air conditioners,[24] ASHPs designed to fully electrify space heating (as opposed to hybrid or dual-fuel systems) are often more expensive to install than an equivalent air condi-

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tioner plus gas furnace in practice. The main reason is that larger heating loads require larger heat pumps (or electric resistance backup), new wiring, and sometimes electrical panel or service upgrades. We estimate that average design heating loads exceed average design cooling loads in about 70% of U.S. homes (see Figure S1). Installers who do not have experience with heat pump technology may also charge higher prices to cover the hassle and risk of working with unfamiliar equipment. Studies frequently assume that equipment costs do not vary with equipment capacity,[21,22] or use only a variable component (cost per unit capacity) without a fixed component,[31] which will underestimate or overestimate the value of downsizing equipment. The variable and fixed cost components are particularly important to represent when analyzing the impact that insulation upgrades have on ASHP costs and benefits.

Finally, studies that quantify the greenhouse gas (GHG) impacts of heat pumps typically lack physics-based heterogeneous housing stock modeling.[22,27,32] The sole study that has used physics-based heterogeneous modeling only analyzed a minimum efficiency heat pump,[28] and used a short-run marginal emissions factor methodology that is no longer considered best practice.[33,34] We use newly available forward-looking emissions factors for a range of five future grid scenarios[34] to understand the GHG impact of ASHPs, and how sensitive those results are to housing stock diversity and assumptions about future grid evolution (see Figure 1). Addressing this GHG impact question credibly is critical, as it is sometimes cited as a reason to delay ASHP deployment.

In this paper, we use the ResStock™ tool to perform subhourly physics simulations of 550,000 statistically representative dwelling units, each representing 242 real dwelling units, covering all single-family and multifamily housing across a wide variety of climates, housing characteristics, and occupant behavior. These simulations are used to analyze six ASHP scenarios—three different ASHP performance levels, with and without insulation upgrades—and a reference equipment replacement scenario (see Figure 1).

The result is a comprehensive picture of how ASHP adoption would affect GHG emissions and energy bills across the diversity of the 130+ million housing units in the U.S., down to the county level and below. Combined with incremental installation cost equations based on regression models of real ASHP project cost data against capacity and rated efficiency, we also quantify the consumer upfront and operating costs (life-cycle costs) of the six scenarios to understand the impact that financing mechanisms could have on ASHP adoption. We explore the sensitivity of energy bill impact and life-cycle cost results to fuel price volatility, financial incentives, and other parameters (see Figure 1). Understanding these impacts is critical when 20 million U.S. households are behind on their energy bills and heat pumps—which can decrease or increase energy bills—are being widely promoted and incentivized, such as the tax credits and rebates for heat pumps—further described in Section 2.7—in the recently passed *Inflation Reduction Act of 2022*.[35]

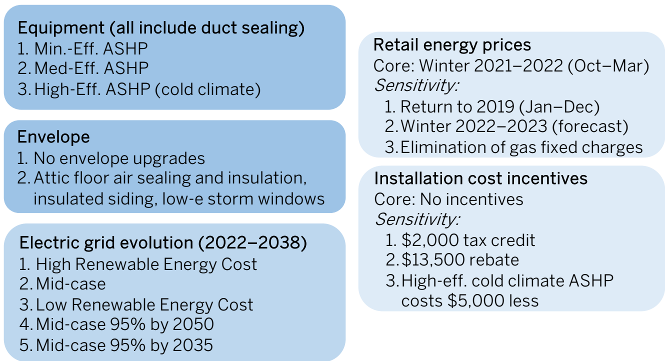

Figure 1: Summary of analysis scenarios: three air-source heat pump (ASHP) scenarios are combined with two different envelope upgrade scenarios for a total of six upgrade scenarios. The greenhouse gas emissions of these six upgrade scenarios are evaluated under five different scenarios of how the electric grid might evolve from 2022 to 2038. The consumer economics are evaluated for one core scenario with three energy price and three installation cost sensitivities.

2. Results

2.1. *ASHPs deliver substantial energy savings and reduce average greenhouse gas emissions in all states and future grid scenarios*

The estimated ranges of GHG emissions impacts of each of the six heat pump scenarios relative to the reference scenario are shown in Figure 2. The color of each state indicates the average annual carbon equivalent emissions savings per household (both on-site and indirect electricity emissions), with each row being a different heat pump scenario and each column being a different future grid scenario. Average annual GHG savings are positive in every state and in every heat pump and grid scenario, even in the conservative "High Renewable Energy Cost" grid scenario. The states span a wide range of climates and grid GHG intensities, with several states rivaling the intensity of higher-carbon electricity regions in Asia, Africa, and Oceania.[36] Thus, the positive savings trends observed here may carry over to those other regions if their grid trajectories fall within the range of scenarios studied here.

We estimate that full, immediate ASHP adoption would reduce annual CO_2e emissions (levelized over the 16-year equipment lifetime[37]) an average of 2.5–4.4 t/yr per dwelling unit, depending on the ASHP and grid scenario. Aggregating the impact for entire residential sector results in a reduction of 330–590 Mt/yr (36–64% of 2020 residential sector emissions and 5–9% of national economy-wide emissions[38]).[1] Full ASHP adoption would substantially

[1] These calculations use long-run marginal emissions rates for electricity based on a 5% increase in load.[34] Long-run marginal and

increase peak demand for electricity in many parts of the United States,[14] particularly if the installed ASHPs are lower efficiency with electric resistance backup and without envelope upgrades. Peak demand impacts were not assessed in this study, though hourly load profile results for similar electrification scenarios are available on the ResStock website.[40]

The results presented here include heat pumps replacing both fossil heating and existing electric heating. Figure S3 shows how emissions impacts vary by the previous heating fuel type. Reductions are highest when replacing a fuel oil heating system and lowest when replacing a heating system that is already electric. Another trend to highlight is that per-household savings are generally higher in cold climates. For example, for the high-efficiency cold climate heat pump scenario and MidCase grid scenario, the savings range from 1.6 tCO_2e/yr in Florida to 9.8 tCO_2e/yr in Maine. As mentioned in the section on GHG methodology, increases in refrigerant emissions are not included in our presentation of results, but can be expected to be around 0.7 tCO_2e per year over the 16-year lifetime of the equipment (using 100-year global warming potential and based on Figure 6 of Pistochini et al.[32]), and thus would not change the direction of these findings.

National site energy savings are also substantial, with average savings of 31–47%, depending on ASHP performance level, and 41–52% when combined with envelope upgrades. Site energy savings vary widely, as shown in the distributions in Figure S2. Full, immediate ASHP adoption would save an estimated 3.8–6.2 EJ/yr (3.6–5.9 quads) of on-site energy use.

2.2. The impact of ASHPs on energy bills is highly variable

Distributions of annual energy bill savings for each ASHP scenario compared to the reference scenario are shown in Figure 3(a), using energy prices from Winter 2021–2022. It is clear that efficiency level and cold-climate performance of ASHPs are highly significant. Negative bill savings—indicating that it costs more to operate the ASHP than the reference scenario equipment—are estimated to occur in 39% of homes with the minimum efficiency ASHP, but only 5% of homes with the high-efficiency ccASHP (19% and 3%, respectively, if combined with envelope upgrades). These bill impacts include new air conditioning use in homes that did not previously have it; when excluding those homes, negative bill savings would occur in 33% of homes (minimum efficiency ASHP) and 1% of homes (ccASHP).

Figure 4 shows how the 5^{th}, 50^{th}, and 95^{th} percentile bill savings vary by public use microdata area (PUMA) across the U.S.[2] While there is geographic variation due to climate, energy prices, and housing stock characteristics in a given PUMA location , there is even more variation between the 5^{th} and 95^{th} percentiles in a given location. This variation—a feature of our highly granular approach—can be explained by the diversity of housing stock characteristics (including buildings types, fuel types, vintages, thermostat setpoints, insulation levels, and air leakage) that vary within each PUMA location and are represented through the use of hundreds of sample homes in each PUMA.

Two of the housing stock characteristics with the largest impact on the energy bill savings variation seen in Figure 4 are primary heating fuel type and presence of air conditioning equipment. These effects are illustrated in Figure S4, which shows that for the 48 million homes that currently heat primarily with electricity, fuel oil, or propane and have central or window/room air conditioning, almost all homes have positive bill savings regardless of heat pump efficiency level (95% to 100% nationally and median savings of \$300 to \$650 per year, depending on efficiency). However, only 73% to 86% of the 6 million homes heating with those fuels but currently without central or room AC would have positive bill savings. The installed ASHPs are assumed to be used for air conditioning in these homes, and would thus provide benefits in terms of improved comfort and resilience to extreme heat, which we do not attempt to monetize in this analysis. Most of the homes with increased energy bills are those in hotter climates but without existing central or window AC where increased cooling costs outweigh heating cost savings, with the largest fraction located in California.

For the 46 million homes currently heating with natural gas and with AC, bill savings depend strongly on ASHP performance level, ranging from 38% positive (-\$70 per year median savings) to 99% positive (\$380 per year median savings). For the 10 million homes heating with natural gas but without AC, only 5% to 58% have positive energy bill savings (median savings of -\$410 to \$40 per year), depending on ASHP performance level. Similarly, the largest fraction of those with negative savings are located in California. These results show the significance that presence of AC and primary heating fuel type have on energy bill savings. Providing cooling to homes that previously did not will likely have substantial co-benefits in the form of avoided mortality and morbidity due to extreme heat.[41] The small fraction of homes without AC (12%[42]) may continue to decrease with a warming climate, which would change the baseline for these energy bill impact findings and result in more homes with positive savings relative to the new baseline.

average emissions rates from the "High Electrification" scenario in Cambium 2022 are very similar to the Mid-case emissions rates used here, so we do not expect the range of reductions would be substantially different when accounting for this larger change in load.[39]

[2]Public use microdata areas (PUMAs) are statistical geographic areas used by the U.S. Census that each contain no fewer than 100,000 people.

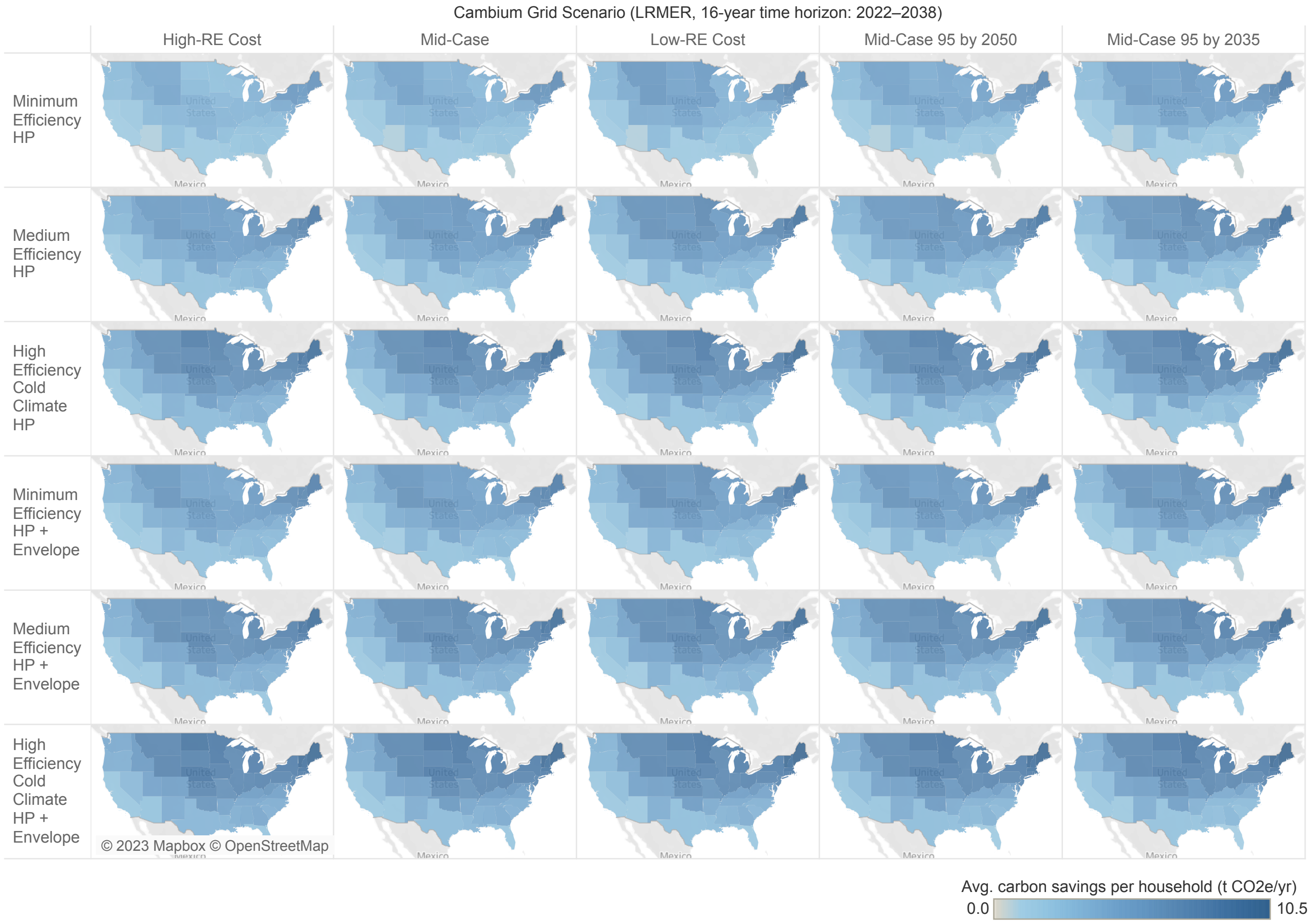

Figure 2: State maps of per-household mean carbon equivalent savings by scenario, under five different future grid scenarios over a 16-year time horizon, levelized with 3% discount rate. Average GHG savings, including both on-site emissions and indirect emissions from electricity generation, are positive in every state and in every grid and heat pump scenario.

2.3. High-efficiency cold-climate heat pumps cost significantly more upfront than minimum efficiency ASHPs

While the high-efficiency ccASHP scenario greatly increases the fraction of homes with positive bill savings, we find that these units currently have a much higher incremental cost over the reference scenario equipment, compared to minimum efficiency ASHPs. The distributions of incremental costs for the six scenarios are shown in Figure 3(b). As described in Section 4.4.6, the reference scenario equipment assumes replacement of both heating equipment and cooling equipment (if present) at the same time. This assumption is supported by survey data showing that 70% of households' main heating and cooling equipment are close in age to each other (in the same 5-year age response category).[42] If the furnace or central air conditioner being replaced with an ASHP is relatively new, then one would want to use a higher incremental cost in net present value (NPV) calculations.

These incremental upfront cost distributions are the result of two sources of variance: (1) the load calculations and equipment capacity that vary with climate, housing characteristics, sizing method, and capacity retention; and (2) the cost equations (Section 4.4.6) that vary with efficiency level, equipment type (ducted or non-ducted), rated capacity, and reference equipment. Distributions of equipment capacities are found in Figure S11.

As an example, in the Cold & Very Cold climate zone, homes with ducts that heat with gas, propane, or fuel oil and have central AC (18 million or 14% of all U.S. dwelling units) have mean ASHP upfront costs of $9,000, $20,000, and $24,000 for the three ASHP scenarios, respectively, which correspond to mean rated ASHP capacities of 2.2, 7.0, and 4.4 tons (8, 25, and 16 kW_{th}). The mean reference scenario equipment has a cost of $11,000, so the resulting mean incremental upgrade costs are -$2,000, $8,000, and $13,000, respectively. The subset of homes without central AC have a mean reference equipment cost of $5,000, so the mean incremental upgrade costs are higher: $3,000,

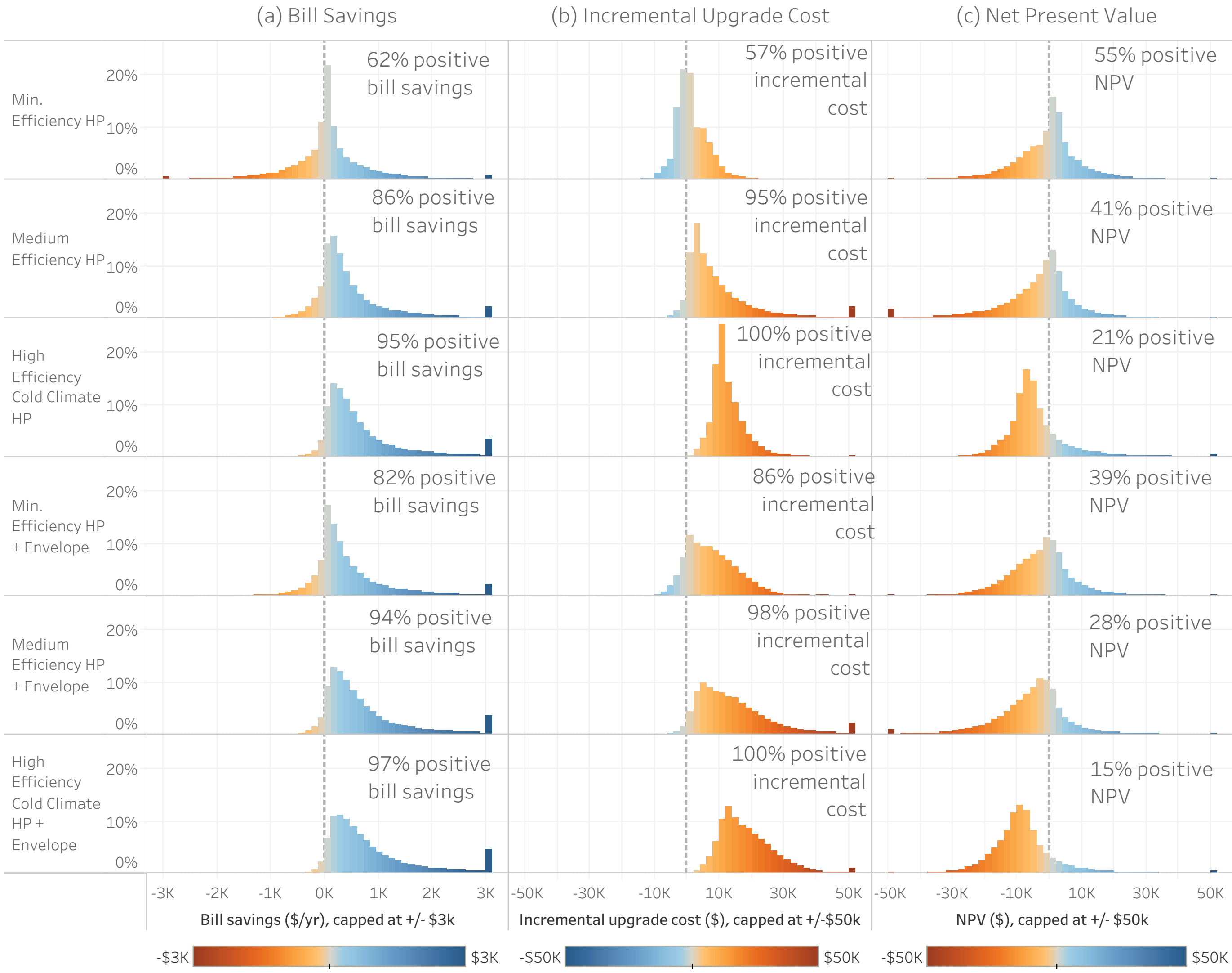

Figure 3: Distribution of energy bill savings, upgrade costs, and unsubsidized net present value (NPV), relative to the reference scenario, using energy prices from Winter 2021–2022. Negative bill savings indicate that it costs more to operate the ASHP than the reference scenario equipment. Negative incremental upgrade cost denotes that the cost of the ASHP is less expensive than new reference case equipment (e.g., a new furnace and air conditioner). Negative unsubsidized NPV means that the upgrade scenario would likely not have a positive cash flow if financed without any subsidies. For the high efficiency cold climate ASHP, the positive bill savings share increases to 99% if homes without air conditioning are excluded (see Figure S4)—although providing cooling to those homes has significant health and resilience benefits. See Figure S5 for distributions of payback period.

$15,000, and $18,000, respectively. Note that the minimum efficiency ASHP is sized for the cooling load and thus has a much smaller mean heating capacity, relying on electric resistance heat when the ASHP alone cannot meet the heating load. The medium efficiency equipment is typically sized larger than the high-efficiency ccASHP because it has worse capacity retention at colder temperatures and therefore requires a higher rated capacity to meet the same design heating load.

All six scenarios we modeled included sealing and insulating all ductwork located in unconditioned space. If additional basic envelope upgrades (Table 2) are implemented prior to installing the ASHP, heating capacities can be reduced further. For the above example segment, the mean rated ASHP capacities are reduced by 2.1 and 1.4 tons (7.4 and 4.9 kW_{th}) for the medium- and high-efficiency ASHPs, respectively. This reduces the mean ASHP installation costs by $4,000 and $2,500, respectively, but the envelope upgrades come at a mean additional upfront cost of $9,000 per dwelling unit for this example segment, so the net effect is an overall increase to upfront costs. However, if the envelope upgrades avoid the need for more expensive ductwork, electrical panel or service wire upgrades, they could result in much larger reductions in upfront costs that are not explicitly quantified in this study. Optimizing envelope upgrades for specific situations was outside

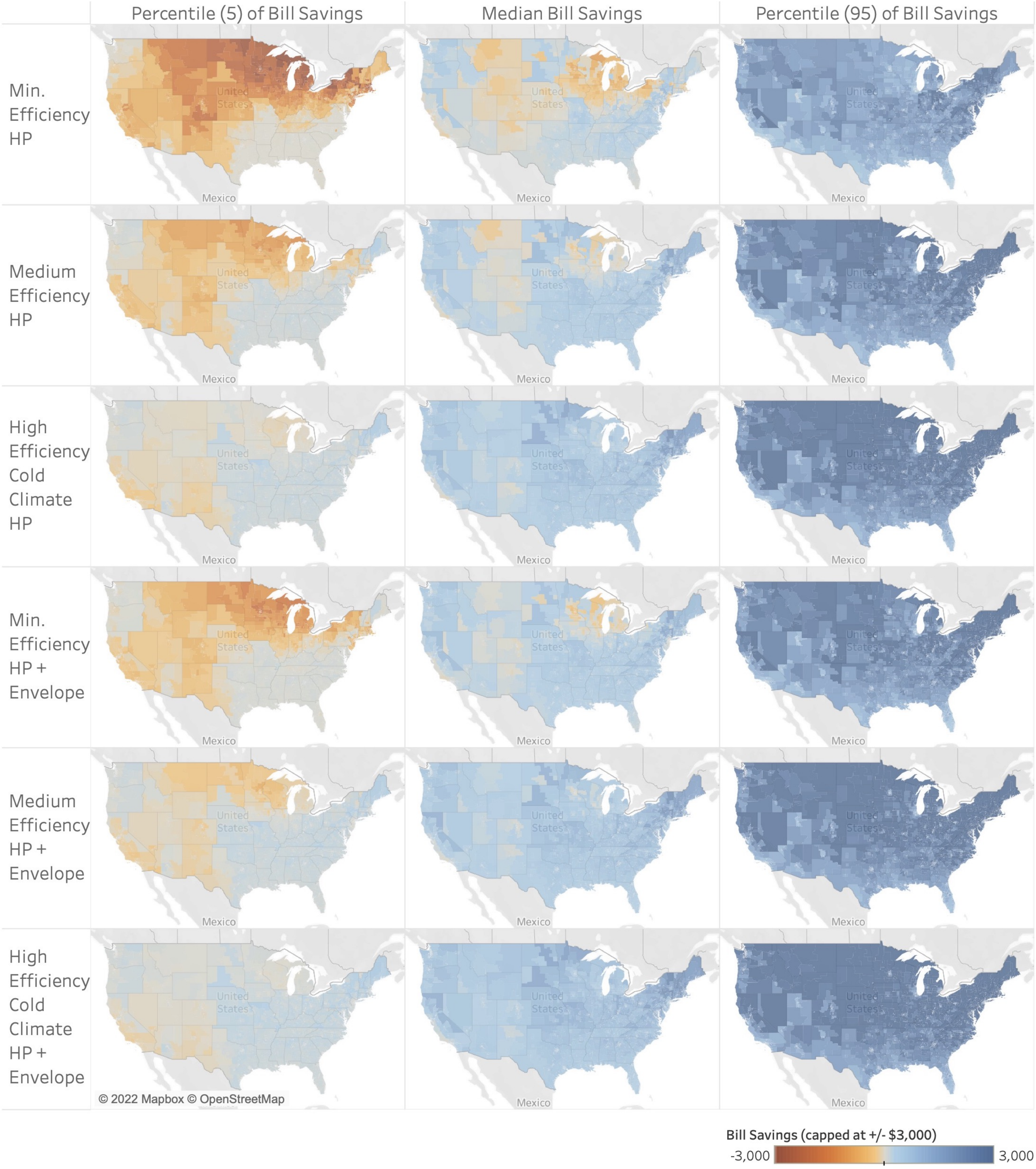

Figure 4: Maps of 5th, 50th, and 95th percentile energy bill savings by public use microdata area (PUMA), compared to the reference scenario. Energy bills were calculated using energy prices from Winter 2021–2022. Note that these results include homes without existing air conditioning that use electricity for air conditioning after receiving a heat pump (see Figure S4).

the scope of this study, but it is possible that less costly upgrades (e.g., focusing solely on attic insulation and air sealing without upgrading wall insulation) would provide much of the downsizing benefit at a lower cost.

2.4. *Cost reductions are needed to improve the value proposition for almost half of all U.S. households*

Distributions of consumer life-cycle costs and benefits of the heat pump scenarios are presented in Figure 3(c), using unsubsidized net present value (NPV), as defined in equation 5 and described in Section 4.6.3. NPV is very sensitive to discount rate, and real consumer discount rates vary widely based on credit scores and financing availability. For this analysis, we used a real discount rate of 3.4%[43], which corresponds to a nominal discount rate of 8–11% based on inflation rates of 5–8% in 2021 and 2022.[44] This range is comparable to national average interest rates for home equity loans in the United States in 2023.[45] While a positive NPV indicates that the investment is financially beneficial compared to the reference scenario, it is not meant to suggest that consumers will adopt the technology. Instead, we use NPV as a proxy for whether the technology can be financed with positive cash flow for the consumer (e.g., by a state or federal green bank, mortgage lender, or other financing agent).

Overall, these results show that a majority of homes can benefit from lower-cost minimum efficiency ASHPs with electric resistance backup, which has the largest share of households with positive unsubsidized NPV (55%). This group includes most homes that use fuel oil, propane, or electricity for heating, and also most homes that use natural gas and have central AC in warmer climates (see Figures S7–S8 for disaggregation by fuel type, presence of AC, and state). These homes see significant bill savings with the minimum efficiency ASHP and do not require more expensive higher-efficiency or cold climate equipment to achieve energy cost savings. Even though the medium and high-efficiency cold-climate scenarios have greater positive bill savings, their higher upfront costs reduce the share of homes with positive unsubsidized NPV to 41% and 21%, respectively.

Homes without existing air conditioning are doubly challenged: (1) they are more likely to see energy bill increases because of the new central air conditioning provided, and (2) with no existing air conditioner, the incremental cost of ASHPs over a furnace or boiler (and maybe window/room AC) is higher than homes with existing central AC. However, they receive an important comfort and resilience benefit that may be worth the higher cost. In the Cold & Very Cold climate zones, the envelope upgrade scenarios slightly increase the share of homes with positive unsubsidized NPV, whereas they generally decrease the share with positive unsubsidized NPV in warmer climates.

2.5. *Bill savings impacts are very sensitive to changes in fuel and electricity prices*

We studied how sensitive the ASHP energy bill impacts are to retail energy prices, which have increased significantly over the past three years since 2019, though increases in electricity (6–14%, depending on census region) were lower than increases in natural gas (22–46%), heating oil (35%), and propane (33–50%). Figure 5 shows state maps of the percentage of homes with positive bill savings for the main case (national weighted average of electricity price to natural gas price of 3.3) and two price sensitivity cases. We find significant sensitivity to energy prices, with a return to 2019 energy prices (elec-to-gas ratio of 4.1) reducing median annual bill savings by $400–600 for homes heating with propane and fuel oil, depending on ASHP efficiency level. Despite these reductions, bill savings would still be predominantly positive for homes heating with propane (87–99%) and fuel oil (66–100%). The impacts for homes heating with natural gas or electricity are much smaller, with median annual bill savings reduced by $77–136 and $18–42, respectively, though the reductions for natural gas are enough to reduce the percentage with positive bill savings from 32–92% to 22–83%, depending on ASHP efficiency level.

On the other hand, if energy prices continue to increase as was forecast for winter 2022–2023 (elec-to-gas ratio of 3.0),[46] national median annual bill savings would be projected to increase another $230–340 for homes heating with fuel oil and $70–110 for natural gas, depending on efficiency level. This would increase the percentage of natural gas homes with positive bill savings from 32–92% to 40–94%. Impacts to homes heating with other fuels would be minimal, with median annual bill savings slightly increasing ($10–30) for electricity and slightly decreasing ($20–60) for propane (because electricity price increases slightly outpace propane price increases in the forecast). A September 2022 survey of 134 oil and gas executives found that 69% expect "the age of inexpensive U.S. natural gas to end by year-end 2025," as liquefied natural gas exports to Europe expand, so a return to 2019 prices may be unlikely.[47]

Because many countries use currently natural gas to generate electricity (38% in the U.S. in 2021), high natural gas prices increase the cost of generating electricity. This moderates the effect that high natural gas prices have on ASHP economics, though this effect may lessen as higher shares of renewable and other non-gas generation come onto the grid, reducing the impact of natural gas prices on wholesale electricity prices. There may be localized differences for electric utilities that use more or less gas for generation, or that have different mechanisms for passing on fuel costs to consumers.

