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The Economic and Emissions Reduction Potential of Air Source Heat Pumps as a Replacement for Natural Gas and Electric Resistance Space Heating in the Contiguous United States

Joshua Schraer
Western Washington University, happygozar@gmail.com

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By

Josh Schraer

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of the Requirements for the Degree
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ADVISORY COMMITTEE

Dr. Imran Sheikh, Chair

Dr. Froylan Sifuentes

Dr. Charles Barnhart

GRADUATE SCHOOL

Dr. David Patrick, Dean

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Joshua Schraer

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Abstract

It is widely believed that to reduce CO_2 emissions the best strategy is to electrify everything, decarbonize the grid, and improve energy efficiency. This research looks specifically at the use of air source heat pumps (AHP) as a tool to reduce the CO_2 emissions of heating energy in the residential sector. The landscape of residential energy use is complicated by a broad range of factors. We compare AHP, natural gas (NG), and electric resistance (ER) heating using data from energy prices, temperature, appliance efficiency, building efficiency and marginal emissions data from 2019 as well as modeled data of what emissions the future grid might produce. With this data we answer the question of what effect AHP units can have on mitigating carbon emissions associated with heating in the residential sector. Using modeled emissions data results show that 37.7% of homes that are currently using NG or ER heating could reduce their emissions by installing a heat pump while realizing an economic saving, another 61.8% could reduce emissions with an added cost. In total 99.7% of BTU's used for heating in the United States could be delivered with lower emissions using air source heat pumps in place of electric resistance and natural gas. Houses that used other forms of heating or no heating at all were not included in this study. Using data from 2019, in total, 129 million metric tons (Mt) could be mitigated with a net savings of $10 billion at an average savings of $72.74 per tonne. Results show that the mitigation potential for replacing NG heating with AHP is greatly expanded as the grid becomes less carbon-intensive over time while the cost to do so is greatly reduced.

Acknowledgements

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List of Acronyms

ACH - Air Changes per Hour

AFUE - Annual Fuel Utilization Efficiency

AHP - Air-source Heat Pump

BA - Balancing Authority

COP - Coefficient of Performance

EIA – Energy Information Administration

GHG - Greenhouse Gas

HDH - Heating Degree Hours

LRMER – Long Run Marginal Emissions Rate

MACC - Marginal Abatement Cost Curve

MEF - Marginal Emissions Factor

NEEP Northeast Energy Efficiency Partnership

NREL - National Renewable Energy Laboratory

NRSDB - National Solar Radiation Database

USCB - United States Census Bureau

Introduction

No strategy that seeks to reduce the future effects of global warming from greenhouse gas (GHG) emissions can ignore the building sector. The building sector accounts for 37% of all global CO_2 emissions. Space heating in homes represents 30.7% of total residential sector demand. 56 million U.S. homes, 68%, use some form of NG appliance as their primary heat source (Wilson et al., 2017). A primary approach in much of the deep decarbonization literature is to “electrify everything” (Jacobson et al., 2017; Williams et al., 2012). With such a substantial portion of energy consumption coming from NG use in homes, a strategy to reduce carbon emissions by replacing existing NG heating with AHPs holds great promise. Although transitioning to all-electric heating will reduce or end onsite emissions from combustion, it is not always a cleaner option. Where electricity generation relies heavily on carbon intensive assets, like coal combustion power plants, previous work has shown that in some cases switching away from fossil fuel end use to electric can increase emissions (Vaishnav & Fatimah, 2020). Fully understanding the change in emissions potential of any decarbonization strategy involving electrification requires understanding the temporal and geographic effects of offsite generation that supplies the electricity.

Heat pumps are not new technology. They have existed in air conditioners and refrigerators for decades (Zogg, 2008). AHP technology does not use energy to generate heat, instead, it uses electricity to move thermal energy from one place to another using a refrigerant as the medium of exchange. Heat pumps have a coefficient of performance (COP), which is the ratio of heat energy transferred to energy input. Heat pumps can operate at efficiencies well above 100%, moving multiple units of energy for every unit consumed. Although the performance of a heat pump is effected by its design, the refrigerant used and other factors unique to the unit, COP is primarily a function of the difference between the exterior and interior air temperatures. The efficiency is limited by the Carnot equation and as the difference between the exterior air and interior air shrinks the COP increases leading to higher efficiencies in milder climates. As the temperature difference grows, the COP of any heat pump decreases leading to less efficient heating. Modern condensing gas furnaces can achieve a rating of over 95% annual fuel utilization efficiency (AFUE), meaning that 95% of the energy inherent in the NG fuel is used to provide heat for the home and 5% escapes mostly through exhaust . Even with a NG turbine running at an efficiency of 33% to generate electricity, a heat pump with a COP of 3 can make the full system efficiency greater than what any NG furnace can achieve. Thus, using less natural gas to produce the same effect of heating one’s home.