2.6. *Fixed charges for natural gas meters can have a significant impact on ASHP economics*

One factor that can change the economics of heat pumps is the fixed customer or meter charges that gas utilities charge alongside volumetric rates. Homes that decide to convert all piped gas end uses to electricity and have their gas service shut off will no longer need to pay the fixed component of their gas bill, which was a median of $11.25 (U.S.D) per month for U.S. residential customers in 2015.[48] The charges vary substantially, with examples of fixed charges in 2022 ranging from less than $5.00 per month in most of California to as high as $34.12 per month (Chicago)[49] or $64.65 per month (New York City).[50] Fixed charges have trended upward over time. In the 30 years between 1985 and 2014, the average fixed customer charge increased by 184%, and some gas utilities have sought to increase fixed customer charges to better represent the cost of serving customers and make utility earnings less dependent on sales volume.[48]

Figure 5 estimates the impact that eliminating the assumed median $11.25 monthly gas customer charge would have on the percentage of homes that would see positive bill savings from the heat pumps measures. For the high-efficiency, cold-climate heat pump case, the percentage increases from 32–92% to 49–97% for homes heating with natural gas. In reality, the impact would be highly regional and would also need to account for the bill impacts of electrifying water heating and other gas end uses, but this illustrates how it could be a significant factor in the economics of heating electrification. If large numbers of customers were to shut off their gas connections, this could shift costs of paying for past and future gas infrastructure investments onto the remaining gas customers, potentially leading to increases in fixed charges or volumetric rates.[51] This would further improve the economics of heat pump adoption, but would be a very serious equity concern for consumers who cannot afford the upfront cost of heating electrification.

2.7. Financial incentives can improve the value proposition for ASHPs, but significant incentive levels would be needed to drive widespread adoption

The *Inflation Reduction Act of 2022*, signed into law in August 2022, includes tax credits and rebate program provisions that have the potential to change the economics of heat pump adoption for the next decade.[52] The $4.5 billion in point-of-sale electrification rebates could incentivize heat pumps for roughly up to 500,000 low-income households at $8,000 per household or 1 million moderate-income households at $4,000 per household. The $4.3 billion in home efficiency rebates could incentivize energy efficiency (including heat pumps) in 500,000 to 2 million other households ($2,000 to $8,000 per household). The residential tax credits have no upper limit on the number of households that could participate, but require high enough income (and therefore taxes paid) to be able to use the full credit amount. Based on simple calculations using tax brackets and standard deductions, we estimate household incomes of $33,000 for single filers and $48,000 for joint filers would be required to be able to claim a $2,000 credit for a heat pump in 2023. Both the rebates and tax credits could spur additional growth in heat pump market adoption, but how much of an effect will they have for those households using the incentives? To understand the potential impact on project NPV, we calculated NPVs for two sensitivity cases, applying incentives of $2,000 (tax credit) and $13,500 ($8,000 heat pump rebate, $2,500 wiring, $1,000 duct sealing, and $2,000 tax credit)[3] as direct additions to the unsubsidized NPV for each household.

The results of these incentives applied to the high-efficiency, cold-climate heat pump scenario for the entire housing stock (not restricted by household income eligibility) are shown in Figure 6. The effect is that the histograms for upgrade costs and NPV are shifted to the left and right, respectively, by the incentive amount. The $2,000 tax credit increases the percentage of homes with positive NPV from 41% to 53% (medium efficiency) and 21% to 27% (high efficiency); the minimum-efficiency unit is not eligible.[4] The combination of $11,500 in rebates and $2,000 in tax credits increases the share with positive NPV to 84% (medium efficiency) and 90% (high efficiency). The effect of these incentive levels on the percentage of homes with positive NPV by state, fuel type, presence of AC, and ASHP efficiency is show in Figures S8–S10.

If one selects the upgrade package with the highest unsubsidized net present value (NPV) for each of the representative 550,000 homes (shown in Figure S7), 59% of the homes (about 65 million) have at least one package with positive unsubsidized NPV. The total incentive value required to make at least one package break even in the remaining 45 million homes is estimated to be $282 billion. This idealized case of perfectly targeted incentive levels can be contrasted with a case where a fixed incentive level is provided to all 110 million eligible households. A $12,000 incentive per household ($1.3 trillion total) would be required to result in 95% of households having a positive NPV). However, it is important to remember that having a positive NPV does not mean that an upgrade will be adopted; low-cost financing would be needed by many households and there are many non-economic reasons why households may choose not to adopt upgrades with positive NPV or to adopt upgrades with negative NPV.

2.8. Reducing the cost of high-efficiency, cold-climate ASHP equipment is necessary to improve the economics of residential electrification

As described in the section on upgrade costs (4.4.1), equipment costs at higher levels of efficiency are more uncertain, with only three samples with heating seasonal performance factor (HSPF) above 11.0 in the data used for

[3]These amounts would be available for households with income less than 80% of the area median income, though the Figure shows the NPV distribution for the entire housing stock. $1,600 is available for insulation and air sealing, but we assume only $1,000 is used, as this is the average cost of duct sealing based on the costs calculated in our analysis. Some households would need electric panel upgrades and would be eligible for up to $4,000 to cover those costs, but we do not include this incentive because we do not explicitly account for panel upgrade costs (electrical upgrade costs are implicitly included in an unknown portion of the cost data used for regressions).

[4]The IRA requires ENERGY STAR certified equipment for rebates and the highest CEE tier equipment for the tax credit. Exact requirements were still being determined as of this writing, but it is expected that the minimum efficiency equipment would not be eligible for either incentive.[52]

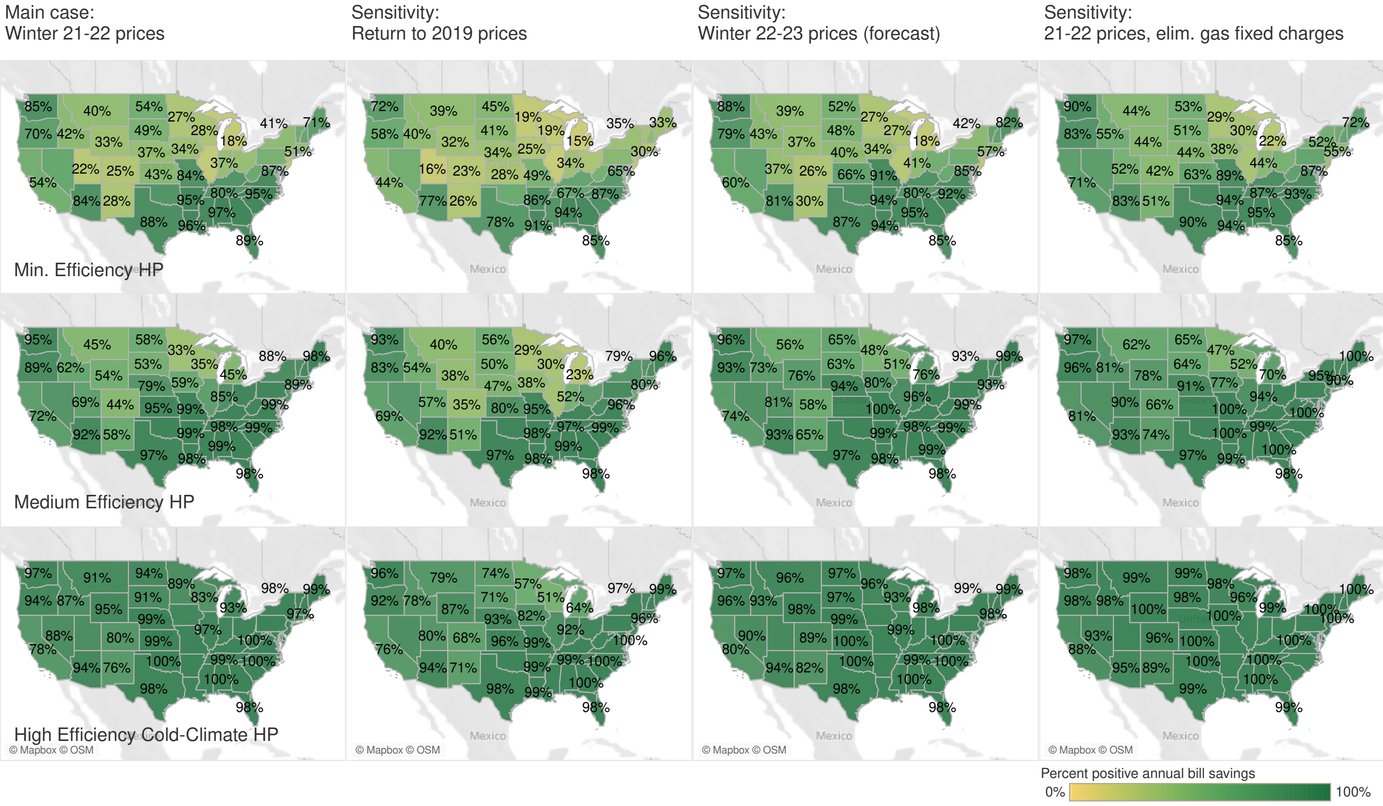

Figure 5: Percentage of households with positive annual energy bill savings; the main case with winter 2021–2022 fuel prices is compared to three sensitivity cases, one with fuel prices returning to 2019 levels, a second using regional fuel price increases forecast for winter 2022–2023,[46] and a third illustrating the impact of eliminating $11.25 in monthly gas customer charges by homes currently heating with natural gas converting to all-electric. Note that these results include homes without existing air conditioning that use electricity for air conditioning after receiving a heat pump (see Figure S4).

regression. Comparing the regression to other data sources (Figure 7) suggests that costs may flatten out somewhat above HSPF 11, once the variable-speed cold-climate tier is reached. To explore sensitivity to the upgrade costs for the high-efficiency, cold-climate heat pump, we include a third sensitivity case in Figure 6 where HSPF 11 is used in the installation cost equation (Tables S5 and S6 and Figure S19) for HSPF 13 and 14 equipment. This effectively decreases the cost of ducted equipment by $4,966, from an average of $22,400 to an average of $17,546. The effect on ductless equipment cost is less pronounced , decreasing the cost of ductless equipment by 8%, from an average of $17,400 to $16,700 (see discussion in Section 4.4.1).

This lower cost would increase the share of households with positive unsubsidized NPV to 38%. This suggests that if costs for high-efficiency equipment are overestimated by our regression as suspected, then the economics for ccASHPs would be favorable for about 38% of consumers instead of 21% as previously presented. At the same time, this demonstrates that research, development, demonstrations, and market stimulation to reduce upfront cost can have a positive impact on consumer economic barriers, but costs would need to be reduced by much more than $5,000 to make the equipment cost-effective enough to finance it and enable widespread adoption. For example, looking at the top-right histogram in Figure 6, a $10,000 cost reduction would shift the histogram to the right, such that 80% of households would have positive unsubsidized NPV.

3. Discussion

3.1. Opportunities to mitigate economic barriers to ASHP adoption

We find that there are substantial economic barriers to widespread ASHP adoption. Although a majority of households can benefit economically from ASHPs today, there are potential energy bill increases for a significant number of households, strongly depending on ASHP efficiency level, cold climate performance, and whether envelope upgrades are also completed. In many cases, especially with high-efficiency equipment, the ASHP installation costs greatly exceed the reference scenario of like-for-like replacement of equipment at end of lifetime.

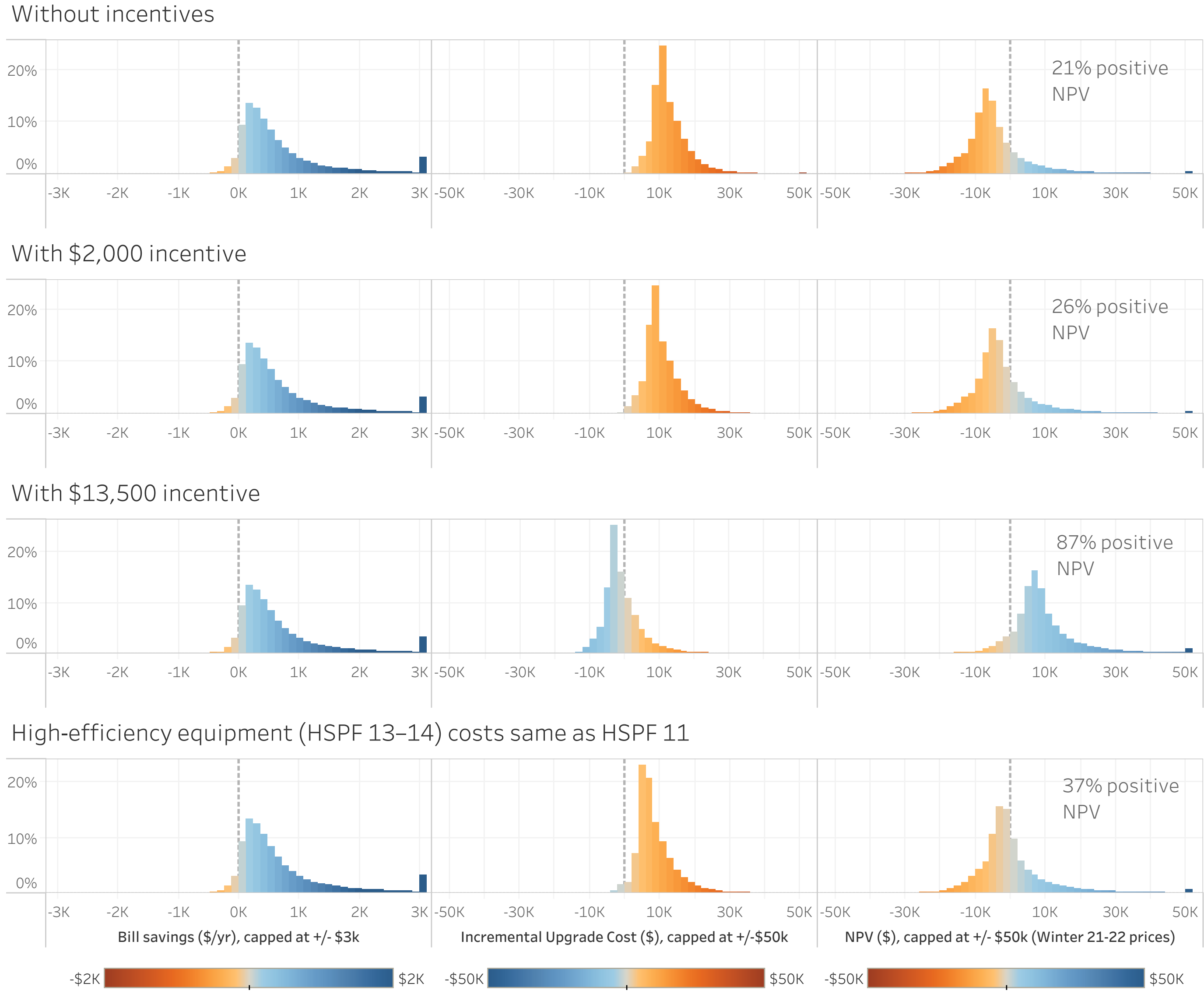

Figure 6: Distribution of energy bill savings, upgrade costs, and net present value (NPV), relative to the reference scenario, for high-efficiency cold-climate heat pump scenario under three sensitivity cases. Figure shows the effect of incentives applied to all simulated households, not just those eligible for the incentives. Note that these results include homes without existing air conditioning that use electricity for air conditioning after receiving a heat pump. If those homes are excluded, 99% of homes are expected to have positive bill savings in this scenario (see Figure S4). See Figure S6 for distributions of payback period under these sensitivity cases.

Technical solutions to mitigating the potential for bill increases include upgrading to higher efficiency cold-climate ASHPs, improving envelope efficiency, or, though not analyzed here, ground-source heat pumps (GSHPs). Most of these options increase the size of the upfront cost barrier, though they all have other societal benefits, such as reducing peak demand.

Though we did not analyze them here, hybrid ASHPs that use existing fossil systems as backup during very cold temperatures are another option that could mitigate potential bill increases without necessarily increasing upfront costs.[24,14] The use of fossil-fired backup heat would decrease the emissions reductions presented in the Results to some degree. However, continued use of natural gas distribution infrastructure for backup heat has other implications, including continued spending for gas distribution system maintenance and expansion ($22 billion in 2021) and continued methane leakage from the gas distribution system (15.3 Mt CO_2e/yr).[53,54] Other solutions to improve the economics of ASHPs include bundling with adoption of on-site or community-scale solar, although depending on financing availability these may also have upfront cost barriers. Bundling electric vehicles or stationary batteries also may have synergies with building electrification in that they can facilitate resilience to power outages, which otherwise might be worsened by electrification.

Policymakers at national, state, and local levels can pursue a number of strategies to mitigate energy bill increases. State utility regulators, city councils, and electric cooperative boards can direct electric utilities to update electric rate structures to promote electrification and avoid potential bill increases. They can also expand awareness and access to rate designs for low-income customers, as well as programs that guarantee bill stability after electrifying. These examples of electric rate policies are present or are being considered by several states and utilities.[55,56,57] Another policy that could help is creating utility programs or markets that enable aggregators and thus consumers to be compensated for grid-responsive control of deployed ASHPs and other appliances. These "virtual power plants" can be used to generate revenue to offset the higher upfront or operational costs of ASHPs. In utility territories where time-of-use electric rate structures are offered, there may be a similar opportunity to control ASHPs to reduce use during more expensive on-peak periods and thus improve the bill savings of ASHPs.

Policymakers can address high upfront cost barriers through incentive programs, financing and tariffed on-bill programs, and bulk purchasing or aggregation of demand for equipment. Policymakers with oversight of research and development efforts can pursue research on lower cost, higher performance, and easier to install equipment. High upfront costs due to overly conservative equipment sizing can also be addressed through the development of tools and guidance on best practices for sizing equipment.[58] Though not explicitly accounted for in this analysis, high consumer upfront costs due to electrical upgrades (panels, service conductors, and transformers) could be reduced if state utility regulators allow these upgrades to be paid by ratepayers as part of the rate base. As with all incentives, the ratepayer equity implications of socializing the cost of behind-the-meter electrical upgrades would need to be evaluated. Whereas photovoltaic net metering and efficiency incentives reduce electricity sales and thus utility revenue, electrification incentives increase electricity sales, which helps to pay for infrastructure and potentially puts downward pressure on retail rates.

Policymakers should be aware that electrification and envelope efficiency can provide a multitude of co-benefits, such as improving health outcomes (e.g., reducing lung irritants that cause asthma and excess deaths such as nitrogen dioxide and $PM_{2.5}$) and improving comfort and extreme weather resilience by providing air conditioning. Quantifying these societal co-benefits and valuing them in ratepayer and taxpayer-funded programs can help justify subsidizing installation costs, similar to how the social cost of carbon is now accounted for by several state regulatory commissions.[59] It is worth noting that some scenarios have greater co-benefits than others. For example, envelope efficiency provides comfort and thermal resilience co-benefits, and variable-speed ASHPs deliver greater comfort and indoor air quality co-benefits than single-speed ASHPs because they circulate and filter air at low fan speeds almost continuously.

Our findings demonstrate that to understand the consequences of ASHP policies and programs, it is essential to consider the full distribution—as opposed to average—of the costs and benefits that ASHP adoption would have on households in the United States. For example, minimum-efficiency ASHPs with electric resistance save \$100 annually on average, but could increase energy bills for 39% of households (33% in homes with existing AC). The high-efficiency ccASHP saves \$740 annually on average and, but still could increase bills for 5% of households (1% in homes with existing AC). However, the ccASHPs currently come at much higher upfront cost that many households will not be able to afford without incentives.

3.2. Limitations and Future Work

3.2.1. Validation of modeled heat pump performance

While the EnergyPlus simulations include details of heat pump performance that are neglected in other modeling efforts, the performance of the heat pumps modeled here may differ from their real-world performance. The mini-split heat pump models (used for all ductless efficiency levels and the ducted cold-climate high-efficiency level) were calibrated with field study data,[60] but conventional form factor heat pump models (used for ducted minimum and medium efficiency levels) have not been validated to the same degree. Work on field testing and model validation of central ducted heat pumps is an important area of ongoing work.

3.2.2. Ductwork airflow constraints on equipment sizing

We chose to size the heat pump equipment based on the larger of the design cooling and heating loads and did not account for how use of existing ductwork might constrain heat pump sizing. In reality, ducted heat pumps that are connected to existing duct systems may be forced to be undersized, and thus rely more on backup electric resistance heat, because of the airflow constraints of the existing ductwork.

Because furnaces deliver heat at higher supply air temperatures than heat pumps, heat pumps need to use higher airflow rates to deliver the same amount of heat under design conditions. Ducted heat pump airflow is typically designed for around 400 ft^3/min. per ton (193 m^3/hr per kW_{th}; e.g.,[61]), whereas non-condensing furnaces are designed for around 156 ft^3/min. per ton (75 m^3/hr per kW_{th}).[62] One HVAC expert estimates that "most duct systems can only handle 2 or 3 tons (7–10 kW_{th}) of airflow (800–1200 ft^3/min. or 1360–2040 m^3/hr)" to maintain a static pressure imposed on the fan of 0.5 inches of water (124 Pa) or less.[63]

The typical solution is to use electric resistance backup when heating loads exceed the maximum heat pump capacity. Undersizing the heat pump is not necessarily a negative; the heat pump itself will cost less, it can result in more efficient performance under low-load conditions by reducing cycling, and can improve cooling dehumidification performance. However, installing the electric resistance heat adds to the upfront cost of installation, and may increase the need for electrical upgrades (circuit, panel, and service wire). Alternative solutions include reducing the home's heating load with insulation and air sealing, installing larger ductwork (estimated cost of $7,000[64]), or supplementing the ducted heat pump with one or more ductless heat pumps (e.g., in a basement or finished attic). These are a complex set of issues and more work is needed to understand how common the airflow constraints are and the trade-offs between the various solutions.

3.2.3. Cost of electrical panel or service wire upgrades

This study does not explicitly model the cost of electrical panel or service wire upgrades that may be required. Electrical upgrade costs are implicitly included in an unknown portion of the cost data used for regressions. Total costs to customers for upgrading electrical panels and potentially service wires, transformers, and utility poles are estimated to range from $2,000 to $30,000, though utilities may cover some of these costs.[65] Further work is needed to understand how many homes would require these different types of electrical upgrades and their costs. A survey of residential electrical panels in the U.S. found that 50–60% of homes already have a service panel greater than 150 amps and 75% of dwellings have at least one free breaker slot in their panel for adding a new load.[66]. Upgrading panels and electrical infrastructure may be more necessary when multiple end uses, including vehicles, are being electrified, as opposed to just the space heating end use considered here. The ability to fully electrify existing dwellings without upgrading service panels is an open question being explored by ongoing research using ResStock.

3.2.4. Electricity and gas rates

This study used marginal volumetric prices for residential electricity and gas, averaged by state. Volumetric prices for propane and fuel oil are averaged by state or, in some cases, region. Ideally one would use electricity and gas rates for individual utilities within each state and would reflect seasonal and time-of-use rate structures for electricity. Electricity rates tend to be lower during winter and during nighttime and early morning hours when heat pumps use more of their electricity, which would affect the overall bill impact estimates. It is important to note that we report *annual* utility bill savings, but households may see an increase in the month-to-month variation in bills; for example, a net decrease in bills may include an increase in winter months and a decrease in summer months.

We assume that all retail energy prices will increase with inflation over the 16-year life of equipment, but ignore other potential trends in retail electricity and gas prices. Future work could explore the sensitivity to longer-term price trends. Although electricity prices have been relatively stable over the past decade, the cost of electricity generation has been decreasing while the cost of delivering that electricity has been increasing.[67] The Inflation Reduction Act of 2022 (IRA) and the Infrastructure Investment and Jobs Act of 2021 are estimated to lead to a net decrease (5% to 13%) in total bulk power system costs in the U.S.[68]. However, electrification of buildings, transportation, and industry has the potential to either increase or decrease the cost of delivering electricity, depending on how the increased revenue compares to increased infrastructure costs. At the same time, electrification could cause natural gas rates to increase in the long term, due to decreasing volumetric sales and number of customers.[51]

3.2.5. Reference scenario minimum efficiency

The reference scenario does not account for the recently proposed update to federal efficiency standards for furnaces and boilers that would require condensing equipment with 95% AFUE. Using 95% instead of 80–85% AFUE for the reference would decrease the energy savings of the heat pump scenarios, but would also decrease the incremental cost of the heat pump scenarios because of the additional expense of installing the PVC venting required for condensing 95% AFUE furnaces and boilers. To estimate the impact that this change would have on our results, we compare between the ResStock sampled households that are assigned 80% AFUE and 95% AFUE furnaces in the baseline. In cold climates, ASHPs save about $100 to $200 per year less for the median household when replacing a 95% AFUE furnace compared to 80% AFUE. The reference case 95% AFUE furnaces cost about $1,800 on average more to replace than the 80% AFUE furnaces. This does not include the additional expense of installing new PVC venting. We expect the result would be a reduced value proposition for ASHPs in cold climates and improved value in mixed and warm climates.

3.2.6. Ground-source heat pumps

Geothermal or ground-source heat pumps (GSHPs) can provide even greater efficiency and cold-climate performance than ASHPs, but are currently an even more expensive solution for serving individual dwelling units. Therefore, we have not included them in this analysis, but acknowledge that analysis of GSHP costs and benefits is an important area for future work. For instance, utility-owned thermal networks that incorporate GSHPs (sometimes called "networked geothermal") offer a compelling pathway for gas utilities to pivot into thermal utilities while eliminating upfront costs of GSHPs for consumers by financing them or including them in the rate base. These networks are a growing solution in Europe and are beginning to be piloted in the U.S.,[69] but more analysis is needed to quantify their efficiency, flexibility, and peak demand benefits.

3.2.7. Distributional impacts to specific income groups and energy justice communities

The version of ResStock used for this analysis did not assign household incomes or other socioeconomic variables to the representative dwelling units; thus, it was not possible to examine how the costs and benefits of ASHPs are distributed across different income groups or communities that are a priority for energy justice initiatives. Income variables and correlations between income and housing characteristics were recently added to ResStock, making such an analysis of the impacts to specific groups possible and a high priority for future work.

3.3. Additional sensitivity analysis

3.3.1. Sensitivity to equipment sizing

To explore the sensitivity of results to the equipment sizing method, we simulated additional scenarios with ASHPs sized based on the cooling load (following ACCA Manual S) and compared with main results where sizing was based on the larger of the design heating or cooling load. The medians and standard deviations of the ASHP capacities with the two methods are presented in Table S1.

As would be expected, we find that sizing ASHPs for the full heating load results in higher median bill savings compared to ASHPs sized with cooling load priority. For instance, the median bill savings in Minnesota is $182/yr for high-efficiency ASHPs sized for heating load, whereas median bills increase by $96/yr when sized for the cooling load because of higher usage of electric resistance backup. However, sizing for cooling load priority typically reduces the upfront ASHP equipment cost (ignoring the fact that larger electric resistance backup may require more significant electrical upgrades); thus, the national percentage of households with positive unsubsidized NPV is higher for ASHPs sized on cooling load due to lower upgrade costs. Additionally, as discussed in Section 3.2.2, ductwork airflow constraints may preclude sizing for the full heating load. However, there may be societal benefits to sizing ASHP for heating loads in that it can reduce peak demand and thus the size of grid infrastructure at the grid edge and bulk power scales. More work is needed to understand considerations for sizing guidance.

3.3.2. Sensitivity to thermostat schedules

When it comes to variable-speed equipment, best practice for energy efficiency is to "set it and forget it," because the equipment is less efficient at the higher compressor speeds used when recovering from setbacks and this efficiency loss typically outweighs any savings from thermostat schedule setbacks.[5] For the main analysis, any existing nighttime and daytime heating setpoint setbacks (distributions are based on RECS 2009 data[72]) were removed for homes receiving medium and high-efficiency heat pump upgrades. To explore the sensitivity of results to the use of temperature setbacks, we ran additional simulations where the setbacks were not removed. In those results, homes that did not use offsets originally saved an average of $10 to $100 more per year than homes that did use offsets, depending on the climate and heat pump efficiency level, indicating that using a thermostat setback for heating with a heat pump can have a significant penalty. Time-of-use rates or other utility demand flexibility programs may offer benefits to using a non-uniform thermostat schedule, but this was not included in this analysis.

[5] For example, the model of the medium-efficiency ASHP has nominal COP values that vary by about 20% across compressor speeds.[70] More significantly, both single-speed and variable-speed equipment can be configured with electric resistance as a second stage of heating that operates when the heat pump is not reaching the setpoint quickly enough, unless the equipment includes electric resistance heat lock out controls or thermostat smart recovery.[71]

3.3.3.

4. Experimental procedures

4.1. Resource availability

4.1.1. Lead contact

Further information and requests for resources and materials should be directed to and will be fulfilled by the lead contact, Eric J. H. Wilson (eric.wilson@nrel.gov).

4.1.2. Materials availability

No materials were used in this study.

4.1.3. Data and code availability

All results data and fuel price inputs uploaded to Zenodo: `https://zenodo.org/doi/10.5281/zenodo.10433623`]

Two interactive dashboards allowing data downloads are available:

- Heat pumps for all - GHG emissions dashboard
- Heat pumps for all - Economic data dashboard

The code used to generate the paper's results is available at `https://github.com/NREL/resstock/tree/run/abctypology`, including the primary scenario definition file with upgrade definitions and costs, conditional probability distributions for all baseline housing characteristics, and detailed simulation arguments for baseline characteristics and upgrades.

4.2. Model overview

We evaluated distributions of costs and benefits of residential ASHP adoption by estimating energy savings, GHG emissions, energy bills, ASHP installation costs, and consumer NPV for approximately 550,000 statistically representative dwelling units for a reference scenario and six upgrade scenarios. This was done using ResStock, a physics-simulation (Q4)[73] model of the U.S. building stock. The models were simulated with a 10 minute simulation timestep. A detailed description of ResStock data sources, calibration, and validation can be found in Wilson et al.[74] The granularity in modeling the diverse housing stock makes

ResStock well-suited for analyzing the distributions of benefits and costs of technologies. A detailed description of the ASHP model, which accounts for fan power, defrost, cycling, capacity vs. outdoor temperature, and supplemental heat use, can be found in the EnergyPlus documentation.[75]

The procedures followed four major steps: 1) definition of scenarios, 2) definition of upgrade costs, 3) simulation with ResStock, and 4) post-processing and analysis of results. Each stage is described in detail in this section.

4.3. Scenario definition

A total of six scenarios (listed in Table 1) plus a baseline were analyzed for this paper. There are three categories of scenarios: ASHP upgrades, ASHP with envelope upgrades, and a reference scenario that upgrades all heating and cooling equipment to federal minimum efficiency standards or higher, without changing fuel type or equipment type. All scenarios represent the circa 2018 residential building stock, with upgrades applied to virtually all dwelling units. All results presented in this paper are filtered to remove dwelling units that are unoccupied and thus typically not fully heated (11%) and units that are not heated (0.5%) or are heated primarily with wood (2.5%), leaving about 113 million occupied dwelling units (i.e., households).

4.3.1. Baseline building stock

The starting point for all six scenarios (the baseline) is ResStock's characterization of the residential building stock of the contiguous U.S. as it existed circa 2018. The data sources used for all 130 high-level ResStock parameters are listed in Table 2 of Wilson et al.,[74] and the conditional probability distributions for each of these parameters (as they existed at the time of this analysis) can be found on the code repository.[6] The approximately 550,000 dwelling unit samples are assigned proportionally, with each sample equally weighted to represent about 242 dwelling units in the real world. Thus, geographic areas with a denser concentration of dwelling units are assigned more ResStock samples. Sample size considerations are discussed in Section 5.1.3 of Wilson et al.[74]

4.3.2. Air-source heat pump upgrade scenarios

The three different efficiency levels of ASHP are described in Table 1. A central[7] ducted ASHP replaces the existing HVAC system for the 79% of homes with an existing duct system (i.e., homes with a forced-air furnace, central air conditioning (AC), or existing ducted ASHP), whereas a ductless ASHP is used as replacement for the 21% of homes without ducts (i.e., homes with radiators or baseboard electric heating and no central AC).

The cooling efficiencies of central AC and ASHPs are represented using seasonal energy efficiency ratio (SEER), whereas the cooling efficiency of window/room ACs is represented using combined energy efficiency ratio (CEER). The heating efficiency of ASHPs is represented by HSPF, and the heating efficiency of a fossil-fuel furnaces and boilers is represented using annual fuel utilization efficiency (AFUE). Note that SEER and HSPF will be replaced with new rating metrics (SEER2 and HSPF2) starting in 2023, but we use the pre-2023 metrics for this analysis.

The minimum-efficiency ASHP scenario is meant to represent the minimum efficiency heat pump available. As of January 1, 2023, the federal minimum efficiency for heat pumps increased from SEER 14, HSPF 8.2 to SEER 15, HSPF 8.8. We use SEER 15, HSPF 9.0 (ducted) and SEER 14.5, HSPF 8.2 (ductless) to align with existing options (sets of inputs) available in ResStock. As a point of reference, as of January 1, 2023, the ENERGY STAR® label specification for heat pumps increased from SEER 15, HSPF 8.5 (v5.0) to SEER 16, HSPF 9.2 (v6.1; using the old SEER1 and HSPF1 rating metrics).

The medium-efficiency ASHP scenario represents a premium variable-speed ASHP that is much more efficient than the minimum scenario, but does not meet criteria commonly used to define cold climate ASHPs (70% capacity retention at 5 °F). It should be noted that there are plenty of ASHP products available with HSPF 10 that do meet cold climate criteria.[30] The high-efficiency cold-climate ASHP scenario represents the best available efficiency level ASHP on the market. The HSPF 13 unit is more efficient than most ASHPs being installed in 2022; only six of the 33,000 ducted ASHP model numbers listed in the NEEP database have HSPF 13. Ductless ASHPs are available with HSPF up to 15.[30]

The performance of three ASHP efficiency levels vs. outdoor temperature for two sample dwelling units is presented in Figure S12 and Figure S13. Annual average COPs by state are presented in Figure S16. These values may be useful to add climate variation to studies choosing to use annual COP values to represent efficiency.[26,27]

We apply these two ASHP upgrades to all building types (single-family, multifamily, and mobile homes) and system types, including the estimated 1.5% of homes with a "shared" cooling system that serves multiple dwelling units in a building. Individual ASHPs may not be the most appropriate solution for these homes, but we include them for completeness. Similarly, it may be challenging to install individual ASHPs in 4–7 story (3%) and 8+ story (2%) buildings where there are long distances between dwelling units and the roof or ground where outdoor units may be located. Mounting mini-split outdoor

[6] `https://github.com/NREL/resstock/tree/run/abctypology/project_national`

[7] The term "central heat pump" is used here to refer to a centrally ducted heat pump that serves an entire dwelling unit, analogous to "central air" or "central AC," and not to be confused with a heating system that serves multiple dwelling units. The term "mini-split" heat pump is sometimes used interchangeably with "ductless" heat pump. Mini-split refers to the fact that the outdoor unit has a smaller form factor than a traditional split air conditioner or heat pump. Mini-split heat pumps can be ductless (e.g., indoor unit(s) mounted on a wall), ducted with concealed "slim ducts," or connected to an existing conventional duct systems.

Table 1: Definitions of the six upgrade scenarios. All six scenarios also included sealing and insulating all ducts located in unconditioned space down to 10% leakage and R-8 (RSI-1.4) insulation. The capacity retention of the heat pumps is assumed to be linear between the listed percentage and temperature and 100% of the rated output capacity at 47 °F (8.3 °C). All capacity retention curves and input values were originally developed for the BEopt software and were derived from a combination of laboratory test data (central ASHPs) and manufacturer reported data collected by NEEP (central ccASHP and ductless ASHPs).[76,30] See section S4 for performance simulation details.

Scenario name	Upgrade details			Applicability criteria:	Capacity retention @ 5 °F (-15 °C)	Minimum temp. for heat pump operation	Sizing method
	Heat pump type	Cooling efficiency (SEER)	Heating efficiency (HSPF)				
Min.-Eff. ASHP	Central single-speed	15	9	with ducts (79%)	47%	0 °F (-18 °C)	Cooling priority
	Ductless var.-speed	14.5	8.2	w/o ducts (21%)		None	
Med.-Eff. ASHP	Central var.-speed	22	10	with ducts (79%)	49%	0 °F (-18 °C)	Max. of heating/ cooling load
	Ductless var.-speed	17	9.5	w/o ducts (21%)		None	
High-Eff. Cold Climate HP	Central var.-speed	24	13	with ducts (79%)	85%	None	
	Ductless var.-speed	29.3	14	w/o ducts (21%)			
Min.-Eff. ASHP + Envelope	Same as Min.-Eff. HP, plus envelope upgrades described in Table 2						
Med.-Eff. ASHP + Envelope	Same as Medium-Eff. HP, plus envelope upgrades described in Table 2						
High-Eff. ccASHP + Envelope	Same as High-Eff. Cold Climate HP, plus envelope upgrades described in Table 2						
Reference Scenario	All heating and cooling equipment replaced with equipment meeting federal minimum standards or like-for-like efficiency (whichever is higher); see Table 6						

Note: SEER and HSPF cannot be expressed in SI units; they are regulated metrics in the United States that describe the result of evaluating regulated products under a specific test procedure at specific standard rating conditions. As determined in accordance with 10 CFR part 430 Subpart B, Appendix M, SEER is the total heat removed from the conditioned space during the annual cooling season, expressed in Btu, divided by the total electrical energy consumed by the air conditioner or heat pump during the same season, expressed in watt-hours; HSPF is the total space heating required in region IV during the space heating season, expressed in Btu, divided by the total electrical energy consumed by the heat pump system during the same season, expressed in watt-hours.[77]

units to the exterior of tall buildings is common in other countries but may not be seen as an acceptable solution in the U.S. (though window AC units are common in mid-rise and high-rise buildings in the U.S.). Nevertheless, we include these cases in our analysis for completeness.

For all scenarios, design heating and cooling loads are calculated using procedures similar to ACCA Manual J. For the minimum efficiency scenario, the ASHP capacity is selected based on the cooling load according to ACCA Manual S. This sizing method was selected to avoid poor moisture control in cooling mode associated with oversized single-speed equipment.[78]. For the medium and high-efficiency scenarios, the ASHP capacity is selected based on maximum of heating or cooling load, which in most situations is the heating load (see Figure S1). This latter practice of sizing variable-speed and cold climate ASHPs to meet all or most of the design heating load is common practice in some ccASHP programs.[79] However, it is worth mentioning that for many homes, sizing to the full heating load may be not practical (without envelope upgrades) because of existing ductwork airflow constraints that limit equipment to 3 tons (10 kW_{th}) or less, or because residential ducted ASHP equipment is not available in sizes larger than 5 tons (18 kW_{th}). Figure S13 shows that large portions of the capacity distributions for the high-efficiency ccASHP scenario exceeds these 3- and 5-ton thresholds, particularly for the case without envelope upgrades. These limitations and potential solutions are further discussed in Section 3.2.2.

All six scenarios also included sealing and insulating all ducts located in unconditioned space to 10% leakage and R-8 (RSI-1.4) insulation (based on best practice guidance[80,81]). This duct sealing was included to prevent ASHPs from being installed in homes with very leaky ducts that would result in even larger capacity requirements. Practically, because ASHPs have lower supply air temperatures than furnaces, duct sealing is also recommended to ensure that the air supplied to rooms is comfortable.

4.3.3. Envelope and ASHP upgrade scenarios

The next three scenarios combine the three ASHP efficiency levels with a set of thermal envelope upgrades: attic air sealing and attic insulation, R-6.5 (RSI-1.1) wall insulation, and low-emissivity (low-e) storm windows (details and applicability criteria are in Table 2).

Table 2: Details of envelope package

Envelope upgrades	Upgrade details	Applicability criteria
Attic floor air sealing and insulation	R-values follow 2021 IECC	Homes with vented attic and attic R-value less than 2021 IECC
R-6.5 (RSI-1.1) wall insulation with re-siding	R-6.5 (RSI-1.1) of continuous wall insulation, e.g., 1" of rigid polyisocyanurate board installed under new siding	Homes older than 1990 with less than R-19 (RSI-3.3) wall insulation
Low-e storm windows	Exterior low-e storm windows	Homes with single and double-pane windows

The attic air sealing and insulation upgrades are applied to the homes with vented attics and attic floor R-values less than specified in the 2021 International Energy Conservation Code (IECC).[82] A derate factor is applied to determine the effective attic insulation level because attic floor insulation often cannot be applied at full thickness near eaves.[83] The rated and effective attic insulation used in the envelope upgrade package is shown in Table 3. The derate factor was calculated using attic perimeter insulation calculations in BEopt based on average attic parameters.[84]

Table 3: Effective attic insulation R-values for envelope upgrades, calculated using attic perimeter insulation calculations in BEopt based on average attic parameters.[84]

IECC climate zone	Attic floor R-value nominal ($ft^2h°F/Btu$) (RSI (m^2K/W))	Attic floor R-value effective ($ft^2h°F/Btu$) (RSI (m^2K/W))
1	30 (5.3)	29 (5.1)
2-3	49 (8.6)	44 (7.8)
4-7	60 (10.6)	51 (9.0)

The low-e storm windows are added to homes with existing single and double-pane windows. Such addition of low-e storm windows reduces the air infiltration and conductive heat transfer associated with windows. The U-value and solar heat gain coefficient (SHGC) value for windows with and without low-e storm windows are shown in Table 4.

The R-6.5 (RSI-1.1) continuous wall insulation upgrade represents adding R-6.5 rigid polyisocyanurate insulation board (1" thickness) at the time of homes' re-siding projects. It is applied to homes on two conditions: 1) the home was built before 1990 so that the siding is at least 30 years old, and b) the existing wall insulation of the homes is less than R-19 (RSI-3.3), to exclude homes that would see relatively little benefit from additional wall insulation.

All three upgrades in the envelope package have associated air infiltration reductions. The assumed air leakage reduction from each upgrade of the envelope package is given in Table 5. The overall whole-home air leakage reduction due to upgrades is calculated using Equation (1).

$$(1 - (1 - r_1) \times (1 - r_2) \times (1 - r_3)) \tag{1}$$

Table 4: Window properties with and without addition of low-e windows

Primary window type	Without storm window		With low-e storm window	
	U-value ($Btu/ft^2h°F$) (U- SI (W/m^2K))	SHGC	U-value ($Btu/ft^2h°F$) (U- SI (W/m^2K))	SHGC
Single-pane, clear, metal frame	1.16 (6.59)	0.76	0.69 (3.92)	0.59
Single-pane, clear, non-metal frame	0.84 (4.77)	0.63	0.4 (2.27)	0.48
Double-pane, clear, metal frame	0.76 (4.32)	0.67	0.38 (2.16)	0.51
Double-pane, clear, non-metal frame	0.49 (2.78)	0.56	0.29 (1.65)	0.42

where r_n is the leakage reduction percentage of an envelope component, n.

For instance, consider a home with single-pane windows and a vented crawlspace where all three of these upgrades apply. In this case, the air leakage reduction from attic air sealing is 8%, R-6.5 wall insulation upgrade is 13%, and low-e storm window upgrade is 21%. Thus, the whole-home air leakage reduction is calculated to be 37%.

4.3.4. Reference scenario

The reference scenario facilitates calculation of incremental upgrade costs and energy savings for the six ASHP scenarios. In the reference scenario, all heating and cooling equipment is replaced with equipment meeting federal minimum standards or like-for-like efficiency (whichever is higher), without any fuel switching, as outlined in Table 6. For example, a gas furnace with an efficiency of 76% AFUE is below the federal minimum standard of 80% AFUE and is replaced with an 80% AFUE gas furnace. HVAC systems with efficiencies greater than the federal minimum standard, as well as electric resistance heating equipment that is not subject to federal standards (electric baseboards, electric furnaces, and so on) are replaced with the same efficiency equipment to facilitate calculation of incremental upgrade costs. For instance, an electric furnace and room AC with an efficiency of CEER 11.9 is

Table 5: Air leakage reduction from each envelope upgrade component.[85,86] Percentage reductions are larger for homes without vented crawlspaces because these homes tend to be leakier with more of their leakage occurring at the crawlspace.

Envelope upgrade	Vented crawlspace	All other foundation types
Attic air sealing and insulation	8%	13%
R-6.5 (RSI-1.1) wall insulation with re-siding	13%	19%
Window upgrade for single pane without storm window	21%	30%
Window upgrade for double-pane or single-pane with storm window	7%	10%

replaced with the same equipment.

4.4. Upgrade costs

Installation costs for the ASHP scenarios were primarily derived from data collected by Less et al.[31] Less et al. adjusted all cost data using location and inflation corrections, normalizing all data to 2019 USD values representative of U.S. national average costs. These corrections were meant to remove variability in installed costs associated with the changing value of the U.S. dollar or with variation in regional markets. Despite these corrections, installed costs of energy upgrades in existing dwellings remain extremely variable. Drivers of this variability are many and remain uncharacterized. They include varying levels of deferred maintenance in existing dwellings, pricing strategies, levels of experience with the upgrade in the market, challenges of integrating upgrades with existing systems and infrastructure in the dwelling, and building codes and permitting requirements in each local jurisdiction.

The available data did not allow us to differentiate costs for projects that required new wiring or electrical service upgrades, because we currently lack detailed cost data for these upgrades, and we lack the ability to identify which dwellings in ResStock require these types of supplementary work. The underlying data collected by Less et al. were for project totals, and they almost never included cost breakdowns for equipment versus labor costs, or for the itemized costs encountered in some upgrades, such as new wiring, new circuit breakers, etc. Less, Casquero-Modrego and Walker (2022) review cost breakdowns for ductless heat pumps in the literature, and they found substantial variation in estimates, with labor commonly accounting for 30–35% of total costs.[87] They similarly reviewed other aspects of heat pump installation that increased installation cost, including cold climate heat pump type ($250 increase), additional interior zones ($1,986 increase), and variable speed compressors ($512 increase), Ongoing work funded by the U.S. Department of Energy is directed towards improving our ability to differentiate these activities and their associated costs in home heat pump upgrades. For example, current work is directed towards characterizing electrical panel upgrades in U.S. dwellings and how they may be avoided, for example, by reducing envelope loads and installing smaller-capacity heat pump technologies, or by limiting the installation of back-up resistance heating.

For this ResStock analysis we wanted to represent costs with both a fixed ($) and a variable ($/ton) component to ensure that the slope of the relationship between nameplate capacity and installation costs was accounted for. This is important to accurately represent the impact that improved thermal envelope efficiency has on the ability to downsize equipment to reduce installation costs.[8] The variability in costs described above makes the prediction of installed costs imprecise for any individual household or system. Our goal in estimating costs based on regression models is to represent average costs across the stock, while accounting for key variables known to impact cost that are also known in our modeling tool. To develop upgrade cost equations for this analysis, we performed new regressions on the Less et al. cost data, inflated costs to 2022 dollars, and cross-referenced the resultant costs with other available sources.

4.4.1. ASHP cost regressions

The Less et al. dataset consists of a mixture of central (ducted) and ductless heat pumps. Most datapoints include tons (nameplate cooling capacity), heating season performance factor (HSPF), and seasonal energy efficiency ratio (SEER). Missing datapoints have been imputed using sample medians. All linear regression models were built in the caret package in R using 10-fold cross-validation repeated five times to estimate out-of-box model errors. Outliers were removed if they had project costs greater than $30,000, $/ton greater than $10,000, or HSPF greater than 15 (not realistic for currently available ASHPs).

Several regressions were performed using different sets of independent variables. Ultimately we selected *tons* and *HSPF* as independent variables for central heat pumps (see Figures S17 and S18 for scatterplots of data used for regression). When cooling efficiency (SEER) was included in addition to heating efficiency, it resulted in negative coefficients for SEER or SEER×HSPF, which led to unrealistic trends. Using SEER and tons without HSPF resulted in costs that were too low relative to other data sources. We considered separate regressions for single-stage and variable-speed heat pumps, but this led to very

[8] We considered using costs from the National Residential Efficiency Measures Database (REMDB),[64] but at the time of analysis, the REMDB costs, particularly for central (ducted) heat pumps, were determined to be outdated and would underpredict today's heat pump costs (see comparison in Less et al.[31]). Updating the REMDB with the latest heat pump costs from Less et al. and other sources is planned future work.

different slopes ($/ton) for the two types, which did not seem realistic.

For ductless heat pumps, data were not sufficient to include a relationship between SEER or HSPF and cost, so *tons* was selected as the sole independent variable for regression. The source data used to build regression models for predicting ductless heat pump costs showed a small, not statistically significant relationship between ductless heat pump installed costs and rated performance. The small differences in cost attributable to equipment ratings were likely overwhelmed by other unrecorded drivers of cost variability, such as existing HVAC equipment type, electrical upgrades required, equipment manufacturer, and installer margins. Together, these made any variability in ductless heat pump cost with rated performance unobservable in our regression model.

In order to include some relationship between efficiency and cost, cost differentials for higher and lower HSPF systems were added using the relationship between HSPF and cost (2.2% per HSPF above or below 10.5) for ductless heat pumps in the National Residential Efficiency Measures Database (REMDB),[64] which drew from online retailers and other sources. This resulted in a weaker relationship between HSPF and cost than was present in the central heat pump regression, but including some relationship to HSPF was deemed better than including none at all. It is unknown why the effect of rated performance appears less in ductless than in ducted heat pump equipment, though others have also reported these cost increments to be small for cold climate equipment and higher rated efficiencies.[87] One possible explanation for this difference could be that pricing strategies differ between the manufacturers and installers of these equipment types.

The cost equations developed here implicitly include any electrical upgrades necessary to install the heat pumps; however, it is unknown how many of the projects included electrical upgrades for new circuits, panel upgrades, or service wire upgrades, which have been estimated to cost in the range of $2,000 to $30,000.[65]. Central heat pump costs implicitly include supplemental electric resistance heat installed with the heat pump. Ductless heat pump costs implicitly include both single-zone and multi-zone (multiple indoor heads serving different rooms) systems.

The use of HSPF instead of SEER for a cost equation differs from the findings of others,[88,64] so this choice should be revisited in future work.

The regression only had three datapoints with HSPF greater than 11 HSPF (all less than $15,000; see Figure S18); extrapolating to 13 HSPF leads to very high costs and may not be appropriate.

4.4.2. Inflating costs to 2022 dollars

All upgrade costs from Less et al.[31] were assumed to be in 2019 (January) dollars and were inflated to 2022 (January) dollars using a factor of 1.12, which was obtained from the U.S. Bureau of Labor Statistics inflation calculator.[44]

4.4.3. Cross-referencing with other cost data sources

The cost equation for central heat pumps (n=317) was compared to data points from other sources of cost data. The comparison of cost vs. HSPF relationships for 3-ton (10.6 kW_{th}) capacity systems is shown in Figure 7. The comparison includes datapoints from Navigant for EIA (2018),[89] the National Renewable Energy Laboratory's (NREL) REMDB (2012),[64] data from ten Energy Smart Ohio case studies[9] the mean cost of four field study installations in Minnesota (HSPF values in the 10–12 range),[91] and high and low estimates from an Elevate study for Dane County, Wisconsin (HSPF values in the 12–13 range).[92]

These comparisons suggest that the central heat pump regression generally captures the trend observed across the other data sources. However, at higher HSPF values, the relationship between installation cost and HSPF is likely flatter than the slope of the regression. As noted above, the regression only had three datapoints with HSPF greater than 11 HSPF and all three had installed costs less than $15,000, so extrapolating to 13 HSPF leads to very high costs and may not be appropriate. The suspected weaker relationship between HSPF and cost at higher HSPF values is supported by the fact that the NEEP list shows that products within the same series have a range of rated HSPF values.[30] For example, Carrier units with the outdoor unit model number "25VNA036A*030*" and indoor unit model numbers starting with "FE4AN*" are listed with HSPF values ranging from 10.5 to 13.0. Such small differences in product configurations are likely not associated with the $6,000 difference in material and labor costs that the regression equation would suggest for a HSPF value difference of 2.5.

The cost equation for ductless heat pumps (n=173) was compared to data points from other sources of cost data. The comparison of cost vs. capacity relationships is shown in Figure 8. The comparison includes datapoints from NREL REMDB v3.1.0 (2018)[93][10] and installed cost data provided by The Heat Pump Store for the multizone systems relevant to this analysis and for single zone systems as well.[90][11] As mentioned above, for this analysis we applied the spread of costs for different ductless heat pump HSPF values from REMDB to the Less et al. 2021 data regression; for clarity, only the line for 11 HSPF is shown in Figure 8.

These comparisons suggest general agreement between

[9]Includes both 2-ton (7 kW_{th}) and 3-ton (10 kW_{th}) systems; HSPF values are unknown, but all were Carrier Greenspeed units which generally have HSPF values in the 10–12 range,[30,90]

[10]The lines for A–E represent five different makes/models, ranging from minimum efficiency 8.2 HSPF and moderate cold climate performance to highest efficiency 14 HSPF and best available cold climate performance. The plotted lines are non-linear because of the assumed relationship between total nameplate capacity and number of zones, which was based on Figure 14 in Armstrong et al.[90]

[11]HSPF values were not reported for Heat Pump Store data; Armstrong et al. states "there is a roughly 30% [wholesale] price difference between leading brands like Daikin, LG, Panasonic, Fujitsu, and Mitsubishi."

the ductless heat pump regression and other cost data sources. The regression results in ductless heat pump costs that are 15–30% higher than the multi-zone costs from The Heat Pump Store, which may be because The Heat Pump Store data represent a more mature market; the company installs thousands of heat pumps each year in Oregon, USA.[90]

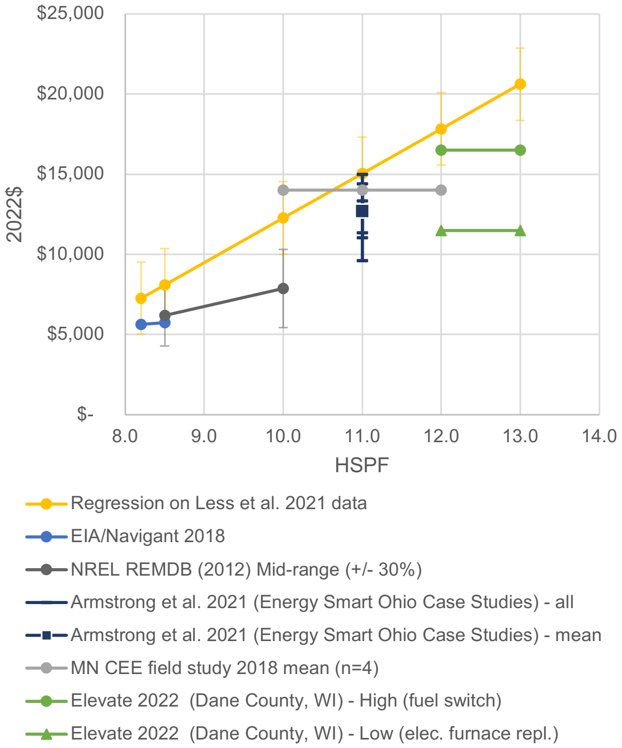

Figure 7: Comparison of central heat pump (3 tons or 10 kW_{th}) installed cost vs. HSPF from different data sources

4.4.4. Duct sealing and insulation costs

As described in the scenario definitions, duct sealing and insulation were applied in all six ASHP scenarios. Costs for sealing and insulating ducts were based on mid-range values from REMDB,[64] and were inflated from 2010 to 2022 dollars using a factor of 1.289. The costs average around $1,000 per dwelling unit, but vary with the surface area of ducts located in unconditioned space calculated for each home, and also on their starting leakiness and insulation level.

4.4.5. Envelope upgrade costs

Upgrade costs for attic insulation and air sealing are from REMDB,[64] are a function of attic floor area and existing insulation levels, and were inflated from 2010 to 2022 dollars using a factor of 1.289.

Upgrade costs for adding wall insulation at time of re-siding are $5 per square foot of exterior wall area, based on Lawrence Berkeley National Laboratory data.[31] Upgrade

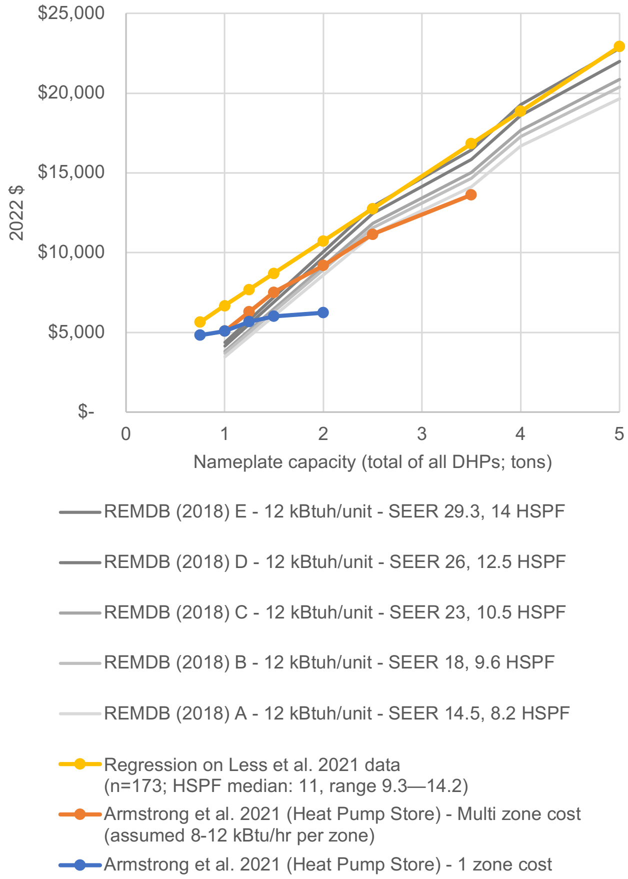

Figure 8: Comparison of ductless heat pump installed cost vs. total nameplate capacity (tons; 1 ton ≈ 3.5 kW_{th}) from different data sources

costs for adding low-e storm windows are $14.70 per square foot of window area, based on REMDB data.[64]

4.4.6. Reference scenario costs

HVAC equipment costs in the reference scenario are from a mix of sources, presented in Table 6. Both fixed ($) and variable ($ per kBtu/h) costs were accounted for each HVAC equipment type. Central AC costs are based on a median from Less et al.[31] combined with the relationship to capacity and SEER from REMDB. Fossil furnace and boiler costs are based on values from Navigant for EIA[89] combined with the relationship to capacity from REMDB. All other HVAC replacement costs—room ACs, wall/floor furnaces, electric baseboards, electric furnaces, and electric boilers—are based on mid-range HVAC equipment costs in REMDB, inflated to 2022 dollars.[64]

4.5. Simulation

ResStock was used to generate the 550,000 statistically representative dwelling units and simulate them under each scenario. While the dwelling unit definitions sampled by ResStock can be used with any simulation engine,

Table 6: Cost of HVAC equipment in reference scenario. Sourced from [31,89,64]

Reference scenario equipment	Existing equipment it applies to	Fixed cost ($)	Variable cost ($ per kBtu/h)	Source
Room AC, CEER 10.9	Room ACs with efficiency ≤ 2023 federal standard	46.4	58.01	REMDB (2012), inflated to 2022
Room AC, CEER 11.9	Room ACs with efficiency > 2023 federal standard	46.4	58.01	REMDB (2012), inflated to 2022
Central AC, SEER 15	Central ACs in southern states with efficiency ≤ 2023 federal standard	4396.03	54.14	Less et al. 2021 median of $6345 (inflated from $5930) with median SEER of 15 and REMDB capacity multiplier (assumed 36 kBtu/hr average)
Central AC, SEER 14	Central ACs in northern states with efficiency ≤ 2023 federal standard	4267.13	54.14	Same as SEER 15, less $128.90 delta between SEER 14 and 15 from REMDB
ASHP, SEER 15, 9.0 HSPF	Air-source heat pumps	3907.01	155.17	Regression on Less et al. 2021 data, described in Section 4.4.1
Fuel boiler (oil), 85% AFUE	Fuel oil boilers with efficiency ≤ federal standard in place in 2022	4077.62	30.94	Navigant 2018 value of $7759 and REMDB capacity multiplier (assumed 119 kBtu/hr average)
Fuel boiler (gas), 82% AFUE	Boilers (piped gas or propane) with efficiency ≤ federal standard in place in 2022	3424.04	30.94	Navigant 2018 value of $6827 and REMDB capacity multiplier (assumed 119 kBtu/hr average)
Fuel boiler, 90% AFUE	Boilers (piped gas, propane, or oil) with efficiency > federal standard in place in 2022	5869.72	41.25	Navigant 2018 value of $10407 and REMDB capacity multiplier (assumed 110 kBtu/hr average)
Fuel furnace, 80% AFUE	Furnaces (piped gas, propane, or oil) with efficiency ≤ federal standard in place in 2022	4203.6	3.48	Navigant 2018 value of $4482 and REMDB capacity multiplier (assumed 80 kBtu/hr average)
Fuel furnace, 92.5% AFUE	Furnaces (piped gas, propane, or oil) with efficiency > federal standard in place in 2022	5876.6	5.03	Navigant 2018 value of $6279 and REMDB capacity multiplier (assumed 80 kBtu/hr average)
Fuel wall/floor furnace, 60% AFUE	Fuel-fired wall/floor furnaces with 60% AFUE	0	51.56	REMDB (2012), inflated to 2022
Fuel wall/floor furnace, 68% AFUE	Fuel-fired wall/floor furnaces with 68% AFUE	0	51.56	REMDB (2012), inflated to 2022
Electric baseboard, 100% efficiency	Electric resistance baseboards	0	59.29	REMDB (2012), inflated to 2022
Electric furnace, 100% AFUE	Electric resistance furnaces	2062	64.45	REMDB (2012), inflated to 2022
Electric boiler, 100% AFUE	Electric resistance boilers	3996	0	REMDB (2012), inflated to 2022
Electric wall furnace, 100% AFUE	Electric resistance wall furnaces	0	59.29	REMDB (2012), inflated to 2022

we used OpenStudio® and EnergyPlus™ to simulate the generated dwelling unit models.

It is worth noting that ResStock samples and simulates individual dwelling units, as opposed to entire multifamily buildings. This is partially because most source data is for dwelling units or households and not buildings, and also because it simplifies running batch simulations on high-performance computing resources when simulation runtimes are similar. Because a simulation of an individual dwelling unit in a scenario is independent of other dwelling units, parallel simulation of modeled dwelling units helps to reduce the computing time significantly. We used BuildStock Batch to manage batch simulations on the parallel processing capabilities of the NREL Eagle high-performance computer. [94] In total, 4.4 million dwelling unit simulations were completed, where each dwelling unit simulation took less than 5 minutes. All simulations used typical meteorological year 3 (TMY3) weather data for around 1,000 local weather stations. [95]

4.6. Post-processing and visualization

The raw annual simulation results for each dwelling unit of a particular scenario were collected and grouped by scenario. The BuildStock Batch tool that manages batch simulations also compiles individual simulation results into a combined results data file for each scenario. [94] Python scripts and Tableau calculations were used to analyze the results and compute energy savings, energy bill savings, upgrade cost, NPVs, and GHG emissions.

4.6.1. Greenhouse gas emission factors

The GHG emissions impacts of the scenarios were estimated using the following inputs. Carbon dioxide equivalent (CO_2e) emissions for on-site fossil fuel use were calculated using factors from Table 7.1.2(1) of draft ANSI/RESNET/ICCC 301-2022 *Standard for the Calculation and Labeling of the Energy Performance of Dwelling and Sleeping Units using an Energy Rating Index* (shown in Table 7).[33] These factors include the combustion and pre-combustion components of CO_2, methane (100-year global warming potential of 29.8), and nitrous oxide (100-year global warming potential of 273). Pre-combustion processes include fuel extraction, processing, and transportation, including fugitive emissions with an assumed fugitive methane emissions rate of 1.37% (includes leaks in the gas distribution system; from ANSI/RESNET/ICCC 301-2022[33] based on a 2019 NETL report[96]).

CO_2e emissions for electricity were calculated using factors from Cambium 2021 data[97] from NREL's 2021 Standard Scenarios for Electricity.[98] We used long-run marginal emissions rates (LRMER), levelized over the expected 16-year lifetime of heat pump equipment (2022–2038) with a 3% discount rate applied (consistent with draft ANSI/RESNET/ICCC 301-2022), for all five of the future grid scenarios in Cambium 2021. Note that these scenarios do not include the impact of power sector incentives in the Inflation Reduction Act of 2022, which are expected to increase the speed of power sector decarbonization. These choices are considered best practice for long-lived efficiency and electrification decisions.[99,34] We chose to use annual factors instead of hourly factors for simplicity of calculation. Present et al. found that the choice of using annual vs. hourly LRMER was much less significant than the time horizon or choice between long-run marginal and short-run marginal factors.[99] ResStock datasets released since this analysis was conducted include emissions impact results that make use of hourly LRMER factors.[40] We applied the LRMER factors with a geographic resolution of 20 Generation and Emission Assessment (GEA) regions, which are based on the U.S. EPA's eGRID regions.[100] As with the on-site fossil factors, these factors include the combustion and pre-combustion components of CO_2, methane, and nitrous oxide, using 100-year global warming potential values. Pre-combustion processes include fuel extraction, processing, and transportation, including fugitive emissions with an assumed fugitive methane emissions rate of 1.08% (assumes power plants avoid leaks in the gas distribution system; based on a 2019 NETL report[96]).[97]. However, this work does not encompass the examination of potential change in the LRMER factors resulting from changes in the load profile due to the electrification of air-to-air heat pumps.

Table 7: GHG emissions factors. Source: Table 7.1.2(1) from draft ANSI/RESNET/ICCC 301[33]

Fuel type	lbs CO_2e/million Btu	kg CO_2e/MWh
Natural gas	147.3	228.0
Propane	177.8	275.2
Fuel oil	195.9	303.2
Electricity	Cambium 2021 (Gagnon et al. 2022)[97]	

Installing larger, two-way heat pumps sized for heating instead of one-way heat pumps (air conditioners) or heat pumps in homes that previously did not have central air conditioning will lead to increased refrigerant use, and therefore leakage. Pistochini et al. found that the incremental increase in R-410A refrigerant leakage emissions when moving from a gas furnace to a heat pump was around 0.07 tCO_2e per year over the 16-year lifetime of the equipment (using 100-year global warming potential and based on Figure 6 of Pistochini et al.[32]), which would have a small (less than 3%) impact on the average dwelling unit emissions reductions of 2.5 t/yr or greater (from Section 2.1). The impact of R-410A refrigerant leakage is 2.2x higher when using 20-year global warming potential values, so the impact would be larger (less than 6%) using that metric. However, Pistochini et al. show that using a 20-year horizon increases the emissions savings of heat pumps overall because the increase in methane leakage impact increases more than the increase in refrigerant leakage impact.[32] Therefore, the choice of time horizon would not be expected to change the direction of emissions impacts reported here. The recent ratification of the Kigali Amendment by the United States[101] will make refrigerant leakage less significant over time, with developed countries targeting an 85% reduction in hydrofluorocarbon production by 2036.[102]

4.6.2. Utility tariffs

The energy bills of the residential dwelling units for each scenario were calculated based on the electricity, natural gas, propane, and residential fuel oil used. In general, we used state average residential electricity and fuel prices (revenue divided by sales) by state from 2019 EIA data and used regional factors from EIA to convert into prices representing winter 2021–2022[46] (see Table S7 for fuel costs of 2019, winter 21-22, and winter 22-23 forecast for each state and Table S8 for regional multipliers).

The average prices for electricity and natural gas were lowered slightly by removing the fixed or customer charge component of bills, resulting in estimates of the average marginal or volumetric \$/kWh and \$/therm rate components in each state (averaged over the utilities in each state and across any seasonal, tiered, or time of use differences). For electricity bill calculations, Equation 2, was used to calculate the customer-weighted national average fixed monthly charge (\$10/customer/month) , where $F_{elec,u}$ represents the monthly fixed electric charge for each utility from the OpenEI Utility Rate Database[103] and $N_{c,u}$ represents number of customers for each utility from EIA data.[104]

$$\text{Customer-weighted } F_{elec,avg} = \frac{\sum F_{elec,u} \times N_{c,u}}{\sum N_{c,u}} \quad (2)$$

The average variable component ($/kWh) of electricity rate for each state was calculated using Equation 3. State average residential electricity data[104] including total revenue (in thousands of dollars), total sales (in MWh) and total customers (quantity) were used. We did not account for seasonal, time-of-use, or tiered electricity rates in this study, but these should be considered for future work, particularly because many electric utilities' rates are currently lower in winter than in summer, which would benefit ASHPs in the near term.

$$rate_{elec,s} = \frac{revenue_{elec,s} - (F_{elec,avg} \times N_{elec,s})}{sales_{elec,s}} \quad (3)$$

The fixed residential electric utility customer charge of $10/customer/month was used throughout the U.S., and a flat (not time-sensitive or tiered), volumetric residential electric rate for each state that varied from 8.7 ¢/kWh in Washington State to 20.4 ¢/kWh in Connecticut. The rates used for each state are shown in Table S7.

For natural gas bill calculations, a fixed utility charge (generally referred to as the "customer charge") of $11.25/customer/month ($F_{ng}$) was used based on a 2015 report from the American Gas Association.[48] The volumetric rate of natural gas for each state was calculated using Equation 4 based on state price,[105] sales,[106] and number of customers ($N_{ng,s}$).[107]

$$rate_{ng,s} = \frac{(sales_{ng,s} \times price_{ng,s}) - (F_{ng} \times N_{ng,s})}{sales_{ng,s}} \quad (4)$$

The results ranged from $0.43/therm in New Mexico to $1.48/therm in Florida. The volumetric rates used for each state are shown in Table S7. We assume that most homes that use natural gas for space heating also use it for one or more other end uses. Thus, the $135 per year gas customer charge is not removed when applying the heat pump upgrades. However, the impact of eliminating this fixed charge is evaluated in a sensitivity case (see Section 2.6).

For residential fuel oil and propane bill calculations, we used weekly data from EIA covering the 2018-2019 winter.[108,109] We averaged the available weeks for each state. When state-level data were not available, we used data from the state's PADD region. When PADD region data were not available, we used the U.S. national average. As with electricity and natural gas, regional factors from EIA were used to increase prices to represent winter 2021–2022[46] (see Table S7 for volumetric fuel costs for 2019, winter 21-22, and winter 22-23 forecast for each state and Table S8 for regional multipliers).

4.6.3. Net present value calculations

The NPV for each customer in each scenario is calculated using Equation 5.

$$NPV = \Sigma \left(\frac{CF_{c,t}}{(1+i)^t} \right) - I_c \quad (5)$$

where t represents the total number of time periods, $CF_{c,t}$ represents the cash flow (incremental change in energy bills) of customer c in t^{th} year, i is the real discount rate, and I_c is the initial incremental investment. We have considered the total time period to be 16 years, assuming the heat pumps' lifetime to be 16 years and assumed real discount rate of 3.4%.[43] Real consumer discount rates vary widely. A positive NPV is not meant to suggest that consumers will adopt the technology, but can be used to help inform whether the technology could be financed with positive cash flow for the consumer.

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6. Author Contributions

Conceptualization, E.J.H.W., J.L.R., and S.R.; Methodology, E.J.H.W., P.M., and B.D.L.; Formal Analysis, E.J.H.W. and P.M.; Visualization, E.J.H.W. and P.M.; Writing – Original Draft, E.J.H.W. and P.M.; Software, P.M.; Writing – Review & Editing, B.D.L., J.L.R., and S.R.; Funding Acquisition, S.R.; Supervision, E.J.H.W. and S.R.; Project Administration, E.J.H.W, J.L.R., and S.R.

7. Declaration of Interests

The authors declare no competing interests. Additional affiliations: Eric J. H. Wilson is currently on detail from the National Renewable Energy Laboratory to the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

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S1. Supplemental Information for Introduction

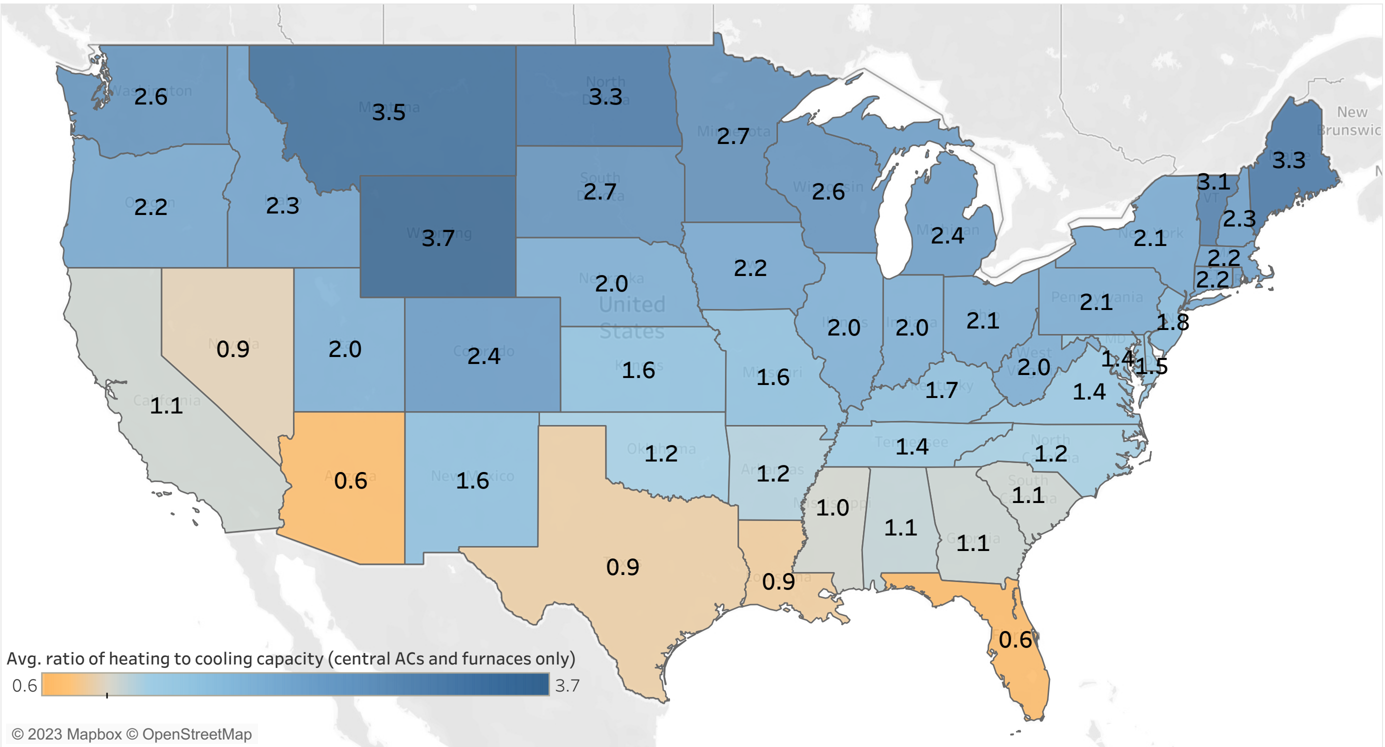

Figure S1: Average ratio of autosized heating capacity to autosized cooling capacity in U.S. homes, by state, under the reference scenario (filtered to include only homes with central air conditioners and furnaces). This is used as a proxy for the ratio of design heating load to design cooling load, and indicates that in most states, a heat pump sized for heating would on average be larger than a heat pump sized for cooling. Related to Section 1 (introduction) and Section 4.3.2 (scenario descriptions).

S2. Supplemental Information for Results

S2.1. Energy Savings Results

While site energy use is not a metric that affects people in the way that emissions and energy bills do, it may be relevant to jurisdictions that use it as a metric for policies or programs, such as state and local building performance standards.[110] The distribution of energy savings of each scenario compared to the reference scenario is shown in Figure S2. The distribution shows that ASHPs reduce site energy use compared to the reference scenario in almost all households; site energy increases in 2–5% of households, depending on the scenario. Almost all of these increases can be attributed to homes that did not have central air conditioning prior to the heat pump installation. The envelope upgrade scenarios further increase energy savings, more for the minimum efficiency ASHP (average of 28%) than for the high-efficiency ccASHP (average of 10%).

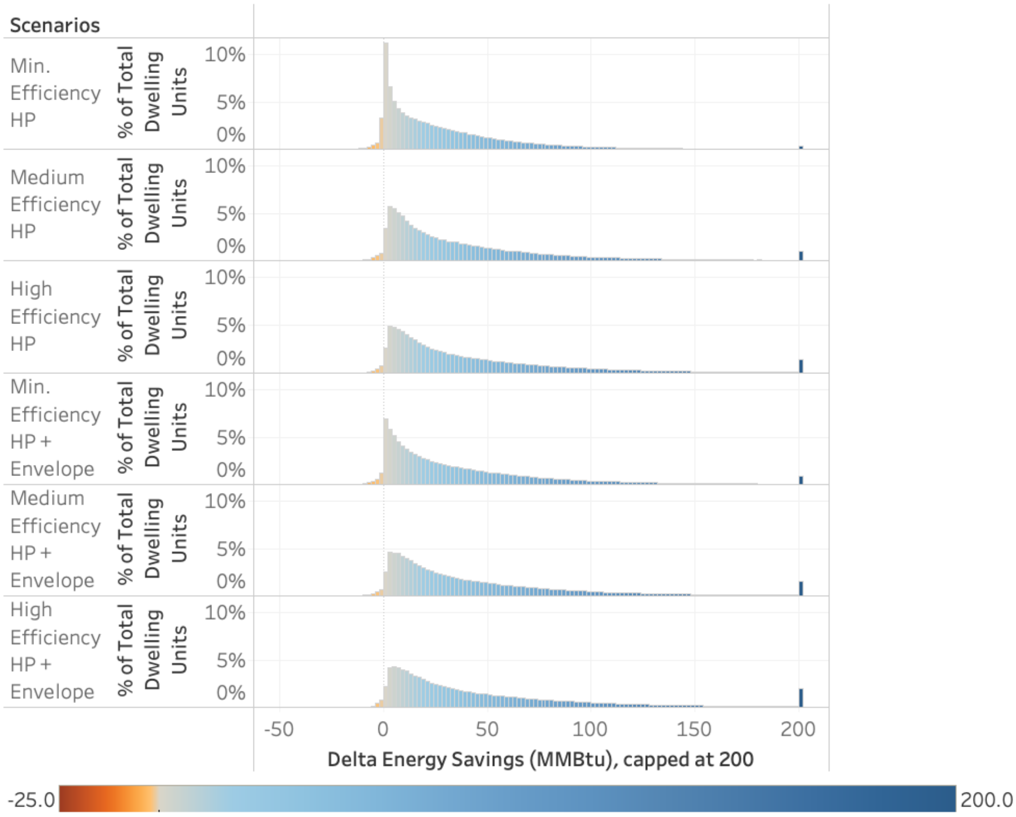

Figure S2: Distribution of incremental site energy savings compared to the reference case. The majority of the negative savings can be attributed to homes which did not have central air conditioning prior to the heat pump installation. Related to Section S2.1 (results). One million Btu (MMBtu) is approximately 0.29 MWh.

S2.2. Greenhouse Gas Savings Results

Heating Fuel	Scenario	Cambium Grid Scenario (LRMER, 16-year time horizon: 2022–2038) High-RE Cost	Mid-Case	Low-RE Cost	Mid-Case 95 by 2050	Mid-Case 95 by 2035	Grand Total
Natural Gas	Minimum Efficiency HP	3.2	3.5	3.9	4.1	4.7	3.9
	Medium Efficiency HP	4.7	4.9	5.1	5.2	5.5	5.1
	High Efficiency Cold Climate HP	5.5	5.6	5.7	5.8	6.0	5.7
	Minimum Efficiency HP + Envelope	4.6	4.8	5.0	5.1	5.5	5.0
	Medium Efficiency HP + Envelope	5.6	5.7	5.8	5.9	6.0	5.8
	High Efficiency Cold Climate HP + Envelope	6.1	6.1	6.2	6.2	6.3	6.2
Electricity	Minimum Efficiency HP	1.4	1.3	1.1	1.0	0.7	1.1
	Medium Efficiency HP	2.3	2.1	1.8	1.6	1.2	1.8
	High Efficiency Cold Climate HP	2.7	2.5	2.1	1.9	1.4	2.1
	Minimum Efficiency HP + Envelope	2.1	1.9	1.6	1.5	1.1	1.7
	Medium Efficiency HP + Envelope	2.7	2.5	2.2	2.0	1.4	2.2
	High Efficiency Cold Climate HP + Envelope	3.0	2.8	2.4	2.2	1.6	2.4
Fuel Oil	Minimum Efficiency HP	7.8	8.2	8.6	8.6	9.5	8.5
	Medium Efficiency HP	9.7	9.9	10.2	10.2	10.6	10.1
	High Efficiency Cold Climate HP	10.6	10.8	10.9	10.9	11.2	10.9
	Minimum Efficiency HP + Envelope	9.6	9.8	10.1	10.1	10.5	10.0
	Medium Efficiency HP + Envelope	10.8	11.0	11.1	11.1	11.3	11.0
	High Efficiency Cold Climate HP + Envelope	11.3	11.4	11.5	11.5	11.6	11.5
Propane	Minimum Efficiency HP	2.0	2.5	3.0	3.1	3.9	2.9
	Medium Efficiency HP	3.8	4.0	4.4	4.4	4.8	4.3
	High Efficiency Cold Climate HP	4.8	4.9	5.1	5.1	5.3	5.1
	Minimum Efficiency HP + Envelope	3.5	3.8	4.1	4.2	4.7	4.0
	Medium Efficiency HP + Envelope	4.8	4.9	5.1	5.1	5.3	5.0
	High Efficiency Cold Climate HP + Envelope	5.4	5.5	5.6	5.6	5.7	5.5
Grand Total		5.3	5.4	5.5	5.5	5.7	5.5

Figure S3: Average per-household CO_2e emissions reductions (levelized over the 16-year equipment lifetime) for each grid scenario and ASHP scenario, broken out by previous heating fuel type. Reductions are highest when replacing a fuel oil heating system and lowest when replacing a heating system that is already electric. Related to Section 2.1 (results).

S2.3. Percent of households with positive utility bill savings by state and fuel type

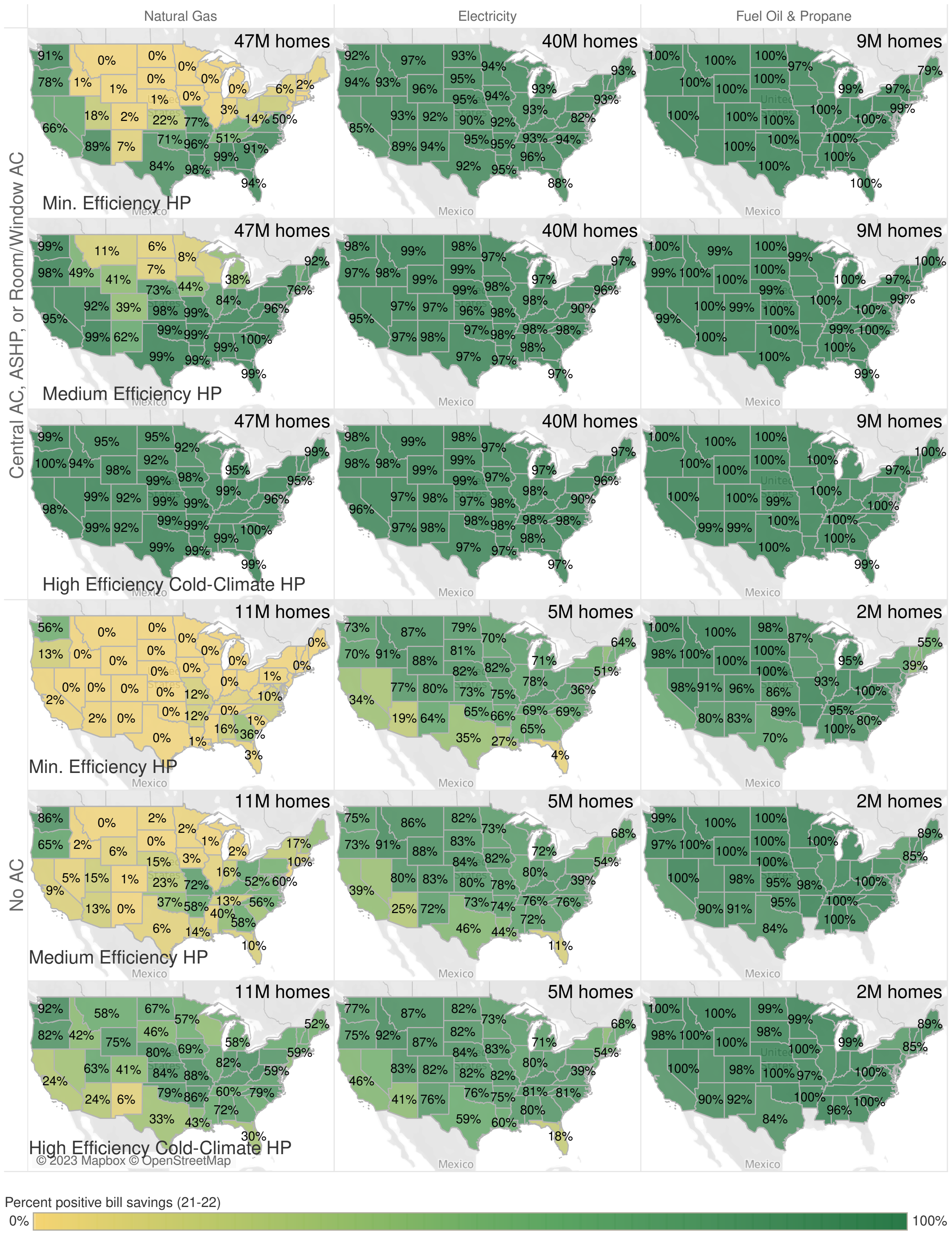

Figure S4: The percentage of households expected see positive utility bill savings resulting from the three ASHP scenarios is shown for each state (as in Figure 5), disaggregated by primary heating fuel type (columns) and presence of air conditioning. Each map is labeled with the number of households it represents. Related to Section 2.2

S2.4. Distributions of payback periods

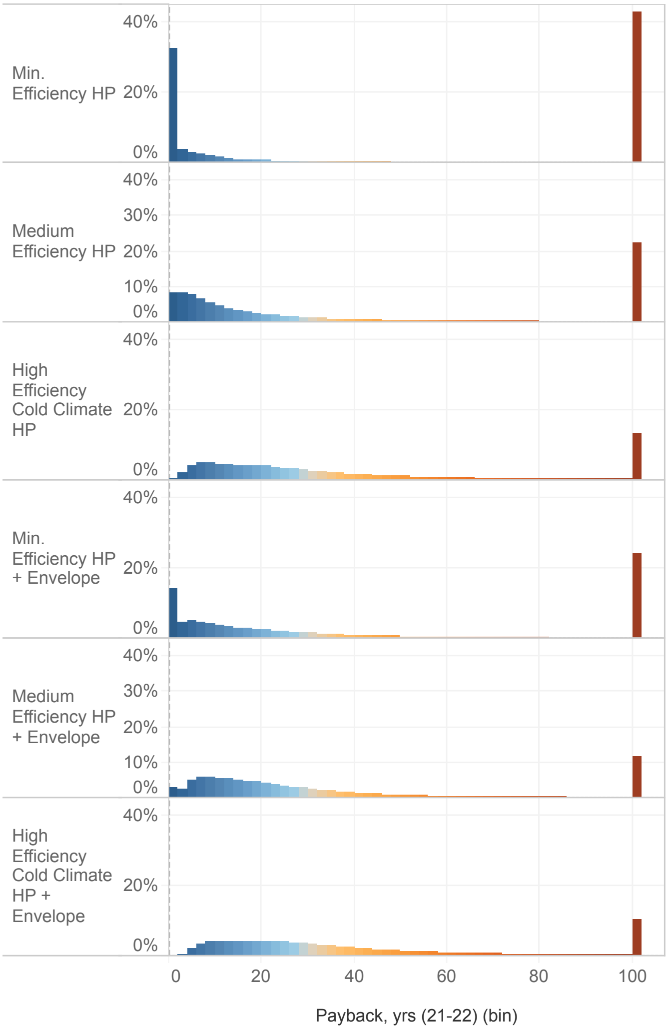

Figure S5: Distributions of payback period relative to the reference scenario, using energy prices from Winter 2021–2022. Home upgrades with negative bill savings have an infinite payback period (capped at 100 years). Home upgrades with a negative incremental upgrade cost (the cost of the ASHP is less expensive than a new furnace/boiler and/or air conditioner) have an immediate payback period. Related to Section 2.4.

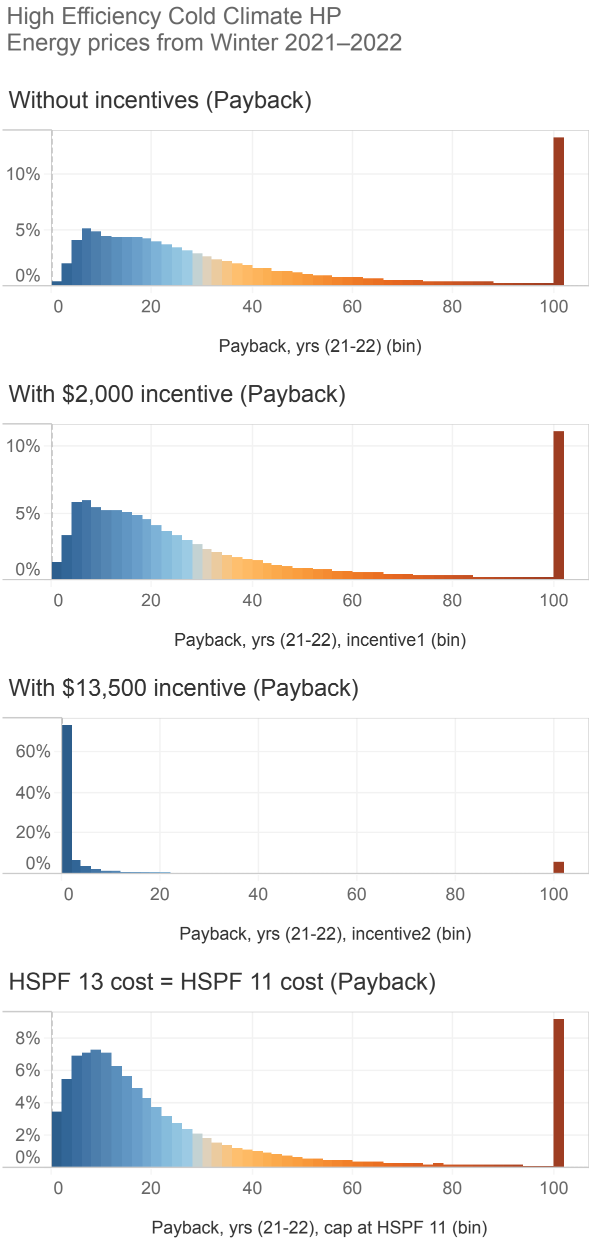

Figure S6: Distributions of payback period under three sensitivity cases. Figure shows the effect of incentives applied to all simulated households, not just those eligible for the incentives. Note that these results include homes without existing air conditioning that use electricity for air conditioning after receiving a heat pump. Note that scales on the vertical axes are different to show detail in histogram shapes. Related to Section 2.4.

S2.5. Distributions of the highest unsubsidized household net present values across six upgrade scenarios, by heating fuel and existing air conditioner type

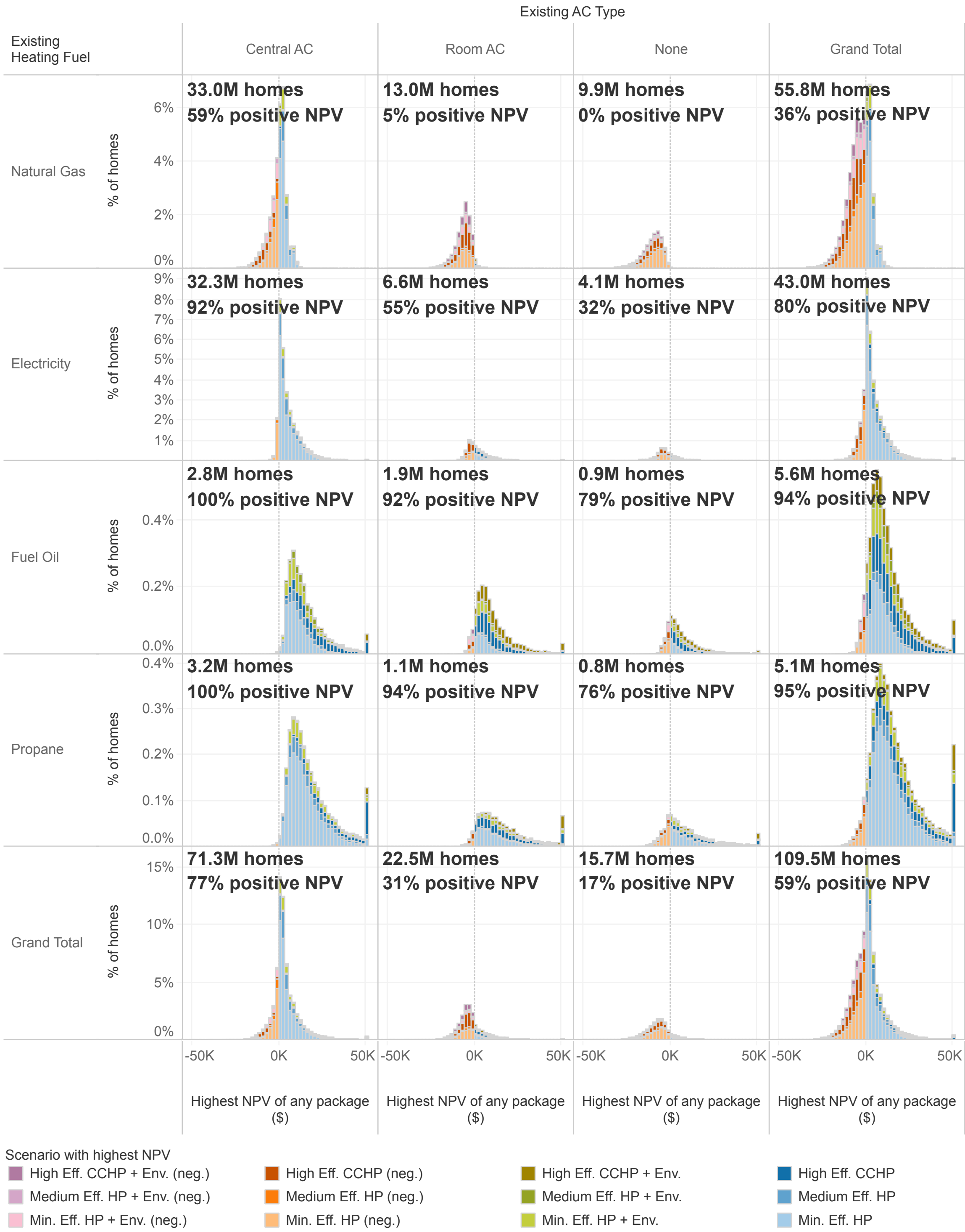

Figure S7: Distributions of the highest unsubsidized NPVs—after selecting the upgrade package with the highest unsubsidized net present value (NPV) for each of the representative 550,000 homes—are shown for different combinations of existing heating fuel and existing air conditioner type. Note that the vertical axis scales are different for each fuel type; each subplot is labeled with the number of homes represented and the percentage of these homes with positive NPV. The color legend indicates the shares of the distributions associated with each upgrade scenario. Using our cost assumptions, the high-efficiency cold-climate ASHP scenario (with or without envelope upgrades) does not have the highest NPV in any of the sampled homes. Related to Section 2

S2.6. Percentage positive net present value by state (unsubsidized, and with two different incentive levels)

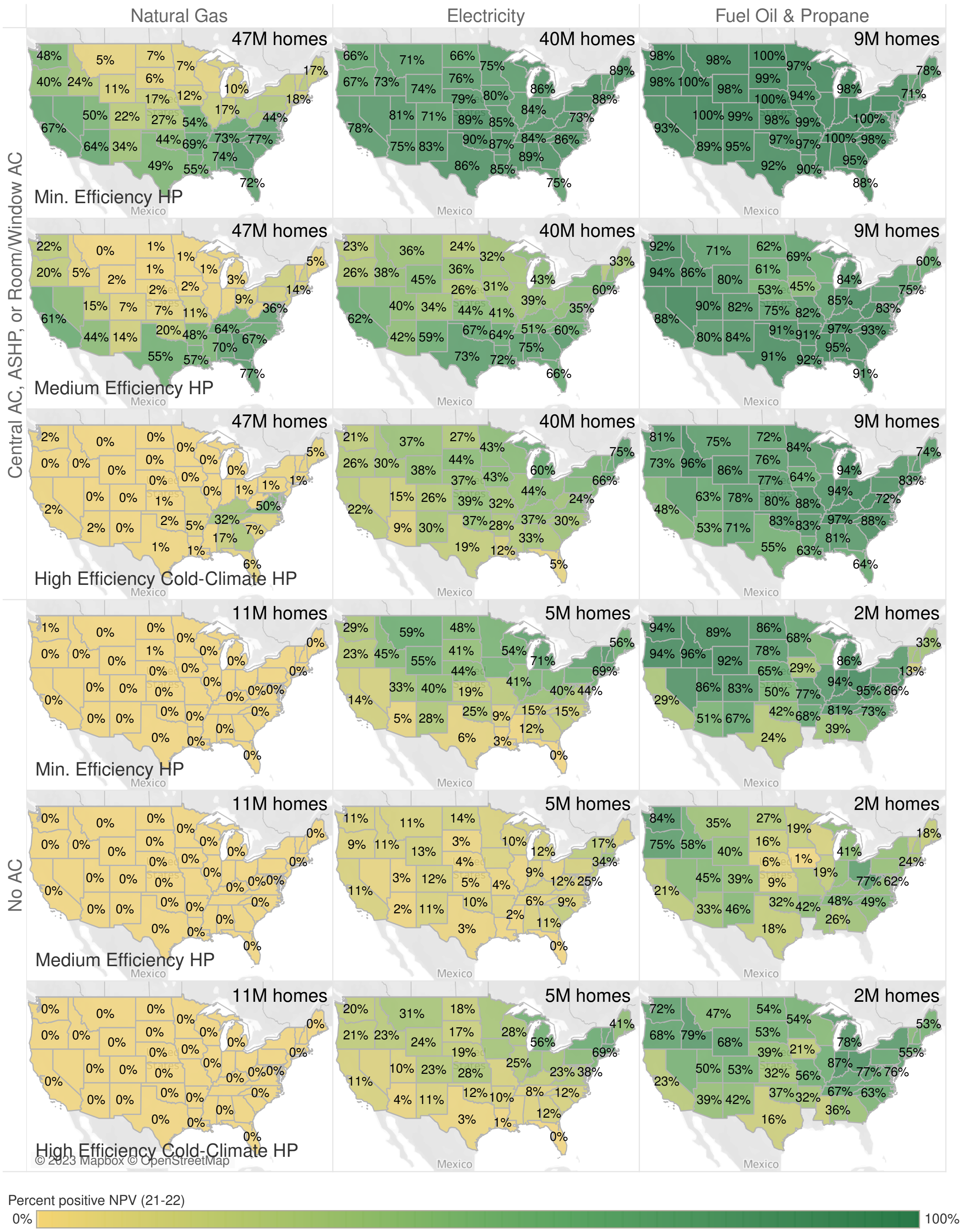

Figure S8: Percentage positive net present value by state, with no incentives, disaggregated by primary heating fuel (columns), presence of AC (rows), and ASHP efficiency level (rows). Related to Section 2.

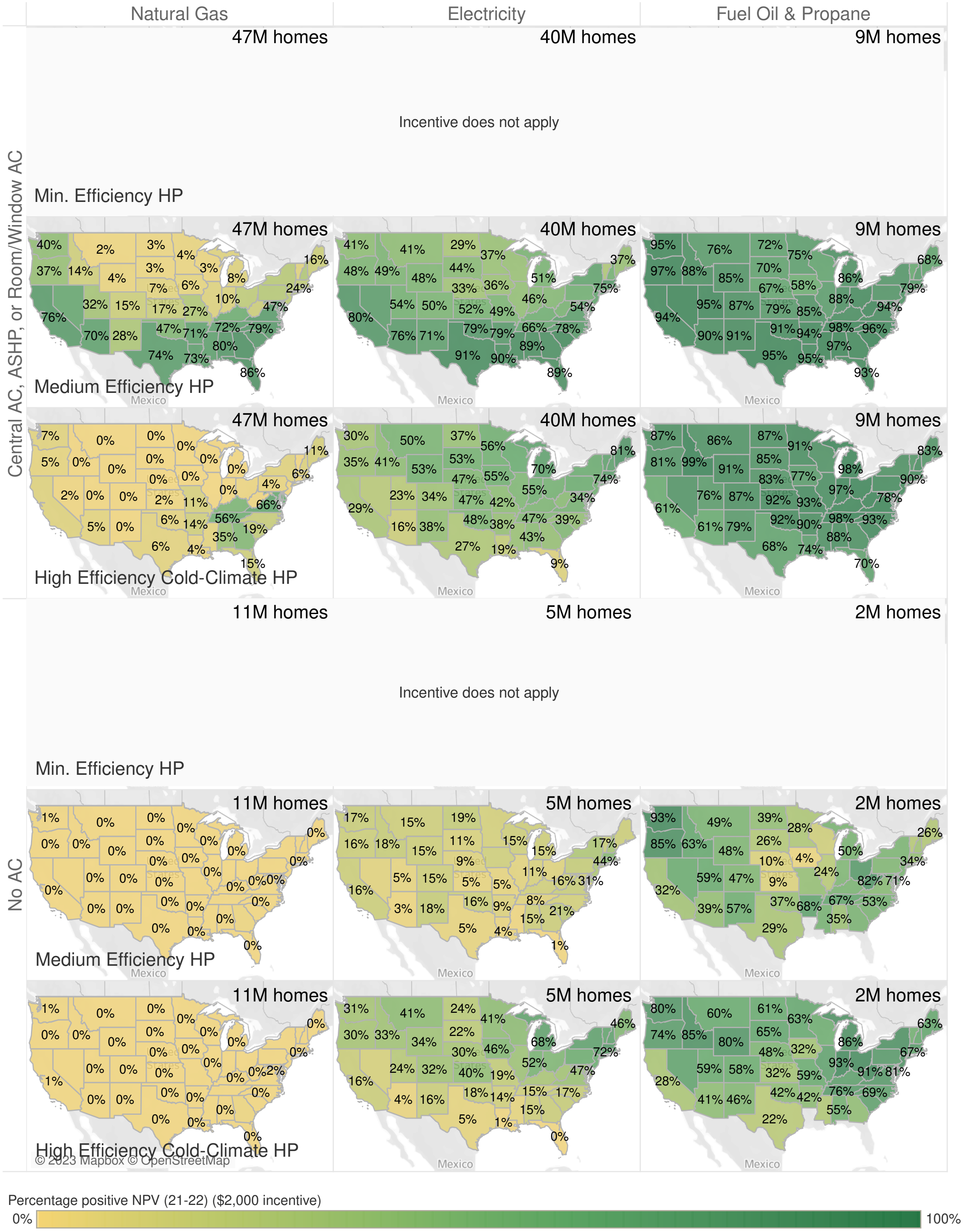

Figure S9: Percentage positive net present value by state, with $2,000 incentive, disaggregated by primary heating fuel (columns), presence of AC (rows), and ASHP efficiency level (rows). Related to Section 2. Related to Section 2.

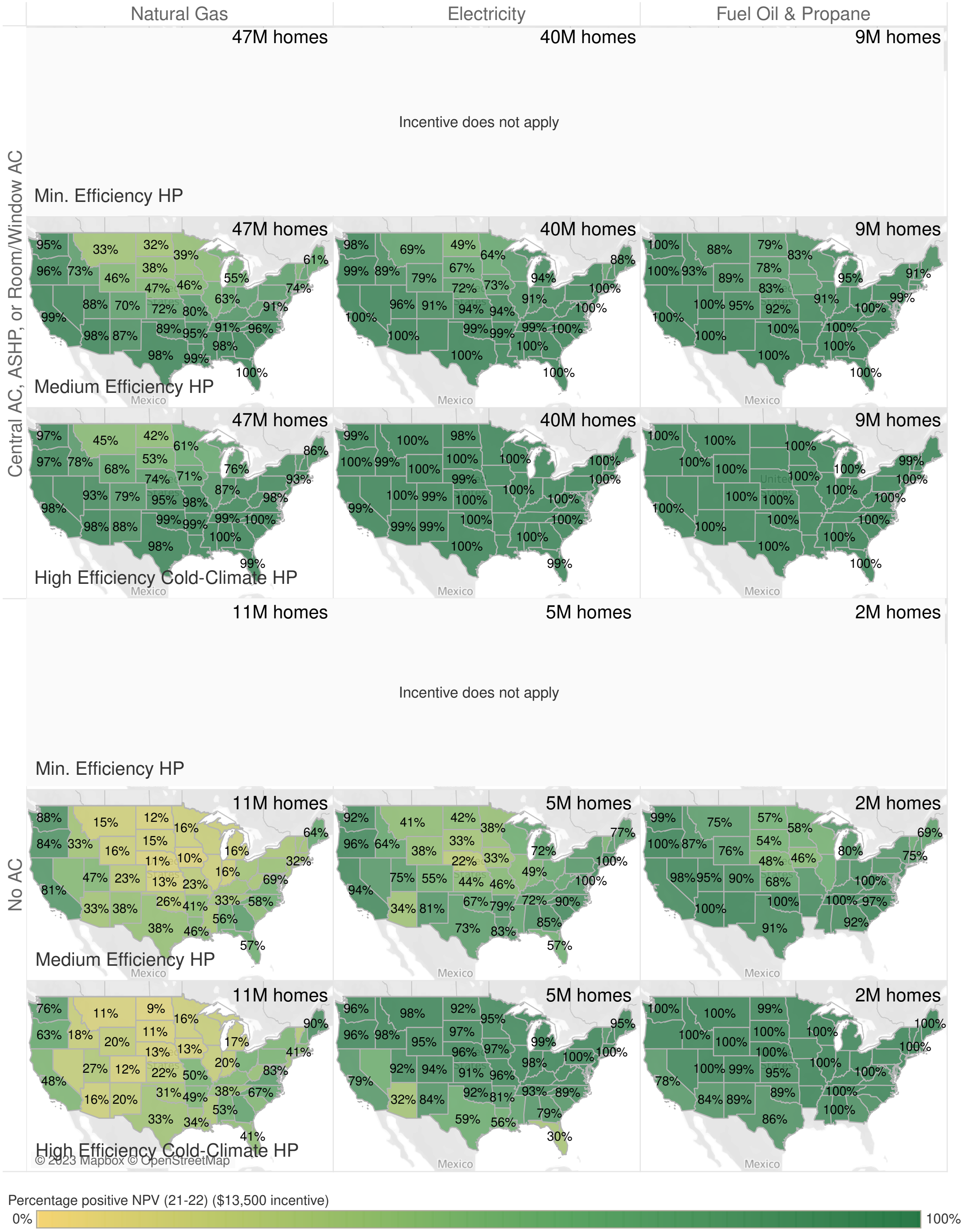

Figure S10: Percentage positive net present value by state, with $13,500 incentive, disaggregated by primary heating fuel (columns), presence of AC (rows), and ASHP efficiency level (rows). Related to Section 2. Related to Section 2.

S2.7. Distributions of ASHP Capacities

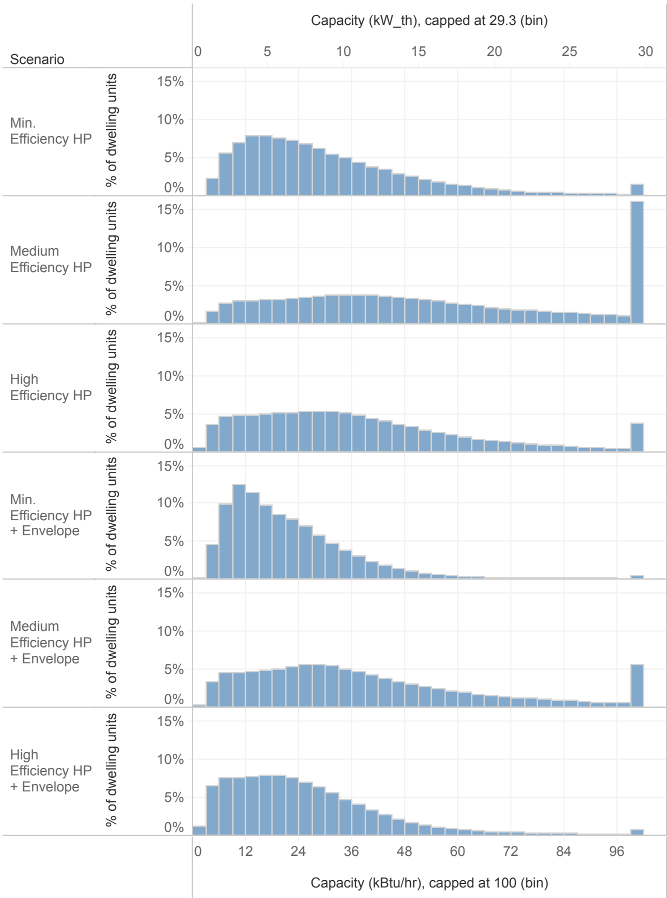

Figure S11: Distribution of heat pump capacities by scenario. The minimum efficiency scenarios are sized based on cooling load whereas the medium and high efficiency scenarios are sized based on maximum heating or cooling load. Related to Section 2.3 (results).

S3. Supplemental Information for Discussion

S3.1. Median ASHP sizes based on different sizing methods

Table S1: Median ASHP sizes based on different sizing methods. Related to Section 3.3.

Scenarios	Maximum load (kBtu/hr) (kW_{th})		Cooling load priority (kBtu/hr) (kW_{th})	
	Median	S.D.	Median	S.D.
Medium-eff. ASHP	48 (14)	58 (17)	27 (8)	22 (6)
High-eff. ccASHP	36 (11)	28 (8)	28 (8)	20 (6)
Medium-eff. ASHP + envelope	34 (10)	40 (12)	20 (6)	16 (5)
High-eff. ccASHP + envelope	25 (7)	19 (6)	21 (6)	14 (4)

S4. Supplemental Information for Experimental Procedures

S4.1. Simulated performance in two homes

In support of Section 4.3.2, we show example ASHP performance vs. temperature hourly results to highlight the significant differences in efficiency and capacity of the three ASHP scenarios. The simulated ASHP net heating coefficient of performance (COP) is presented as a function of outdoor dry-bulb temperature in Figure S12. Net COP includes fan electricity in the denominator and fan waste heat in the numerator. Net ASHP heating capacities are presented in Figure S13 for the three efficiency levels. We considered a single-family detached building with geometry floor area of 1500–1999 ft^2 (139–186 m^2) and 1970s vintage in north central Minnesota (Very Cold climate region). The net heating COP is calculated using Equation D.1.

$$COP_{net,heating} = \frac{\dot{Q}_{net}}{\dot{P}_{net}} = \frac{\dot{Q}_{gross} + \eta_{fan} v' \dot{Q}_{gross}}{\dot{P}_{gross} + \eta_{fan} v' \dot{Q}_{gross}} \tag{D.1}$$

where, $\dot{Q}_{net}$ represents net heating capacity and $\dot{P}_{net}$ represents net heating power of the heat pump. $\dot{Q}_{gross}$ and $\dot{P}_{gross}$ represents gross heating capacity and power respectively which does not account for fan heat. η_{fan} is the fan efficiency and v' is the indoor volumetric flow rate per unit of gross heating capacity.

The net heating COP increases with efficiency level, high-efficiency cold climate HP having highest COP. The use of auxiliary heating is also lowest for the high-efficiency ccASHP. The spread of COP values for a given outdoor temperature is due to the inclusion of a COP vs. compressor speed relationship, and because of modeling the effect of defrost cycles on COP. It may seem counterintuitive that the COP decreases in the -15 °C to 0 °C range. This is the effect of modeling defrost, which starts to be needed below 0 °C and becomes less necessary below -15 or -20 °C when there is less moisture in the air.

S4.2. Performance curve inputs

A bi-quadratic curve, shown in Equations D.2 and D.3, is how the EnergyPlus simulation engine represents the relationship between indoor and outdoor conditions and the capacity and COP of the heat pump coil.

$$F_{clg} = a + b(T_{wb,i}) + c(T_{wb,i})^2 + d(T_{db,o}) + e(T_{db,o})^2 + f(T_{wb,i})(T_{db,o}) \tag{D.2}$$

$$F_{htg} = a + b(T_{wb,i}) + c(T_{db,i})^2 + d(T_{db,o}) + e(T_{db,o})^2 + f(T_{wb,i})(T_{db,o}) \tag{D.3}$$

where, F is the modification factor applied to gross cooling/heating capacity or gross cooling/heating energy input ratio (EIR; inverse of COP), $T_{wb,i}$ is the wet-bulb temperature of the air entering the indoor coil ($°C$), $T_{db,o}$ is the dry-bulb temperature of the air entering the outdoor coil ($°C$), $T_{db,i}$ is the dry-bulb temperature of the air entering the indoor coil ($°C$). $a, b, c, d, e, and\ f$ are the curve coefficients.

Table S2 presents the capacity curve coefficients as a function of temperature and Table S3 presents the COP curve coefficients as a function of temperature at different speeds for both central HP and ductless HP for each efficiency. Table S4 show how the normalized gross capacity and gross COP change with compressor speed for each efficiency HP.

Sample EnergyPlus input blocks showing all heat pump coil inputs including capacity and EIR performance curves are shown in Listing 1.

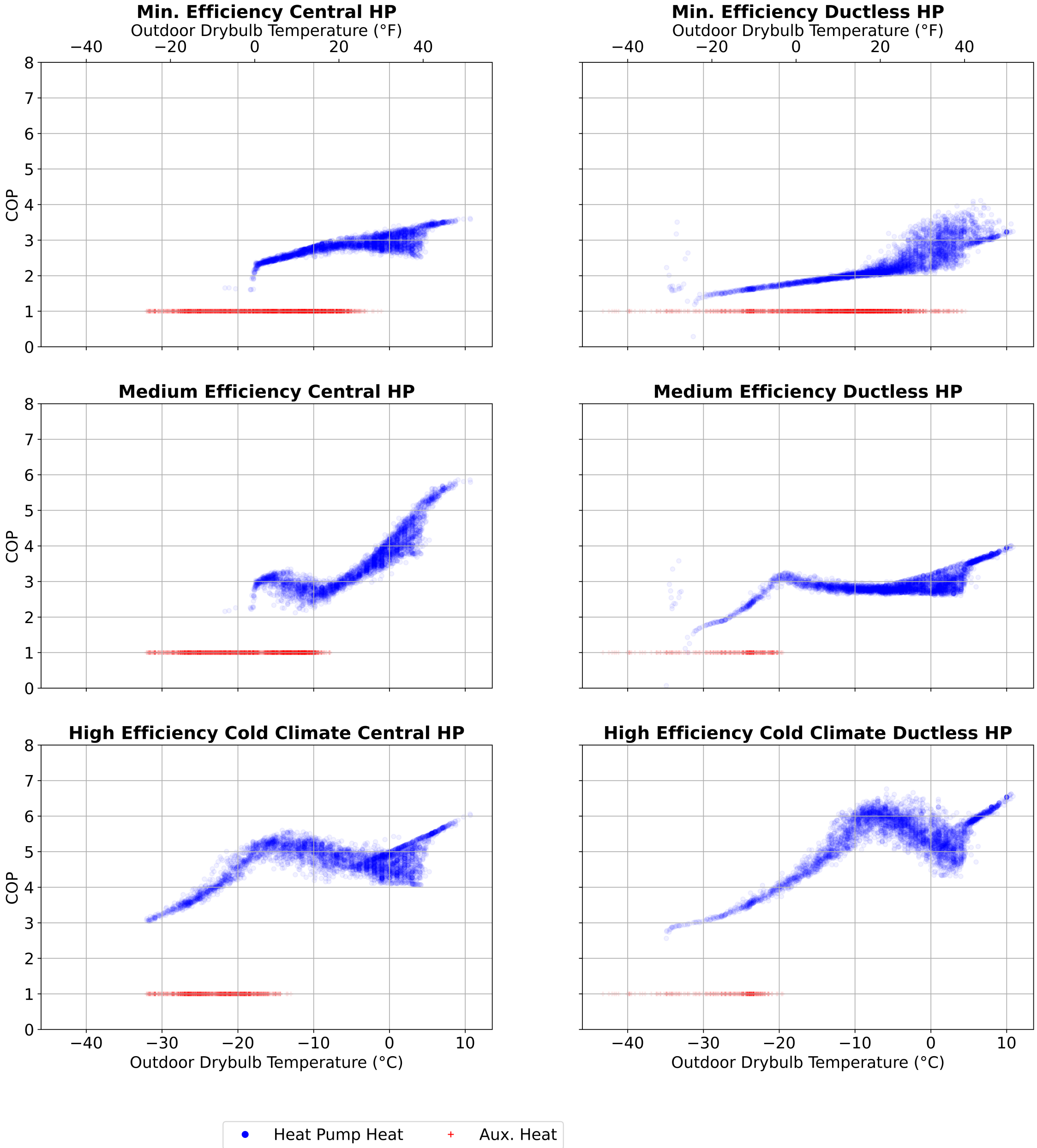

Figure S12: COP vs. outdoor dry-bulb temperature for the three ASHP efficiency levels for two sample dwelling units (central ASHP dwelling unit ID=275051 and ductless ASHP dwelling unit ID=204582), both located in a very cold climate (north central Minnesota). Related to Section 4.3.2 (ASHP scenarios).

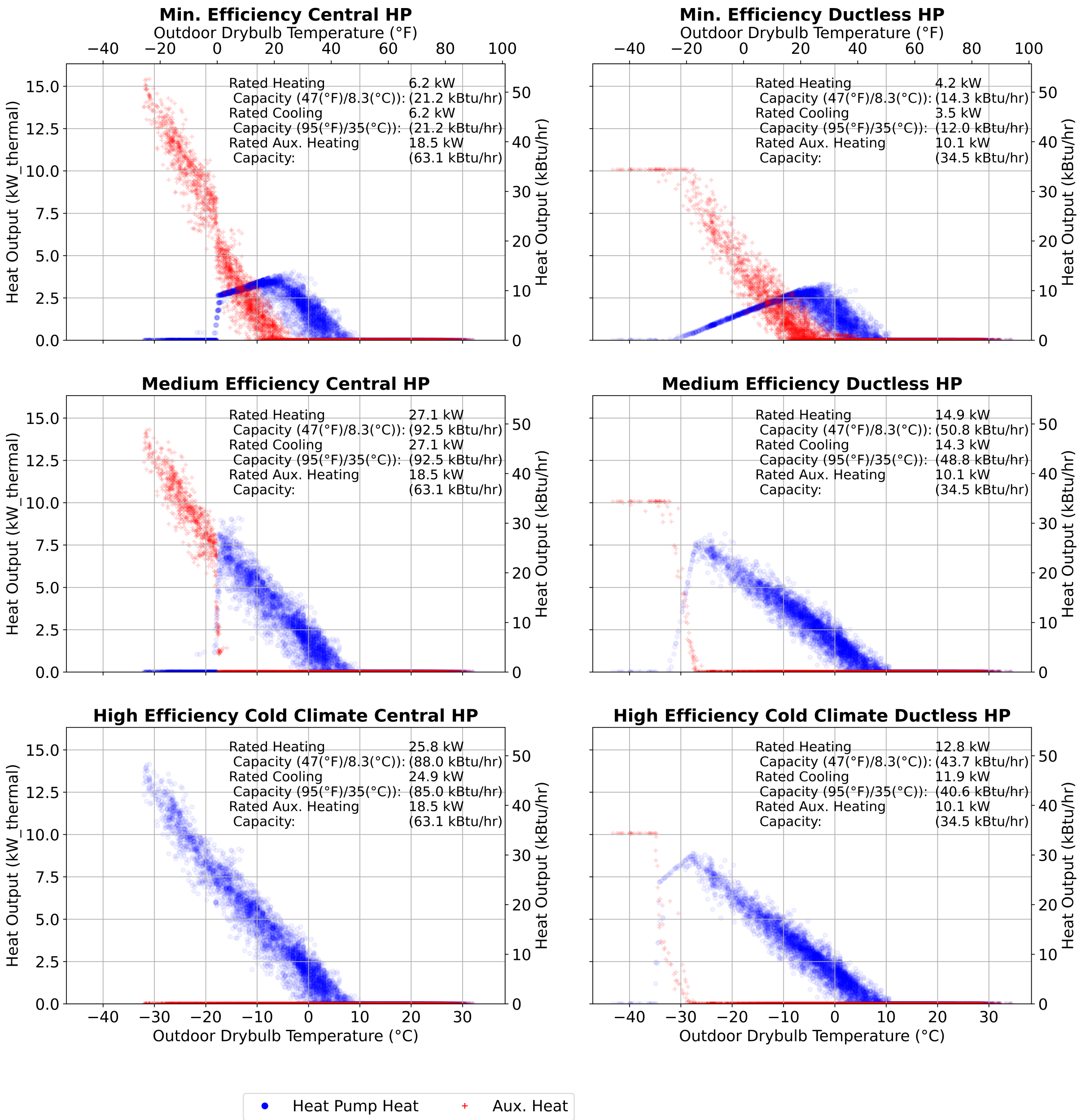

Figure S13: Heat output vs. outdoor dry-bulb temperature for the three ASHP efficiency levels for two sample dwelling units (central ASHP dwelling unit ID=275051 and ductless ASHP dwelling unit ID=204582), both located in a very cold climate (north central Minnesota). The rated heating, cooling, and auxiliary heating capacities are specified in each plot. This figure shows how heating capacity is reduced at colder temperatures for the minimum efficiency ASHPs, because they are sized for the design cooling load. For the medium and high efficiency ASHPs, maximum heating capacity is also reduced (at varying rates), but this is not as apparent in these plots because the medium and high-efficiency ASHPs are sized for the heating load. On the ductless ASHP plots, one can see a few hours with reduced heat pump output that exceed the 99% design outdoor dry-bulb temperature (-27 °C or -17 °F) for which the ASHP was sized. The compressor lockout temperature of -17 °C (0 °F) can be seen in effect for the medium efficiency central ASHP. Related to Section 4.3.2 (ASHP scenarios).

Table S2: Capacity coefficients at different speeds for both central HP and ductless HP for each efficiency level. $a, b, c, d, e, and\ f$ are the curve coefficients as used in Equations D.2 and D.3.

		Central HP						Ductless HP					
Capacity Coefficients		Min. Efficiency		Medium Efficiency		High Efficiency Cold Climate		Min. Efficiency		Medium Efficiency		High Efficiency Cold Climate	
		Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
Speed 1	a	8.80E-01	1.56E+00	8.93E-01	1.71E+00	1.10E+00	1.01E+00	1.00E+00	1.01E+00	1.00E+00	1.01E+00	1.10E+00	1.01E+00
	b	-2.90E-03	-7.44E-02	-9.73E-03	-7.46E-02	-1.04E-02	6.51E-03	-1.04E-02	6.51E-03	-1.04E-02	6.51E-03	-1.04E-02	6.51E-03
	c	-3.34E-05	3.10E-03	6.36E-05	2.97E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	d	2.24E-02	1.46E-03	3.91E-02	5.78E-03	1.45E-02	3.92E-03	2.60E-02	3.92E-03	2.60E-02	3.92E-03	1.45E-02	3.92E-03
	e	1.64E-04	-4.11E-05	-2.51E-06	-1.03E-04	0.00E+00	-2.23E-04	0.00E+00	-2.23E-04	0.00E+00	-2.23E-04	0.00E+00	-2.23E-04
	f	-2.19E-05	-4.27E-04	-2.73E-04	-6.69E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Speed 2	a			9.24E-01	1.15E+00	Same as Speed 1		Same as Speed 1		Same as Speed 1		Same as Speed 1	
	b			-5.97E-03	-2.45E-02								
	c			0.00E+00	1.77E-03								
	d			2.78E-02	5.86E-03								
	e			6.59E-05	-7.72E-05								
	f			-1.89E-04	-6.65E-04								
Speed 3	a			9.62E-01	6.46E-01	Same as Speed 1		Same as Speed 1		Same as Speed 1		Same as Speed 1	
	b			-9.49E-03	2.14E-02								
	c			1.09E-04	6.59E-04								
	d			2.47E-02	6.94E-03								
	e			3.42E-05	-6.74E-05								
	f			-1.26E-04	-6.88E-04								
Speed 4	a			9.36E-01	9.18E-01	Same as Speed 1		Same as Speed 1		Same as Speed 1		Same as Speed 1	
	b			-5.48E-03	-6.03E-03								
	c			-8.59E-06	1.36E-03								
	d			2.49E-02	5.33E-03								
	e			5.31E-05	-5.66E-05								
	f			-1.56E-04	-6.39E-04								

Table S3: EIR coefficients at different speeds for both central HP and ductless HP for each efficiency level. $a, b, c, d, e, and\ f$ are the curve coefficients as used in Equations D.2 and D.3.

		Central HP						Ductless HP					
EIR Coefficients		Min. Efficiency		Medium Efficiency		High Efficiency Cold Climate		Min. Efficiency		Medium Efficiency		High Efficiency Cold Climate	
		Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
Speed 1	a	7.17E-01	-3.50E-01	4.67E-01	-4.59E-02	9.66E-01	4.29E-01	9.66E-01	4.29E-01	9.66E-01	4.29E-01	9.66E-01	4.29E-01
	b	1.03E-02	1.17E-01	2.03E-02	6.83E-02	5.91E-03	-3.60E-03	5.91E-03	-3.60E-03	5.91E-03	-3.60E-03	5.91E-03	-3.60E-03
	c	4.61E-04	-3.40E-03	1.27E-03	-2.19E-03	1.91E-04	4.58E-05	1.91E-04	4.58E-05	1.91E-04	4.58E-05	1.91E-04	4.58E-05
	d	-6.48E-03	-1.23E-03	-1.70E-02	-1.72E-02	-1.30E-02	2.65E-02	-1.30E-02	2.65E-02	-1.30E-02	2.65E-02	-1.30E-02	2.65E-02
	e	4.56E-04	6.01E-04	3.17E-03	1.04E-03	4.23E-05	-1.59E-04	4.23E-05	-1.59E-04	4.23E-05	-1.59E-04	4.23E-05	-1.59E-04
	f	-6.98E-04	-4.67E-04	-3.50E-03	-2.00E-04	-5.24E-04	-1.59E-04	-5.24E-04	-1.59E-04	-5.24E-04	-1.59E-04	-5.24E-04	-1.59E-04
Speed 2	a			4.51E-01	1.70E+00	Same as Speed 1		Same as Speed 1		Same as Speed 1		Same as Speed 1	
	b			2.93E-02	-1.05E-01								
	c			3.93E-04	2.18E-03								
	d			-9.79E-03	-1.67E-02								
	e			5.39E-04	9.54E-04								
	f			-1.18E-03	-1.26E-04								
Speed 3	a			5.73E-01	-6.25E-03	Same as Speed 1		Same as Speed 1		Same as Speed 1		Same as Speed 1	
	b			2.29E-02	4.63E-02								
	c			2.66E-04	-1.42E-03								
	d			-1.07E-02	1.19E-02								
	e			4.91E-04	4.81E-04								
	f			-6.81E-04	-5.17E-04								
Speed 4	a			9.36E-01	-5.18E-01	Same as Speed 1		Same as Speed 1		Same as Speed 1		Same as Speed 1	
	b			-5.48E-03	9.93E-02								
	c			-8.59E-06	-2.76E-03								
	d			2.49E-02	1.40E-02								
	e			5.31E-05	4.35E-04								
	f			-1.56E-04	-5.57E-04								

Table S4: Gross normalized capacity and gross COP at each speed for both central HP and ductless HP for each efficiency level

		Central HP						Ductless HP					
		Min. Efficiency		Medium Efficiency		High Efficiency Cold Climate		Min. Efficiency		Medium Efficiency		High Efficiency Cold Climate	
		Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
Speed 1	Gross Capacity (kW)			0.41	0.41	0.29	0.35	0.33	0.41	0.33	0.41	0.29	0.35
Speed 2	Gross Capacity (kW)			0.56	0.56	0.47	0.51	0.50	0.55	0.50	0.56	0.47	0.51
Speed 3	Gross Capacity (kW)			0.83	0.83	0.64	0.67	0.67	0.70	0.67	0.70	0.64	0.67
Speed 4	Gross Capacity (kW)	1	1	1	1	1	1	1	1	1	1	1	1
Speed 1	Gross COP			5.13	4.65	8.04	7.88	4.2	4.36	5.15	5.14	8.61	9.03
Speed 2	Gross COP			4.83	4.48	6.4	6.82	3.37	3.78	4.12	4.45	6.89	7.81
Speed 3	Gross COP			4.08	3.76	5.86	5.71	3.08	3.17	3.78	3.74	6.31	6.55
Speed 4	Gross COP	4.29	4.63	4.11	3.4	5.34	4.21	2.79	2.35	3.42	2.76	5.73	4.84

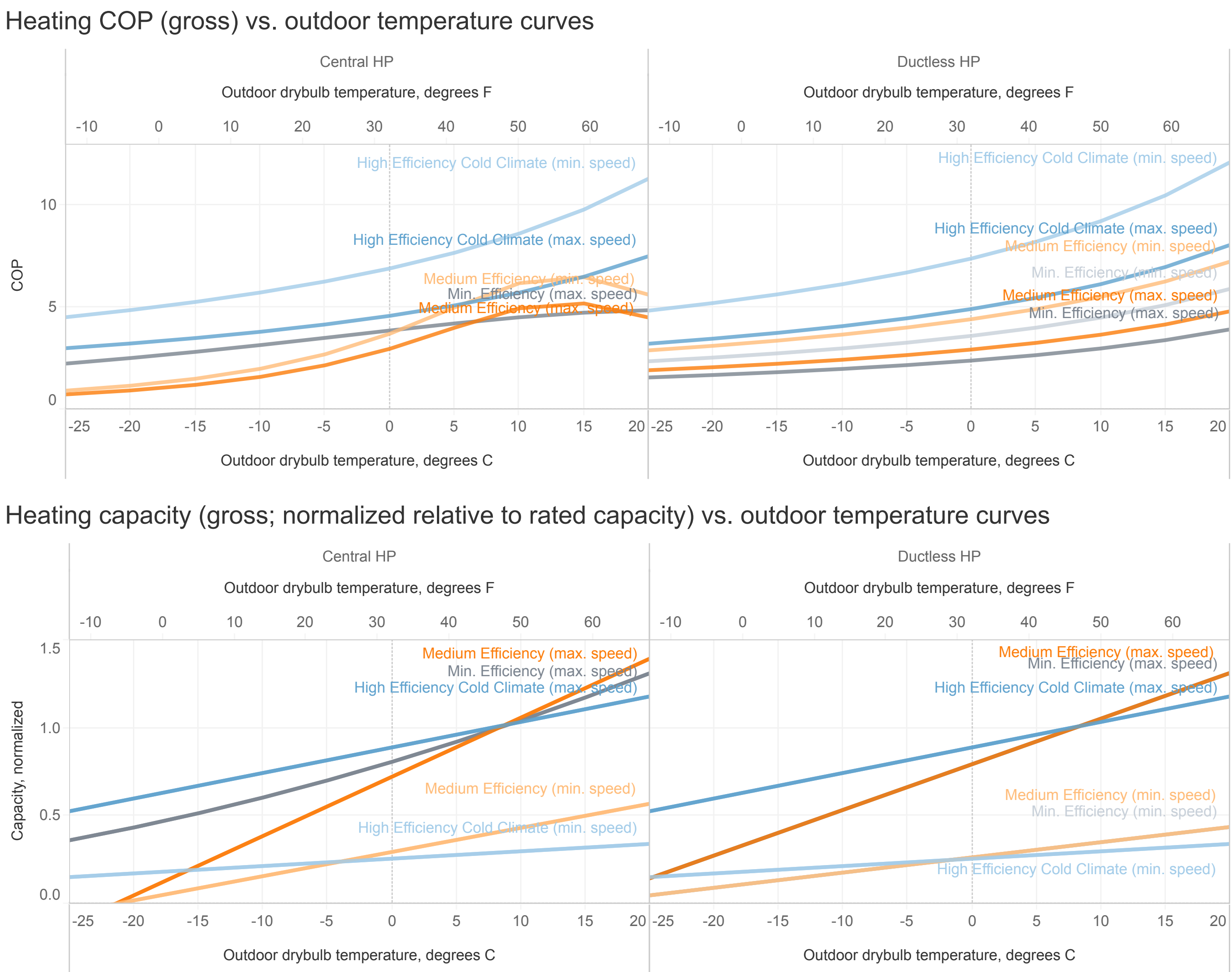

Figure S14: Idealized gross heating COP (top) and normalized capacity (bottom) vs. outdoor dry-bulb temperature performance curves for the three ASHP efficiency levels (central and ductless). These figures were created using the curve coefficients specified in EnergyPlus input blocks, with a constant 20 °C indoor dry-bulb temperature for plotting purposes. Variable-speed heat pumps are modeled as multi-speed coils with four speeds. The plots show lines for speeds 4 (maximum) and 1 (minimum). These are idealized curves and should not be used to represent performance without modeling the effects of defrost, supplemental heating, pan heater, etc. The values shown are gross COP and capacity, meaning they do not account for heat from the air handler fan. Related to Section 4.3.2 (ASHP scenarios).

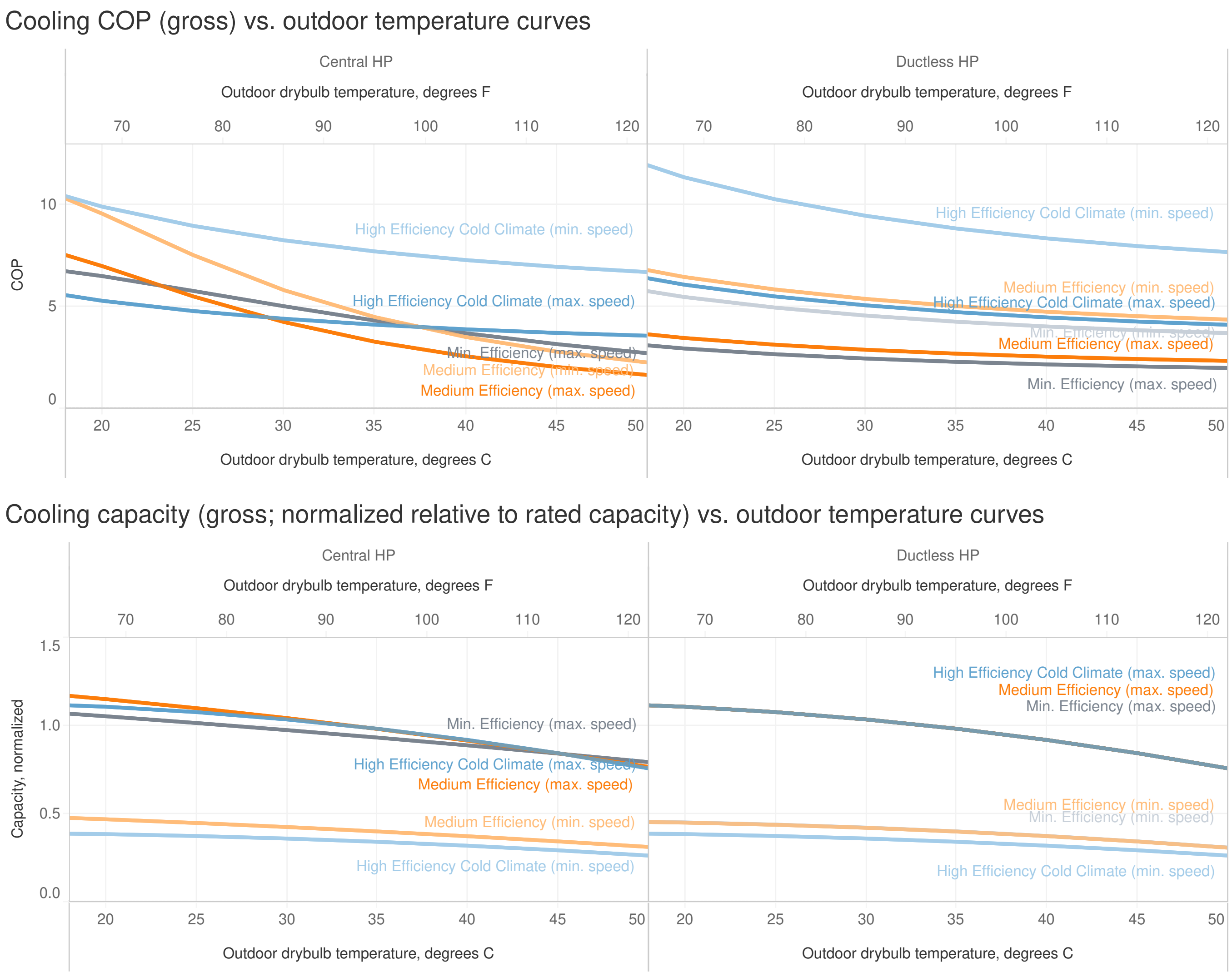

Figure S15: Idealized gross cooling COP (top) and normalized capacity (bottom) vs. outdoor dry-bulb temperature performance curves for the three ASHP efficiency levels (central and ductless). These figures were created using the curve coefficients specified in EnergyPlus input blocks, with a constant 17 °C indoor wet-bulb temperature for plotting purposes. Variable-speed heat pumps are modeled as multi-speed coils with four speeds. The plots show lines for speeds 4 (maximum) and 1 (minimum). The values shown are gross COP and capacity, meaning they do not account for heat from the air handler fan. Related to Section 4.3.2 (ASHP scenarios).

Listing 1: A sample of the HP object along with capacity and COP performance curve in EnergyPlus. The sample object is for central ASHP dwelling unit ID

```
Coil:Cooling:DX:MultiSpeed,
  res ashp clg coil,                       !- Name
  ,                                        !- Availability Schedule Name
  res ashp clg unitary system Fan - Cooling Coil Node, !- Air Inlet Node Name
  Node 28,                                 !- Air Outlet Node Name
  ,                                        !- Condenser Air Inlet Node Name
  AirCooled,                               !- Condenser Type
  -25,                                     !- Minimum Outdoor Dry-Bulb Temperature for Compressor Operation {C}
  ,                                        !- Supply Water Storage Tank Name
  ,                                        !- Condensate Collection Water Storage Tank Name
  No,                                      !- Apply Part Load Fraction to Speeds Greater than 1
  No,                                      !- Apply Latent Degradation to Speeds Greater than 1
  0,                                       !- Crankcase Heater Capacity {W}
  10,                                      !- Maximum Outdoor Dry-Bulb Temperature for Crankcase Heater Operation {C}
  0,                                       !- Basin Heater Capacity {W/K}
  2,                                       !- Basin Heater Setpoint Temperature {C}
  ,                                        !- Basin Heater Operating Schedule Name
  Electricity,                             !- Fuel Type
```

```
  4,                                      !- Number of Speeds
  13262.4321762621,                       !- Speed Gross Rated Total Cooling Capacity 1 {W}
  0.842822783170288,                      !- Speed Gross Rated Sensible Heat Ratio 1
  4.65237533479379,                       !- Speed Gross Rated Cooling COP 1 {W/W}
  0.802928184753504,                      !- Speed Rated Air Flow Rate 1 {m3/s}
  773.3,                                  !- Speed Rated Evaporator Fan Power Per Volume Flow Rate 1 {W/(m3/s)}
  Cool-Cap-fT1,                           !- Speed Total Cooling Capacity Function of Temperature Curve Name 1
  Cool-Cap-fFF1,                          !- Speed Total Cooling Capacity Function of Flow Fraction Curve Name 1
  Cool-EIR-fT1,                           !- Speed Energy Input Ratio Function of Temperature Curve Name 1
  Cool-EIR-fFF1,                          !- Speed Energy Input Ratio Function of Flow Fraction Curve Name 1
  Cool-PLF-fPLR1,                         !- Speed Part Load Fraction Correlation Curve Name 1
  1000,                                   !- Speed Nominal Time for Condensate Removal to Begin 1 {s}
  1.5,                                    !- Speed Ratio of Initial Moisture Evaporation Rate and Steady State
      Latent Capacity 1 {dimensionless}
  3,                                      !- Speed Maximum Cycling Rate 1 {cycles/hr}
  45,                                     !- Speed Latent Capacity Time Constant 1 {s}
  0.2,                                    !- Speed Rated Waste Heat Fraction of Power Input 1 {dimensionless}
  ConstantBiquadratic 1,                  !- Speed Waste Heat Function of Temperature Curve Name 1
  0.9,                                    !- Speed Evaporative Condenser Effectiveness 1 {dimensionless}
  AutoSize,                               !- Speed Evaporative Condenser Air Flow Rate 1 {m3/s}
  AutoSize,                               !- Speed Rated Evaporative Condenser Pump Power Consumption 1 {W}
  18134.3460369298,                       !- Speed Gross Rated Total Cooling Capacity 2 {W}
  0.793487387863992,                      !- Speed Gross Rated Sensible Heat Ratio 2
  4.47806277457836,                       !- Speed Gross Rated Cooling COP 2 {W/W}
  1.03233623754022,                       !- Speed Rated Air Flow Rate 2 {m3/s}
  773.3,                                  !- Speed Rated Evaporator Fan Power Per Volume Flow Rate 2 {W/(m3/s)}
  Cool-Cap-fT2,                           !- Speed Total Cooling Capacity Function of Temperature Curve Name 2
  Cool-Cap-fFF2,                          !- Speed Total Cooling Capacity Function of Flow Fraction Curve Name 2
  Cool-EIR-fT2,                           !- Speed Energy Input Ratio Function of Temperature Curve Name 2
  Cool-EIR-fFF2,                          !- Speed Energy Input Ratio Function of Flow Fraction Curve Name 2
  Cool-PLF-fPLR2,                         !- Speed Part Load Fraction Correlation Curve Name 2
  1000,                                   !- Speed Nominal Time for Condensate Removal to Begin 2 {s}
  1.5,                                    !- Speed Ratio of Initial Moisture Evaporation Rate and Steady State
      Latent Capacity 2 {dimensionless}
  3,                                      !- Speed Maximum Cycling Rate 2 {cycles/hr}
  45,                                     !- Speed Latent Capacity Time Constant 2 {s}
  0.2,                                    !- Speed Rated Waste Heat Fraction of Power Input 2 {dimensionless}
  ConstantBiquadratic 1,                  !- Speed Waste Heat Function of Temperature Curve Name 2
  0.9,                                    !- Speed Evaporative Condenser Effectiveness 2 {dimensionless}
  AutoSize,                               !- Speed Evaporative Condenser Air Flow Rate 2 {m3/s}
  AutoSize,                               !- Speed Rated Evaporative Condenser Pump Power Consumption 2 {W}
  27066.1881148205,                       !- Speed Gross Rated Total Cooling Capacity 3 {W}
  0.7039025016,                           !- Speed Gross Rated Sensible Heat Ratio 3
  3.76321310800196,                       !- Speed Gross Rated Cooling COP 3 {W/W}
  1.14704026393358,                       !- Speed Rated Air Flow Rate 3 {m3/s}
  773.3,                                  !- Speed Rated Evaporator Fan Power Per Volume Flow Rate 3 {W/(m3/s)}
  Cool-Cap-fT3,                           !- Speed Total Cooling Capacity Function of Temperature Curve Name 3
  Cool-Cap-fFF3,                          !- Speed Total Cooling Capacity Function of Flow Fraction Curve Name 3
  Cool-EIR-fT3,                           !- Speed Energy Input Ratio Function of Temperature Curve Name 3
  Cool-EIR-fFF3,                          !- Speed Energy Input Ratio Function of Flow Fraction Curve Name 3
  Cool-PLF-fPLR3,                         !- Speed Part Load Fraction Correlation Curve Name 3
  1000,                                   !- Speed Nominal Time for Condensate Removal to Begin 3 {s}
  1.5,                                    !- Speed Ratio of Initial Moisture Evaporation Rate and Steady State
      Latent Capacity 3 {dimensionless}
  3,                                      !- Speed Maximum Cycling Rate 3 {cycles/hr}
  45,                                     !- Speed Latent Capacity Time Constant 3 {s}
  0.2,                                    !- Speed Rated Waste Heat Fraction of Power Input 3 {dimensionless}
  ConstantBiquadratic 1,                  !- Speed Waste Heat Function of Temperature Curve Name 3
  0.9,                                    !- Speed Evaporative Condenser Effectiveness 3 {dimensionless}
  AutoSize,                               !- Speed Evaporative Condenser Air Flow Rate 3 {m3/s}
  AutoSize,                               !- Speed Rated Evaporative Condenser Pump Power Consumption 3 {W}
  32479.4257377847,                       !- Speed Gross Rated Total Cooling Capacity 4 {W}
  0.72049229668,                          !- Speed Gross Rated Sensible Heat Ratio 4
  3.39862912173757,                       !- Speed Gross Rated Cooling COP 4 {W/W}
  1.44527073255631,                       !- Speed Rated Air Flow Rate 4 {m3/s}
  773.3,                                  !- Speed Rated Evaporator Fan Power Per Volume Flow Rate 4 {W/(m3/s)}
  Cool-Cap-fT4,                           !- Speed Total Cooling Capacity Function of Temperature Curve Name 4
  Cool-Cap-fFF4,                          !- Speed Total Cooling Capacity Function of Flow Fraction Curve Name 4
  Cool-EIR-fT4,                           !- Speed Energy Input Ratio Function of Temperature Curve Name 4
  Cool-EIR-fFF4,                          !- Speed Energy Input Ratio Function of Flow Fraction Curve Name 4
  Cool-PLF-fPLR4,                         !- Speed Part Load Fraction Correlation Curve Name 4
  1000,                                   !- Speed Nominal Time for Condensate Removal to Begin 4 {s}
  1.5,                                    !- Speed Ratio of Initial Moisture Evaporation Rate and Steady State
      Latent Capacity 4 {dimensionless}
  3,                                      !- Speed Maximum Cycling Rate 4 {cycles/hr}
  45,                                     !- Speed Latent Capacity Time Constant 4 {s}
  0.2,                                    !- Speed Rated Waste Heat Fraction of Power Input 4 {dimensionless}
  ConstantBiquadratic 1,                  !- Speed Waste Heat Function of Temperature Curve Name 4
  0.9,                                    !- Speed Evaporative Condenser Effectiveness 4 {dimensionless}
  AutoSize,                               !- Speed Evaporative Condenser Air Flow Rate 4 {m3/s}
  AutoSize;                               !- Speed Rated Evaporative Condenser Pump Power Consumption 4 {W}

Curve:Biquadratic,
  Cool-Cap-fT1,                           !- Name
  1.7139851972,                           !- Coefficient1 Constant
```

```
    -0.0746167716,                     !- Coefficient2 x
    0.00297468936,                     !- Coefficient3 x**2
    0.00577633536,                     !- Coefficient4 y
    -0.000103131468,                   !- Coefficient5 y**2
    -0.00066888504,                    !- Coefficient6 x*y
    13.88,                             !- Minimum Value of x {BasedOnField A2}
    23.88,                             !- Maximum Value of x {BasedOnField A2}
    18.33,                             !- Minimum Value of y {BasedOnField A3}
    51.66;                             !- Maximum Value of y {BasedOnField A3}

  Curve:Biquadratic,
    Cool-EIR-fT1,                      !- Name
    -0.0459238618,                     !- Coefficient1 Constant
    0.06829090668,                     !- Coefficient2 x
    -0.00219033396,                    !- Coefficient3 x**2
    -0.01723331952,                    !- Coefficient4 y
    0.00103872132,                     !- Coefficient5 y**2
    -0.000199631628,                   !- Coefficient6 x*y
    13.88,                             !- Minimum Value of x {BasedOnField A2}
    23.88,                             !- Maximum Value of x {BasedOnField A2}
    18.33,                             !- Minimum Value of y {BasedOnField A3}
    51.66;                             !- Maximum Value of y {BasedOnField A3}

  Curve:Biquadratic,
    Cool-Cap-fT2,                      !- Name
    1.15285674,                        !- Coefficient1 Constant
    -0.0245373048,                     !- Coefficient2 x
    0.00176665212,                     !- Coefficient3 x**2
    0.0058603014,                      !- Coefficient4 y
    -7.723512e-05,                     !- Coefficient5 y**2
    -0.00066472488,                    !- Coefficient6 x*y
    13.88,                             !- Minimum Value of x {BasedOnField A2}
    23.88,                             !- Maximum Value of x {BasedOnField A2}
    18.33,                             !- Minimum Value of y {BasedOnField A3}
    51.66;                             !- Maximum Value of y {BasedOnField A3}

  Curve:Biquadratic,
    Cool-EIR-fT2,                      !- Name
    1.7046091386,                      !- Coefficient1 Constant
    -0.10488220416,                    !- Coefficient2 x
    0.00218213676,                     !- Coefficient3 x**2
    -0.01672851276,                    !- Coefficient4 y
    0.000954018,                       !- Coefficient5 y**2
    -0.000126467244,                   !- Coefficient6 x*y
    13.88,                             !- Minimum Value of x {BasedOnField A2}
    23.88,                             !- Maximum Value of x {BasedOnField A2}
    18.33,                             !- Minimum Value of y {BasedOnField A3}
    51.66;                             !- Maximum Value of y {BasedOnField A3}

  Curve:Biquadratic,
    Cool-Cap-fT3,                      !- Name
    0.6461992122,                      !- Coefficient1 Constant
    0.0213513228,                      !- Coefficient2 x
    0.00065910348,                     !- Coefficient3 x**2
    0.00693808596,                     !- Coefficient4 y
    -6.7378068e-05,                    !- Coefficient5 y**2
    -0.00068810796,                    !- Coefficient6 x*y
    13.88,                             !- Minimum Value of x {BasedOnField A2}
    23.88,                             !- Maximum Value of x {BasedOnField A2}
    18.33,                             !- Minimum Value of y {BasedOnField A3}
    51.66;                             !- Maximum Value of y {BasedOnField A3}

  Curve:Biquadratic,
    Cool-EIR-fT3,                      !- Name
    -0.00625401600000031,              !- Coefficient1 Constant
    0.0463319604,                      !- Coefficient2 x
    -0.00142349076,                    !- Coefficient3 x**2
    0.0118725714,                      !- Coefficient4 y
    0.00048109464,                     !- Coefficient5 y**2
    -0.00051695172,                    !- Coefficient6 x*y
    13.88,                             !- Minimum Value of x {BasedOnField A2}
    23.88,                             !- Maximum Value of x {BasedOnField A2}
    18.33,                             !- Minimum Value of y {BasedOnField A3}
    51.66;                             !- Maximum Value of y {BasedOnField A3}

  Curve:Biquadratic,
    Cool-Cap-fT4,                      !- Name
    0.9177891678,                      !- Coefficient1 Constant
    -0.0060322572,                     !- Coefficient2 x
    0.00136327212,                     !- Coefficient3 x**2
    0.00532574064,                     !- Coefficient4 y
    -5.6581092e-05,                    !- Coefficient5 y**2
    -0.00063857808,                    !- Coefficient6 x*y
    13.88,                             !- Minimum Value of x {BasedOnField A2}
    23.88,                             !- Maximum Value of x {BasedOnField A2}
```

```
  18.33,                                  !- Minimum Value of y {BasedOnField A3}
  51.66;                                  !- Maximum Value of y {BasedOnField A3}

Curve:Biquadratic,
  Cool-EIR-fT4,                           !- Name
  -0.518432777,                           !- Coefficient1 Constant
  0.0992787624,                           !- Coefficient2 x
  -0.00276048324,                         !- Coefficient3 x**2
  0.013988232,                            !- Coefficient4 y
  0.00043519356,                          !- Coefficient5 y**2
  -0.00055720224,                         !- Coefficient6 x*y
  13.88,                                  !- Minimum Value of x {BasedOnField A2}
  23.88,                                  !- Maximum Value of x {BasedOnField A2}
  18.33,                                  !- Minimum Value of y {BasedOnField A3}
  51.66;                                  !- Maximum Value of y {BasedOnField A3}

Coil:Heating:DX:MultiSpeed,
  res ashp htg coil,                      !- Name
  Always On Discrete,                     !- Availability Schedule Name
  res ashp htg asys Fan - Heating Coil Node, !- Air Inlet Node Name
  res ashp htg asys Heating Coil - Supplemental Coil Node, !- Air Outlet Node Name
  -17.7777777777778,                      !- Minimum Outdoor Dry-Bulb Temperature for Compressor Operation {C}
  ,                                       !- Outdoor Dry-Bulb Temperature to Turn On Compressor {C}
  20,                                     !- Crankcase Heater Capacity {W}
  12.7777777777778,                       !- Maximum Outdoor Dry-Bulb Temperature for Crankcase Heater Operation {C}
  DefrostEIR,                             !- Defrost Energy Input Ratio Function of Temperature Curve Name
  4.44444444444444,                       !- Maximum Outdoor Dry-Bulb Temperature for Defrost Operation {C}
  ReverseCycle,                           !- Defrost Strategy
  Timed,                                  !- Defrost Control
  0.058333,                               !- Defrost Time Period Fraction
  AutoSize,                               !- Resistive Defrost Heater Capacity {W}
  No,                                     !- Apply Part Load Fraction to Speeds Greater than 1
  Electricity,                            !- Fuel Type
  4,                                      !- Region number for Calculating HSPF
  4,                                      !- Number of Speeds
  13262.4321762621,                       !- Speed Gross Rated Heating Capacity 1 {W}
  5.13214216652667,                       !- Speed Gross Rated Heating COP 1 {W/W}
  0.79801022238059,                       !- Speed Rated Air Flow Rate 1 {m3/s}
  773.3,                                  !- Speed Rated Supply Air Fan Power Per Volume Flow Rate 1 {W/(m3/s)}
  HP_Heat-Cap-fT1,                        !- Speed Heating Capacity Function of Temperature Curve Name 1
  HP_Heat-CAP-fFF1,                       !- Speed Heating Capacity Function of Flow Fraction Curve Name 1
  HP_Heat-EIR-fT1,                        !- Speed Energy Input Ratio Function of Temperature Curve Name 1
  HP_Heat-EIR-fFF1,                       !- Speed Energy Input Ratio Function of Flow Fraction Curve Name 1
  HP_Heat-PLF-fPLR1,                      !- Speed Part Load Fraction Correlation Curve Name 1
  0.2,                                    !- Speed Rated Waste Heat Fraction of Power Input 1 {dimensionless}
  ConstantBiquadratic,                    !- Speed Waste Heat Function of Temperature Curve Name 1
  18134.3460369298,                       !- Speed Gross Rated Heating Capacity 2 {W}
  4.83399764602255,                       !- Speed Gross Rated Heating COP 2 {W/W}
  0.992120817013707,                      !- Speed Rated Air Flow Rate 2 {m3/s}
  773.3,                                  !- Speed Rated Supply Air Fan Power Per Volume Flow Rate 2 {W/(m3/s)}
  HP_Heat-Cap-fT2,                        !- Speed Heating Capacity Function of Temperature Curve Name 2
  HP_Heat-CAP-fFF2,                       !- Speed Heating Capacity Function of Flow Fraction Curve Name 2
  HP_Heat-EIR-fT2,                        !- Speed Energy Input Ratio Function of Temperature Curve Name 2
  HP_Heat-EIR-fFF2,                       !- Speed Energy Input Ratio Function of Flow Fraction Curve Name 2
  HP_Heat-PLF-fPLR2,                      !- Speed Part Load Fraction Correlation Curve Name 2
  0.2,                                    !- Speed Rated Waste Heat Fraction of Power Input 2 {dimensionless}
  ConstantBiquadratic,                    !- Speed Waste Heat Function of Temperature Curve Name 2
  27066.1881148205,                       !- Speed Gross Rated Heating Capacity 3 {W}
  4.07762718276032,                       !- Speed Gross Rated Heating COP 3 {W/W}
  1.0783921924062,                        !- Speed Rated Air Flow Rate 3 {m3/s}
  773.3,                                  !- Speed Rated Supply Air Fan Power Per Volume Flow Rate 3 {W/(m3/s)}
  HP_Heat-Cap-fT3,                        !- Speed Heating Capacity Function of Temperature Curve Name 3
  HP_Heat-CAP-fFF3,                       !- Speed Heating Capacity Function of Flow Fraction Curve Name 3
  HP_Heat-EIR-fT3,                        !- Speed Energy Input Ratio Function of Temperature Curve Name 3
  HP_Heat-EIR-fFF3,                       !- Speed Energy Input Ratio Function of Flow Fraction Curve Name 3
  HP_Heat-PLF-fPLR3,                      !- Speed Part Load Fraction Correlation Curve Name 3
  0.2,                                    !- Speed Rated Waste Heat Fraction of Power Input 3 {dimensionless}
  ConstantBiquadratic,                    !- Speed Waste Heat Function of Temperature Curve Name 3
  32479.4257377847,                       !- Speed Gross Rated Heating Capacity 4 {W}
  4.11113258508659,                       !- Speed Gross Rated Heating COP 4 {W/W}
  1.31563847473557,                       !- Speed Rated Air Flow Rate 4 {m3/s}
  773.3,                                  !- Speed Rated Supply Air Fan Power Per Volume Flow Rate 4 {W/(m3/s)}
  HP_Heat-Cap-fT4,                        !- Speed Heating Capacity Function of Temperature Curve Name 4
  HP_Heat-CAP-fFF4,                       !- Speed Heating Capacity Function of Flow Fraction Curve Name 4
  HP_Heat-EIR-fT4,                        !- Speed Energy Input Ratio Function of Temperature Curve Name 4
  HP_Heat-EIR-fFF4,                       !- Speed Energy Input Ratio Function of Flow Fraction Curve Name 4
  HP_Heat-PLF-fPLR4,                      !- Speed Part Load Fraction Correlation Curve Name 4
  0.2,                                    !- Speed Rated Waste Heat Fraction of Power Input 4 {dimensionless}
  ConstantBiquadratic;                    !- Speed Waste Heat Function of Temperature Curve Name 4

Curve:Biquadratic,
  DefrostEIR,                             !- Name
  0.1528,                                 !- Coefficient1 Constant
  0,                                      !- Coefficient2 x
  0,                                      !- Coefficient3 x**2
```

```
  0,                                      !- Coefficient4 y
  0,                                      !- Coefficient5 y**2
  0,                                      !- Coefficient6 x*y
  -100,                                   !- Minimum Value of x {BasedOnField A2}
  100,                                    !- Maximum Value of x {BasedOnField A2}
  -100,                                   !- Minimum Value of y {BasedOnField A3}
  100;                                    !- Maximum Value of y {BasedOnField A3}

Curve:Biquadratic,
  HP_Heat-Cap-fT1,                        !- Name
  0.893321031576,                         !- Coefficient1 Constant
  -0.00973374264,                         !- Coefficient2 x
  6.3643968e-05,                          !- Coefficient3 x**2
  0.0391130520048,                        !- Coefficient4 y
  -2.50816824e-06,                        !- Coefficient5 y**2
  -0.000272588652,                        !- Coefficient6 x*y
  -100,                                   !- Minimum Value of x {BasedOnField A2}
  100,                                    !- Maximum Value of x {BasedOnField A2}
  -100,                                   !- Minimum Value of y {BasedOnField A3}
  100;                                    !- Maximum Value of y {BasedOnField A3}

Curve:Biquadratic,
  HP_Heat-EIR-fT1,                        !- Name
  0.466648487,                            !- Coefficient1 Constant
  0.020263329,                            !- Coefficient2 x
  0.00126839196,                          !- Coefficient3 x**2
  -0.0170161326,                          !- Coefficient4 y
  0.00317499588,                          !- Coefficient5 y**2
  -0.00349609608,                         !- Coefficient6 x*y
  -100,                                   !- Minimum Value of x {BasedOnField A2}
  100,                                    !- Maximum Value of x {BasedOnField A2}
  -100,                                   !- Minimum Value of y {BasedOnField A3}
  100;                                    !- Maximum Value of y {BasedOnField A3}

Curve:Biquadratic,
  HP_Heat-Cap-fT2,                        !- Name
  0.9237345336,                           !- Coefficient1 Constant
  -0.00597077568,                         !- Coefficient2 x
  0,                                      !- Coefficient3 x**2
  0.02781672876,                          !- Coefficient4 y
  6.5916828e-05,                          !- Coefficient5 y**2
  -0.000189254232,                        !- Coefficient6 x*y
  -100,                                   !- Minimum Value of x {BasedOnField A2}
  100,                                    !- Maximum Value of x {BasedOnField A2}
  -100,                                   !- Minimum Value of y {BasedOnField A3}
  100;                                    !- Maximum Value of y {BasedOnField A3}

Curve:Biquadratic,
  HP_Heat-EIR-fT2,                        !- Name
  0.450656859,                            !- Coefficient1 Constant
  0.0292902642,                           !- Coefficient2 x
  0.00039314484,                          !- Coefficient3 x**2
  -0.0097895178,                          !- Coefficient4 y
  0.00053936928,                          !- Coefficient5 y**2
  -0.0011808828,                          !- Coefficient6 x*y
  -100,                                   !- Minimum Value of x {BasedOnField A2}
  100,                                    !- Maximum Value of x {BasedOnField A2}
  -100,                                   !- Minimum Value of y {BasedOnField A3}
  100;                                    !- Maximum Value of y {BasedOnField A3}

Curve:Biquadratic,
  HP_Heat-Cap-fT3,                        !- Name
  0.9620542196,                           !- Coefficient1 Constant
  -0.00949277772,                         !- Coefficient2 x
  0.000109212948,                         !- Coefficient3 x**2
  0.0247078314,                           !- Coefficient4 y
  3.4225092e-05,                          !- Coefficient5 y**2
  -0.000125697744,                        !- Coefficient6 x*y
  -100,                                   !- Minimum Value of x {BasedOnField A2}
  100,                                    !- Maximum Value of x {BasedOnField A2}
  -100,                                   !- Minimum Value of y {BasedOnField A3}
  100;                                    !- Maximum Value of y {BasedOnField A3}

Curve:Biquadratic,
  HP_Heat-EIR-fT3,                        !- Name
  0.5725180114,                           !- Coefficient1 Constant
  0.02289624912,                          !- Coefficient2 x
  0.000266018904,                         !- Coefficient3 x**2
  -0.0106675434,                          !- Coefficient4 y
  0.00049092156,                          !- Coefficient5 y**2
  -0.00068136876,                         !- Coefficient6 x*y
  -100,                                   !- Minimum Value of x {BasedOnField A2}
  100,                                    !- Maximum Value of x {BasedOnField A2}
  -100,                                   !- Minimum Value of y {BasedOnField A3}
  100;                                    !- Maximum Value of y {BasedOnField A3}
```

```
Curve:Biquadratic,
  HP_Heat-Cap-fT4,                        !- Name
  0.93607915412,                          !- Coefficient1 Constant
  -0.005481563544,                        !- Coefficient2 x
  -8.5897908e-06,                         !- Coefficient3 x**2
  0.02491053192,                          !- Coefficient4 y
  5.3087076e-05,                          !- Coefficient5 y**2
  -0.000155750364,                        !- Coefficient6 x*y
  -100,                                   !- Minimum Value of x {BasedOnField A2}
  100,                                    !- Maximum Value of x {BasedOnField A2}
  -100,                                   !- Minimum Value of y {BasedOnField A3}
  100;                                    !- Maximum Value of y {BasedOnField A3}

Curve:Biquadratic,
  HP_Heat-EIR-fT4,                        !- Name
  0.668195855,                            !- Coefficient1 Constant
  0.0146719548,                           !- Coefficient2 x
  0.00044596332,                          !- Coefficient3 x**2
  -0.0114392286,                          !- Coefficient4 y
  0.00049710348,                          !- Coefficient5 y**2
  -0.00069095592,                         !- Coefficient6 x*y
  -100,                                   !- Minimum Value of x {BasedOnField A2}
  100,                                    !- Maximum Value of x {BasedOnField A2}
  -100,                                   !- Minimum Value of y {BasedOnField A3}
  100;                                    !- Maximum Value of y {BasedOnField A3}

Coil:Heating:Electric,
  res ashp supp heater,                   !- Name
  Always On Discrete,                     !- Availability Schedule Name
  1,                                      !- Efficiency
  18523.2739356856,                       !- Nominal Capacity {W}
  res ashp htg asys Heating Coil - Supplemental Coil Node, !- Air Inlet Node Name
  Node 18;                                !- Air Outlet Node Name
```

S4.3. Annual average ASHP COPs by state

Figure S16 shows the annual average net heating COP by state for the three central and three ducted ASHP efficiency levels modeled. The average COP values are strongly correlated with climate. This can be contrasted with previous work that used an average COP of 3 as a threshold for "the achievable performance of a high efficiency heat pump technology in most climate zones." [27]

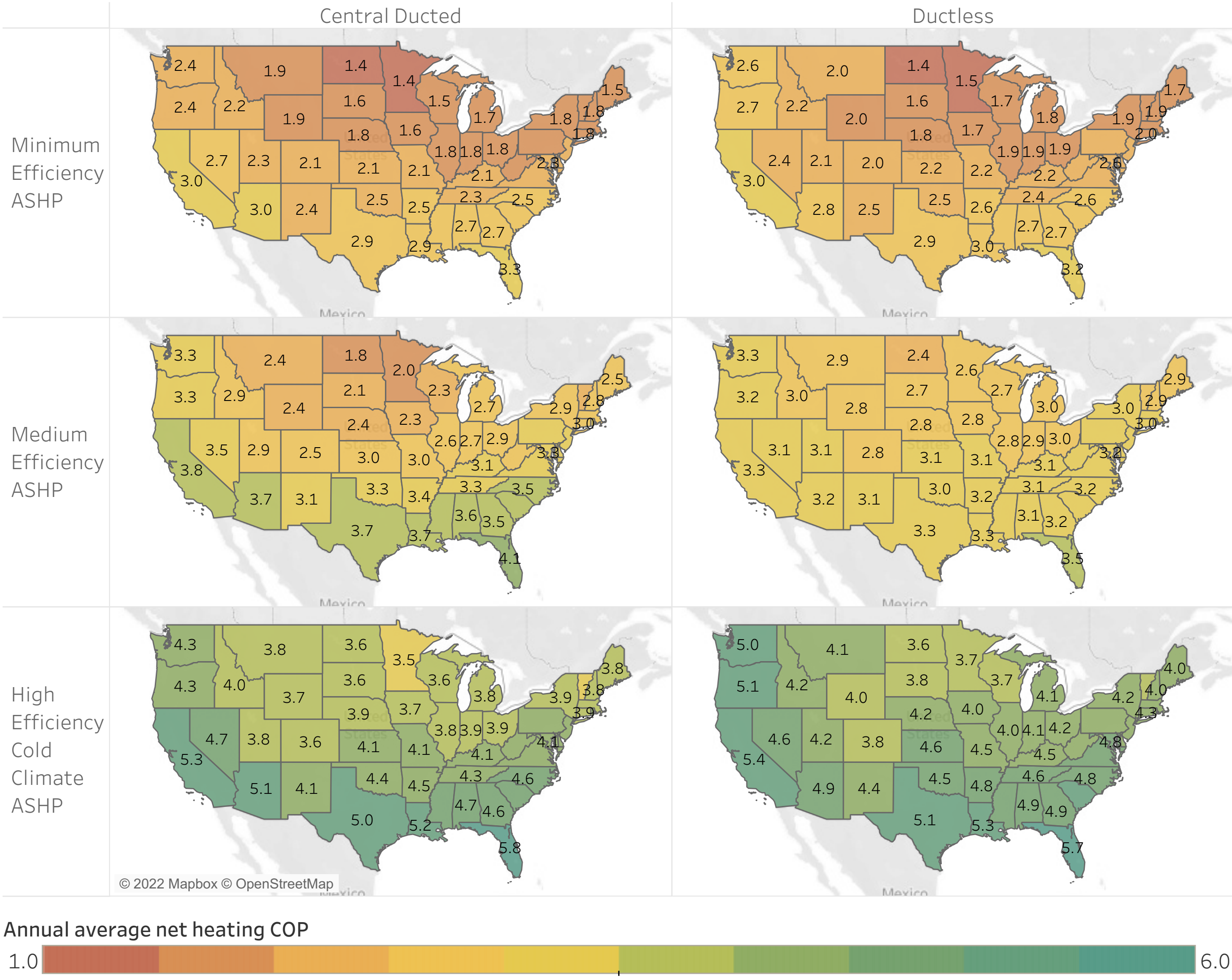

Figure S16: Annual average net heating coefficients of performance (COPs) by state. The annual average net heating COP values were estimated by filtering ResStock samples down to those that had existing electric resistance heating. For each state, the total electricity used for heating, including furnace fan electricity, for these samples is divided by the total electricity used for heating for each ASHP scenario. This includes all electricity used for the ASHP, backup electric resistance, and the air handler fan. Related to Section 4.3.2 (ASHP scenarios).

S4.4. Heat pump cost regressions

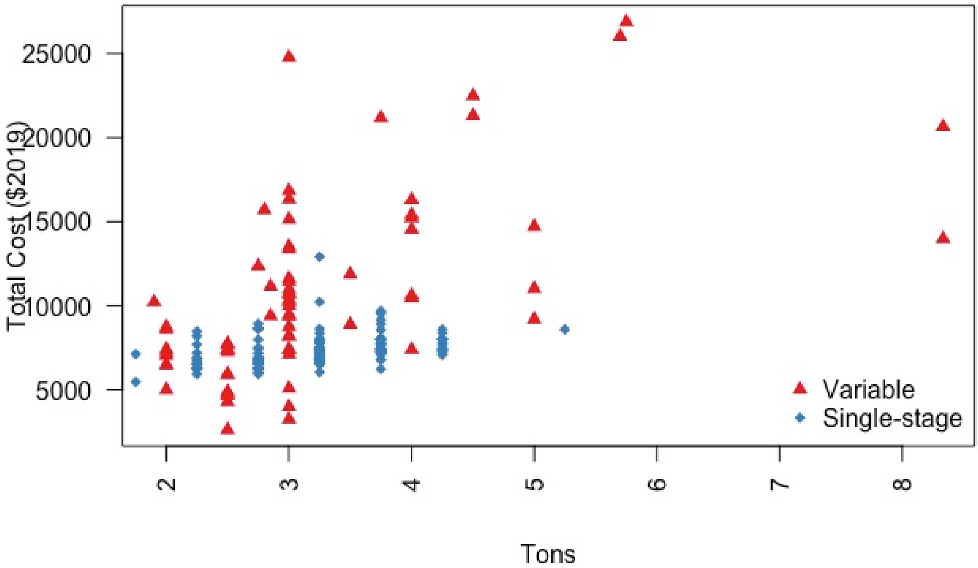

Figure S17: Central (ducted) air-source heat pump installation costs vs. tons of nameplate capacity (1 ton ≈ 3.5 kW_{th}). Related to Section 4.4.1 (ASHP cost regressions). Source data: Less et al.[31] (n=317)

Table S5: Cost regression results for central (ducted) air-source heat pumps (2019 dollars). Related to Section 4.4.1 (ASHP cost regressions). Source data: Less et al.[31] All the upgrade costs were inflated to 2022 dollars using factor of 1.12. One ton of capacity is approximately 3.5 kW_{th}.

	Estimate	Std. Err.	t value	Pr(>|t|)	
(Intercept)	-18857.7	2140.5	-8.81	<2e-16	***
tons	1662.5	183.4	9.06	<2e-16	***
HSPF	2482.9	247.6	10.03	<2e-16	***

$2,259 RMSE, 0.40 R^2, n=317

Table S6: Cost regression results for ductless air-source heat pumps (2019 dollars). Related to Section 4.4.1 (ASHP cost regressions). Source data: Less et al.[31] All the upgrade costs were inflated to 2022 dollars using factor of 1.12. One ton of capacity is approximately 3.5 kW_{th}. An additional 2.2% was added (or subtracted) for every point of HSPF above (or below) 10.5, based on the relationship between cost and HSPF for ductless heat pumps in the National Residential Efficiency Measures Database (REMDB).[64]

	Estimate	Std. Err.	t value	Pr(>|t|)	
(Intercept)	2325.5	584.3	3.98	9.9e-05	***
tons	3623.9	183.9	19.71	<2e-16	***

$3,626 RMSE, 0.71 R^2, n=187, HSPF median 11, range 9.3–14.2

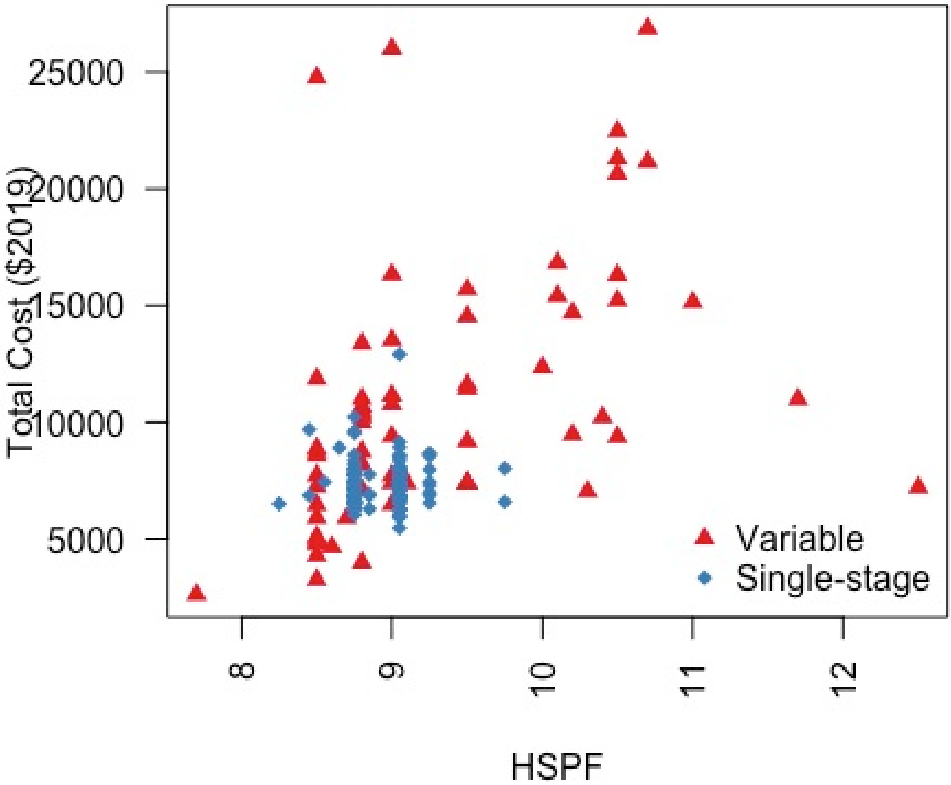

Figure S18: Central (ducted) air-source heat pump installation costs vs. rated heating season performance factor (HSPF). Related to Section 4.4.1 (ASHP cost regressions). Source data: Less et al.[31] (n=317)

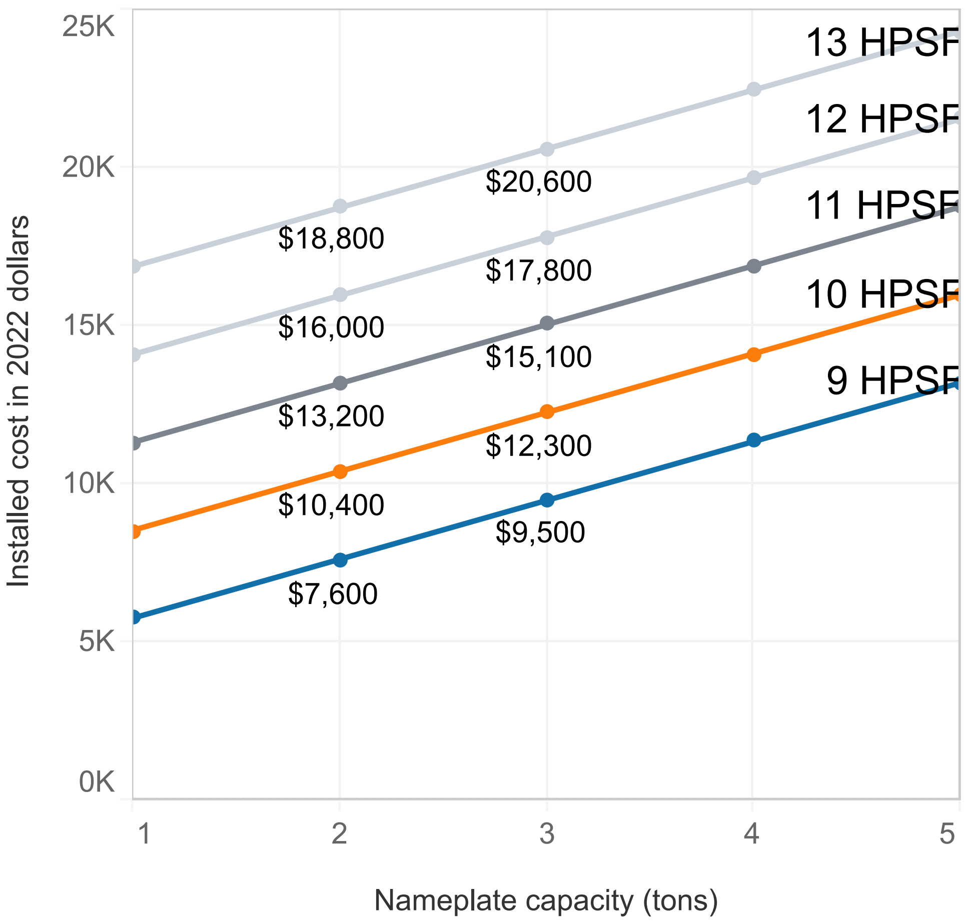

Figure S19: Cost regression results for central heat pumps. Related to Section 4.4.1 (ASHP cost regressions). Source data: Less et al.[31]. One ton of capacity is approximately 3.5 kW_{th}.

S4.5. Fuel price inputs for each state

Table S7: Marginal retail residential fuel prices for each state for 2019 (derived from EIA data by removing fixed charge component as described in Section 4.6.2), winter 21-22 (with regional multipliers derived from EIA data[46]), and winter 22-23 (with regional multipliers derived from EIA short-term winter outlook[46]). The final three rows summarize the prices with weighted national averages in sales units, $/kWh, and electricity-to-fuel price ratios for each year case. Related to Section 4.6.2 (Utility tariffs).

State	2019 prices				Winter 21-22 prices				Winter 22-23 prices (forecast)			
	Natural Gas ($/therm)	Electricity ($/kWh)	Fuel Oil ($/gal)	Propane ($/gal)	Natural Gas ($/therm)	Electricity ($/kWh)	Fuel Oil ($/gal)	Propane ($/gal)	Natural Gas ($/therm)	Electricity ($/kWh)	Fuel Oil ($/gal)	Propane ($/gal)
AL	1.17	0.12	3.24	2.57	1.53	0.13	4.37	3.44	1.77	0.13	5.08	3.33
AZ	0.91	0.11	3.24	2.42	1.23	0.13	4.37	3.22	1.51	0.14	5.08	3.13
AR	0.85	0.09	3.24	2.19	1.11	0.10	4.37	2.92	1.28	0.10	5.08	2.83
CA	0.94	0.17	3.24	2.42	1.27	0.20	4.37	3.22	1.57	0.20	5.08	3.13
CO	0.58	0.11	3.24	2.12	0.79	0.12	4.37	2.82	0.98	0.13	5.08	2.74
CT	1.27	0.20	3.31	2.98	1.55	0.22	4.47	3.97	1.81	0.24	5.21	4.11
DE	0.96	0.11	3.13	3.15	1.26	0.12	4.22	4.21	1.45	0.13	4.91	4.08
DC	1.07	0.12	4.04	3.22	1.39	0.13	5.45	4.31	1.61	0.13	6.35	4.17
FL	1.48	0.11	2.88	4.78	1.93	0.12	3.89	6.40	2.23	0.12	4.53	6.19
GA	1.24	0.11	2.88	2.32	1.61	0.12	3.89	3.11	1.87	0.12	4.53	3.01
ID	0.45	0.09	3.24	2.46	0.61	0.10	4.37	3.28	0.75	0.10	5.08	3.19
IL	0.66	0.12	2.66	1.64	0.96	0.12	3.59	2.46	1.22	0.13	4.18	2.48
IN	0.68	0.12	2.75	2.05	0.99	0.12	3.72	3.08	1.25	0.13	4.33	3.10
IA	0.62	0.11	2.45	1.33	0.90	0.12	3.31	2.00	1.15	0.13	3.85	2.02
KS	0.72	0.12	2.66	1.54	1.06	0.12	3.59	2.32	1.34	0.13	4.18	2.34
KY	0.85	0.10	2.67	2.23	1.10	0.11	3.60	2.98	1.27	0.11	4.19	2.88
LA	0.78	0.09	3.24	2.45	1.02	0.10	4.37	3.28	1.18	0.10	5.08	3.17
ME	1.40	0.16	3.01	3.00	1.70	0.17	4.07	3.99	2.00	0.19	4.73	4.14
MD	1.02	0.12	3.23	3.28	1.34	0.13	4.36	4.38	1.54	0.14	5.08	4.24
MA	1.27	0.20	3.27	3.14	1.55	0.22	4.41	4.18	1.82	0.24	5.14	4.33
MI	0.65	0.14	2.68	2.02	0.95	0.15	3.62	3.03	1.20	0.16	4.22	3.06
MN	0.64	0.12	2.66	1.62	0.93	0.12	3.59	2.44	1.18	0.13	4.18	2.46
MS	0.76	0.10	3.24	2.53	1.00	0.11	4.37	3.38	1.15	0.12	5.08	3.27
MO	0.84	0.10	2.66	1.77	1.22	0.11	3.59	2.66	1.55	0.11	4.18	2.68
MT	0.53	0.10	3.24	1.89	0.72	0.11	4.37	2.52	0.89	0.12	5.08	2.45
NE	0.59	0.10	2.53	1.34	0.86	0.10	3.41	2.02	1.09	0.11	3.97	2.04
NV	0.68	0.11	3.24	2.42	0.92	0.12	4.37	3.22	1.13	0.13	5.08	3.13
NH	1.34	0.18	3.11	3.28	1.64	0.20	4.20	4.37	1.92	0.21	4.89	4.53
NJ	0.78	0.14	3.30	3.85	0.96	0.16	4.45	5.13	1.12	0.17	5.19	5.31
NM	0.43	0.11	3.24	2.42	0.59	0.12	4.37	3.22	0.73	0.13	5.08	3.13
NY	1.09	0.16	3.54	3.27	1.33	0.18	4.78	4.36	1.56	0.19	5.56	4.52
NC	0.99	0.10	2.89	2.82	1.29	0.11	3.90	3.78	1.49	0.12	4.54	3.66
ND	0.53	0.09	2.66	1.42	0.77	0.10	3.59	2.14	0.98	0.10	4.18	2.16
OH	0.77	0.11	2.69	2.67	1.13	0.12	3.63	4.02	1.44	0.12	4.22	4.05
OK	0.72	0.09	3.24	1.91	0.94	0.10	4.37	2.56	1.09	0.11	5.08	2.48
OR	0.75	0.10	3.24	2.42	1.02	0.11	4.37	3.22	1.26	0.12	5.08	3.13
PA	0.97	0.13	2.87	3.04	1.19	0.14	3.88	4.04	1.39	0.15	4.51	4.19
RI	1.32	0.20	3.36	3.54	1.61	0.22	4.53	4.72	1.89	0.23	5.27	4.89
SC	0.96	0.12	2.88	3.23	1.25	0.13	3.89	4.32	1.44	0.14	4.53	4.18
SD	0.53	0.11	2.66	1.48	0.78	0.11	3.59	2.23	0.99	0.12	4.18	2.25
TN	0.69	0.10	3.24	3.02	0.90	0.11	4.37	4.04	1.04	0.12	5.08	3.91
TX	0.75	0.11	3.24	2.44	0.98	0.12	4.37	3.26	1.13	0.13	5.08	3.15
UT	0.59	0.09	3.24	2.55	0.80	0.10	4.37	3.39	0.98	0.11	5.08	3.30
VT	1.12	0.16	2.86	3.46	1.36	0.17	3.86	4.61	1.60	0.19	4.49	4.78
VA	1.02	0.11	2.88	3.10	1.33	0.12	3.89	4.15	1.53	0.13	4.52	4.01
WA	0.77	0.09	3.24	2.42	1.05	0.10	4.37	3.22	1.29	0.10	5.08	3.13
WV	0.77	0.10	3.29	3.22	1.01	0.11	4.43	4.31	1.16	0.12	5.16	4.17
WI	0.59	0.13	2.69	1.57	0.86	0.14	3.63	2.36	1.09	0.14	4.23	2.39
WY	0.62	0.10	3.24	2.17	0.84	0.11	4.37	2.89	1.04	0.12	5.08	2.81
U.S. avg. (in units listed above)	0.90	0.13	3.04	2.68	1.20	0.14	4.11	3.65	1.43	0.14	4.78	3.61
U.S. avg. (in $/kWh)	0.03	0.13	0.07	0.10	0.04	0.14	0.10	0.14	0.05	0.14	0.12	0.13
U.S. avg. elec-to-fuel price ratio	4.1	1.0	1.7	1.3	3.3	1.0	1.4	1.0	3.0	1.0	1.2	1.1

Table S8: Regional multipliers for winter 21-22 (historical) and winter 22-23 (forecast), both derived from EIA short-term winter outlook.[46] Related to Section 4.6.2 (Utility tariffs).

Region	Winter 21-22				Winter 22-23			
	Natural Gas (%)	Electricity (%)	Fuel Oil (%)	Propane (%)	Natural Gas (%)	Electricity (%)	Fuel Oil (%)	Propane (%)
Northeast	21.93	8.14	34.95	33.2	43.17	16.86	57.09	38
Midwest	45.83	6.4	34.95	50.33	85.48	11.2	57.09	51.63
South	30.28	7.89	34.95	33.77	50.5	14.91	57.09	29.44
West	35.73	13.77	34.95	33.2	67.24	18.12	57.09	29.44

Table S9: Mean and standard deviation of upfront costs for each housing segments of **Cold & Very Cold** climate zone

Main Heating Fuel (group)	HVAC Ducts	Scenario	Percent of all homes	Number of homes	Avg. ASHP Rated Heating Capacity (tons)	Avg. ASHP Rated Heating Capacity (kW_{th})	Avg. Upgrade cost	Std. dev. of Upgrade cost	Avg. Ref. Equip. Cost	Avg. Incr. Upgrade Cost	ResStock sample count
Electricity	Has ducts	Min. Efficiency HP	4%	5M	1.8	6	$8K	$3K	$8K	-$0K	19,221
		Medium Efficiency HP	4%	5M	5.1	18	$17K	$8K	$8K	$9K	19,221
		High Efficiency HP	4%	5M	3.3	12	$22K	$5K	$8K	$14K	19,221
		Min. Efficiency HP + Envelope	4%	5M	1.5	5	$13K	$8K	$8K	$5K	19,221
		Medium Efficiency HP + Envelope	4%	5M	3.8	13	$21K	$11K	$8K	$13K	19,221
		High-Eff.+Env.	4%	5M	2.4	9	$26K	$9K	$8K	$18K	19,221
	No ducts	Min. Efficiency HP	3%	4M	1.8	6	$10K	$4K	$3K	$7K	15,572
		Medium Efficiency HP	3%	4M	7.7	27	$34K	$40K	$3K	$31K	15,572
		High Efficiency HP	3%	4M	3.1	11	$17K	$10K	$3K	$14K	15,572
		Min. Efficiency HP + Envelope	3%	4M	1.4	5	$15K	$8K	$3K	$12K	15,572
		Medium Efficiency HP + Envelope	3%	4M	5.3	19	$31K	$32K	$3K	$29K	15,572
		High Efficiency HP + Envelope	3%	4M	2.1	7	$19K	$12K	$3K	$17K	15,572
Fuel Oil, Natural Gas, Propane	Has ducts	Min. Efficiency HP	21%	27M	2.2	8	$9K	$3K	$9K	-$0K	112,907
		Medium Efficiency HP	21%	27M	7.0	25	$21K	$9K	$9K	$12K	112,907
		High Efficiency HP	21%	27M	4.4	16	$24K	$6K	$9K	$15K	112,907
		Min. Efficiency HP + Envelope	21%	27M	1.6	6	$17K	$8K	$9K	$8K	112,907
		Medium Efficiency HP + Envelope	21%	27M	4.9	17	$25K	$12K	$9K	$17K	112,907
		High Efficiency HP + Envelope	21%	27M	3.1	11	$30K	$10K	$9K	$22K	112,907
	No ducts	Min. Efficiency HP	6%	8M	2.2	8	$11K	$5K	$5K	$6K	32,866
		Medium Efficiency HP	6%	8M	10.5	37	$45K	$43K	$5K	$40K	32,866
		High Efficiency HP	6%	8M	4.4	15	$22K	$12K	$5K	$18K	32,866
		Min. Efficiency HP + Envelope	6%	8M	1.6	5	$18K	$9K	$5K	$14K	32,866
		Medium Efficiency HP + Envelope	6%	8M	6.9	24	$40K	$32K	$5K	$36K	32,866
		High Efficiency HP + Envelope	6%	8M	2.8	10	$25K	$13K	$5K	$21K	32,866

Table S10: Mean and standard deviation of upfront costs for each housing segments of **Mixed-Humid** climate zone

Main Heating Fuel (group)	HVAC Ducts	Scenario	Percent of all homes	Number of homes	Avg. ASHP Rated Heating Capacity (tons)	Avg. ASHP Rated Heating Capacity (kW_{th})	Avg. Upgrade cost	Std. dev. of Upgrade cost	Avg. Ref. Equip. Cost	Avg. Incr. Upgrade Cost	ResStock sample count
Electricity	Has ducts	Min. Efficiency HP	11%	15M	2.6	9	$9K	$4K	$11K	-$2K	61,152
		Medium Efficiency HP	11%	15M	4.0	14	$15K	$6K	$11K	$4K	61,152
		High Efficiency HP	11%	15M	2.9	10	$21K	$4K	$11K	$11K	61,152
		Min. Efficiency HP + Envelope	11%	15M	2.0	7	$15K	$9K	$11K	$4K	61,152
		Medium Efficiency HP + Envelope	11%	15M	2.9	10	$20K	$10K	$11K	$9K	61,152
		High Efficiency HP + Envelope	11%	15M	2.2	8	$27K	$9K	$11K	$16K	61,152
	No ducts	Min. Efficiency HP	2%	2M	2.6	9	$13K	$6K	$3K	$9K	8,936
		Medium Efficiency HP	2%	2M	4.8	17	$22K	$14K	$3K	$18K	8,936
		High Efficiency HP	2%	2M	2.9	10	$16K	$9K	$3K	$13K	8,936
		Min. Efficiency HP + Envelope	2%	2M	1.8	6	$18K	$10K	$3K	$15K	8,936
		Medium Efficiency HP + Envelope	2%	2M	3.0	11	$24K	$14K	$3K	$20K	8,936
		High Efficiency HP + Envelope	2%	2M	1.9	7	$20K	$11K	$3K	$17K	8,936
Fuel Oil, Natural Gas, Propane	Has ducts	Min. Efficiency HP	13%	17M	3.0	10	$10K	$4K	$11K	-$1K	70,116
		Medium Efficiency HP	13%	17M	5.2	18	$17K	$7K	$11K	$6K	70,116
		High Efficiency HP	13%	17M	3.6	13	$23K	$5K	$11K	$11K	70,116
		Min. Efficiency HP + Envelope	13%	17M	2.1	7	$18K	$9K	$11K	$6K	70,116
		Medium Efficiency HP + Envelope	13%	17M	3.6	13	$23K	$11K	$11K	$12K	70,116
		High Efficiency HP + Envelope	13%	17M	2.5	9	$30K	$10K	$11K	$18K	70,116
	No ducts	Min. Efficiency HP	4%	6M	2.9	10	$14K	$7K	$5K	$9K	22,823
		Medium Efficiency HP	4%	6M	5.9	21	$27K	$16K	$5K	$22K	22,823
		High Efficiency HP	4%	6M	3.5	12	$19K	$10K	$5K	$14K	22,823
		Min. Efficiency HP + Envelope	4%	6M	1.8	6	$20K	$10K	$5K	$15K	22,823
		Medium Efficiency HP + Envelope	4%	6M	3.6	13	$27K	$16K	$5K	$23K	22,823
		High Efficiency HP + Envelope	4%	6M	2.2	8	$23K	$12K	$5K	$18K	22,823

Table S11: Mean and standard deviation of upfront costs for each housing segments of **Marine** climate zone

Main Heating Fuel (group)	HVAC Ducts	Scenario	Percent of all homes	Number of homes	Avg. ASHP Rated Heating Capacity (tons)	Avg. ASHP Rated Heating Capacity (kW_{th})	Avg. Upgrade cost	Std. dev. of Upgrade cost	Avg. Ref. Equip. Cost	Avg. Incr. Upgrade Cost	ResStock sample count
Electricity	Has ducts	Min. Efficiency HP	1%	1M	1.6	6	$7K	$3K	$6K	$1K	4,831
		Medium Efficiency HP	1%	1M	2.2	8	$12K	$4K	$6K	$6K	4,831
		High Efficiency HP	1%	1M	1.7	6	$19K	$3K	$6K	$13K	4,831
		Min. Efficiency HP + Envelope	1%	1M	1.3	5	$12K	$8K	$6K	$6K	4,831
		Medium Efficiency HP + Envelope	1%	1M	1.6	6	$16K	$9K	$6K	$10K	4,831
		High Efficiency HP + Envelope	1%	1M	1.3	5	$24K	$8K	$6K	$18K	4,831
	No ducts	Min. Efficiency HP	1%	2M	1.7	6	$10K	$4K	$2K	$8K	6,991
		Medium Efficiency HP	1%	2M	2.4	8	$13K	$8K	$2K	$11K	6,991
		High Efficiency HP	1%	2M	1.7	6	$11K	$6K	$2K	$9K	6,991
		Min. Efficiency HP + Envelope	1%	2M	1.3	5	$16K	$9K	$2K	$14K	6,991
		Medium Efficiency HP + Envelope	1%	2M	1.6	6	$18K	$11K	$2K	$16K	6,991
		High Efficiency HP + Envelope	1%	2M	1.2	4	$17K	$10K	$2K	$15K	6,991
Fuel Oil, Natural Gas, Propane	Has ducts	Min. Efficiency HP	2%	3M	2.1	7	$9K	$3K	$6K	$3K	12,142
		Medium Efficiency HP	2%	3M	2.8	10	$13K	$4K	$6K	$7K	12,142
		High Efficiency HP	2%	3M	2.3	8	$20K	$3K	$6K	$14K	12,142
		Min. Efficiency HP + Envelope	2%	3M	1.5	5	$17K	$9K	$6K	$11K	12,142
		Medium Efficiency HP + Envelope	2%	3M	2.0	7	$21K	$9K	$6K	$15K	12,142
		High Efficiency HP + Envelope	2%	3M	1.6	6	$29K	$9K	$6K	$22K	12,142
	No ducts	Min. Efficiency HP	1%	1M	2.0	7	$10K	$4K	$3K	$7K	3,511
		Medium Efficiency HP	1%	1M	2.7	9	$14K	$7K	$3K	$11K	3,511
		High Efficiency HP	1%	1M	2.0	7	$12K	$6K	$3K	$9K	3,511
		Min. Efficiency HP + Envelope	1%	1M	1.3	5	$19K	$9K	$3K	$16K	3,511
		Medium Efficiency HP + Envelope	1%	1M	1.7	6	$21K	$10K	$3K	$18K	3,511
		High Efficiency HP + Envelope	1%	1M	1.3	4	$20K	$9K	$3K	$17K	3,511

Table S12: Mean and standard deviation of upfront costs for each housing segments of **Hot-Dry & Mixed-Dry** climate zone

Main Heating Fuel (group)	HVAC Ducts	Scenario	Percent of all homes	Number of homes	Avg. ASHP Rated Heating Capacity (tons)	Avg. ASHP Rated Heating Capacity (kW_{th})	Avg. Upgrade cost	Std. dev. of Upgrade cost	Avg. Ref. Equip. Cost	Avg. Incr. Upgrade Cost	ResStock sample count
Electricity	Has ducts	Min. Efficiency HP	3%	4M	2.7	10	$9K	$5K	$9K	$0K	17,985
		Medium Efficiency HP	3%	4M	3.0	10	$13K	$5K	$9K	$4K	17,985
		High Efficiency HP	3%	4M	2.8	10	$21K	$5K	$9K	$12K	17,985
		Min. Efficiency HP + Envelope	3%	4M	2.0	7	$15K	$9K	$9K	$6K	17,985
		Medium Efficiency HP + Envelope	3%	4M	2.1	8	$19K	$10K	$9K	$9K	17,985
		High Efficiency HP + Envelope	3%	4M	2.1	7	$27K	$9K	$9K	$17K	17,985
	No ducts	Min. Efficiency HP	1%	1M	2.1	7	$11K	$7K	$2K	$9K	4,625
		Medium Efficiency HP	1%	1M	2.3	8	$12K	$8K	$2K	$10K	4,625
		High Efficiency HP	1%	1M	2.0	7	$12K	$7K	$2K	$10K	4,625
		Min. Efficiency HP + Envelope	1%	1M	1.3	5	$17K	$9K	$2K	$15K	4,625
		Medium Efficiency HP + Envelope	1%	1M	1.4	5	$17K	$10K	$2K	$15K	4,625
		High Efficiency HP + Envelope	1%	1M	1.3	5	$18K	$10K	$2K	$16K	4,625
Fuel Oil, Natural Gas, Propane	Has ducts	Min. Efficiency HP	6%	8M	2.8	10	$10K	$4K	$10K	$0K	32,706
		Medium Efficiency HP	6%	8M	3.1	11	$13K	$5K	$10K	$3K	32,706
		High Efficiency HP	6%	8M	2.9	10	$21K	$4K	$10K	$11K	32,706
		Min. Efficiency HP + Envelope	6%	8M	2.0	7	$17K	$9K	$10K	$7K	32,706
		Medium Efficiency HP + Envelope	6%	8M	2.2	8	$20K	$9K	$10K	$10K	32,706
		High Efficiency HP + Envelope	6%	8M	2.1	7	$29K	$9K	$10K	$19K	32,706
	No ducts	Min. Efficiency HP	1%	2M	2.3	8	$11K	$6K	$3K	$8K	7,680
		Medium Efficiency HP	1%	2M	2.5	9	$13K	$8K	$3K	$10K	7,680
		High Efficiency HP	1%	2M	2.2	8	$13K	$7K	$3K	$9K	7,680
		Min. Efficiency HP + Envelope	1%	2M	1.3	5	$19K	$9K	$3K	$16K	7,680
		Medium Efficiency HP + Envelope	1%	2M	1.4	5	$20K	$10K	$3K	$17K	7,680
		High Efficiency HP + Envelope	1%	2M	1.3	5	$20K	$9K	$3K	$17K	7,680

Table S13: Mean and standard deviation of upfront costs for each housing segments of **Hot-Humid** climate zone

Main Heating Fuel (group)	HVAC Ducts	Scenario	Percent of all homes	Number of homes	Avg. ASHP Rated Heating Capacity (tons)	Avg. ASHP Rated Heating Capacity (kW_{th})	Avg. Upgrade cost	Std. dev. of Upgrade cost	Avg. Ref. Equip. Cost	Avg. Incr. Upgrade Cost	ResStock sample count
Electricity	Has ducts	Min. Efficiency HP	13%	17M	3.3	11	$10K	$5K	$11K	-$0K	70,976
		Medium Efficiency HP	13%	17M	3.1	11	$13K	$4K	$11K	$3K	70,976
		High Efficiency HP	13%	17M	3.1	11	$22K	$4K	$11K	$11K	70,976
		Min. Efficiency HP + Envelope	13%	17M	2.4	8	$16K	$9K	$11K	$5K	70,976
		Medium Efficiency HP + Envelope	13%	17M	2.2	8	$19K	$9K	$11K	$8K	70,976
		High Efficiency HP + Envelope	13%	17M	2.3	8	$28K	$9K	$11K	$17K	70,976
	No ducts	Min. Efficiency HP	1%	1M	3.1	11	$15K	$6K	$3K	$11K	4,641
		Medium Efficiency HP	1%	1M	3.1	11	$15K	$7K	$3K	$12K	4,641
		High Efficiency HP	1%	1M	2.9	10	$16K	$7K	$3K	$12K	4,641
		Min. Efficiency HP + Envelope	1%	1M	1.9	7	$20K	$9K	$3K	$17K	4,641
		Medium Efficiency HP + Envelope	1%	1M	1.9	7	$21K	$9K	$3K	$17K	4,641
		High Efficiency HP + Envelope	1%	1M	1.8	6	$21K	$9K	$3K	$18K	4,641
Fuel Oil, Natural Gas, Propane	Has ducts	Min. Efficiency HP	3%	4M	4.3	15	$13K	$5K	$12K	$1K	18,075
		Medium Efficiency HP	3%	4M	4.2	15	$16K	$4K	$12K	$4K	18,075
		High Efficiency HP	3%	4M	4.1	14	$24K	$4K	$12K	$12K	18,075
		Min. Efficiency HP + Envelope	3%	4M	3.0	10	$20K	$9K	$12K	$8K	18,075
		Medium Efficiency HP + Envelope	3%	4M	3.0	10	$23K	$9K	$12K	$11K	18,075
		High Efficiency HP + Envelope	3%	4M	2.9	10	$31K	$9K	$12K	$20K	18,075
	No ducts	Min. Efficiency HP	1%	1M	4.0	14	$18K	$7K	$5K	$13K	3,139
		Medium Efficiency HP	1%	1M	4.0	14	$19K	$8K	$5K	$13K	3,139
		High Efficiency HP	1%	1M	3.6	13	$19K	$8K	$5K	$13K	3,139
		Min. Efficiency HP + Envelope	1%	1M	2.3	8	$24K	$9K	$5K	$19K	3,139
		Medium Efficiency HP + Envelope	1%	1M	2.3	8	$24K	$10K	$5K	$19K	3,139
		High Efficiency HP + Envelope	1%	1M	2.1	7	$25K	$9K	$5K	$19K	3,139