Reducing CO_2 emissions from residential heating requires identifying the locations where electrification of heating demand can have a significant impact on emissions. In some locations electrification of heating may also provide an economic benefit. The United States of America is a geographically vast and climatically diverse country. Temperatures and weather patterns vary from one location to another substantially. The pricing of energy varies greatly by geography as well. An estimated 1,510 residential electricity providers sell electricity at rates that range from $0.22/kWh in Massachusetts to $0.097/kWh in Arkansas. NG prices vary from $6.4 per thousand cubic feet in New Mexico to $21.66 in Florida (EIA, 2019). These prices reflect state averages as of 2019 and not individual utility rates which can be higher or lower within the same state. The CO_2 emissions from electricity generated and then transmitted through the grid vary by location, season, and time of day. Balancing Authorities (BA) are tasked with ensuring that the supply and demand of electricity are finely balanced within their designated geographic area. The grid allows the electricity consumed in one location to come from a generation source far away in a different BA. While the interchange of electricity across BAs serves many valuable purposes it makes assigning a discrete carbon intensity value for each challenging as electricity is a fungible resource. Research has shown that in some BAs 40% of the carbon emissions from the electricity used are produced in a different region (de Chalendar et al., 2019). Providing greater resolution in carbon accounting, both geographically and temporally, will be of great use during the process of de-carbonization. In this research we use Wattime and Cambium emissions data to calculate the amount of CO_2 released from generating the electricity to power the AHPs used to replace other heating methods. How this data is generated and why it was chosen is covered in the methodology section.

Transitioning to an energy landscape where all NG residential heating demand is met by AHP technology will have significant consequences for electricity demand and carbon emissions. A total of 56 million homes use piped gas as their primary heating source (United States Census Bureau, 2019a). The transition from NG heating to electric heating in these households will inevitably increase electricity demand. More importantly, in locations where electricity demand peaks in the winter it will complicate and strain the existing grid by increasing peak demand, in some cases by more than the grid can transmit (Waite & Modi, 2020). Other research has drawn attention to the reality that increasing electricity demand will increase the need for new generation sources at the margin.(Hawkes, 2014) Often peak demand has been supplied by the deployment of inefficient and expensive NG turbines or electricity imports from distant producers contributing disproportionately to marginal emission factors (MEF) (Callaway et al., 2018; Graff Zivin et al., 2014; Hawkes, 2014; Siler-Evans et al., 2012). Previous research has predicted GHG emissions in the future for limited geographic regions using diverse grid models and equipment types. Predictions from these studies forecast everything from increased electricity demand having a negligible effect on the grid due to increased renewable deployment to a future need for inefficient gas peaker plant deployment (Calderón et al., 2019; Tarroja et al., 2018). Waite and Modi (2020) examine the load implications of an "all-electric" approach to space heating and find that transmission capacity would have to increase by 70% nationally to achieve a complete transition away from onsite fossil fuel heating.

Previous research has used The National Renewable Energy Laboratory's (NREL) ResStock analysis tool to simulate and analyze the effect of AHP deployment (Deetjen et al., 2021; Pistochini et al., 2022). These studies capture the heterogeneity of regional housing archetypes across the nation, but the computational resources needed to do simulations limit the number of areas that can be analyzed. Deetjen et al (2021), model 400 representative houses in 55 U.S. cities to conclude that 70% of homes could reduce emissions by installing a heat pump while 32% of homes would benefit economically. Pistochini et al. (2022) use two different house models to run simulations in 99 U.S. locations to conclude the CO_2 reduction potential of a heat pump over a furnace at 38-53%. In Goldstein et al. (2020) a database of tax assessor data for 93 million households was used to evaluate the carbon footprint of the U.S. residential housing stock, but it does not focus on AHP deployment. Although these studies stretch across the United States, they fail to examine emission reduction potential for non-urban areas and a direct relationship between AHP deployment and the cost of saved carbon in all areas of the U.S. is also not established.

In this research, we use the most comprehensive temperature data available to examine the effects of heat pump deployment for most existing homes. All electric resistance and forced air natural gas homes, representing 85.7 million out of 125 million total housing units in the EIA's 2015 estimates. Where previous studies run at most 400 simulations in densely populated urban areas and extrapolate the results, this research runs 522 thousand separate simulations for all $4km^2$ x $4km^2$ geographic "blocks" that make up the United States. These individual simulations represent a single home which is then extrapolated to represent the number of homes in each block. The CO_2 mitigation potential and financial ramifications of AHP deployment are evaluated and the cost savings or added expenses are determined and measured in dollars per tonne of CO_2. Also included is an examination of what emissions might look like under a future scenario that considers a future grid that produces less CO_2 than the current one. This represents the most geographically granular view of the effects of AHP deployment for the present day and over the lifetime of the installed AHP unit.

Methodology

Electricity Generation and Emissions

Previous studies have drawn attention to the reality that monthly or yearly estimates of emissions have significant shortcomings and why hourly accounting of emissions from grid power generation based on location is often superior with regards to accuracy (Graff Zivin et al., 2014; Miller et al., 2022). Modeling CO_2 emissions of a system as complicated as the grid is far beyond the scope of this paper. For this study, we use data provided by Wattime (WattTime, 2023). Wattime uses an empirical model based on hourly emissions data for every fossil fuel power plant in the U.S. The current model used to generate data leverages historic continuous emissions monitoring data for power plants from the EPA as well as data from real-time APIs for grid conditions, interchange, and weather (Cofield et al., 2022). For this study 2019 data was aggregated to 1-hour resolution before being used in calculations. Marginal emissions values are reported in pounds per megawatt-hour. Where any of the 522,318 weather data points used in this analysis did not fall within a Wattime geographic region (mainly on the coasts) they were assigned to the region that had the closest boundary.

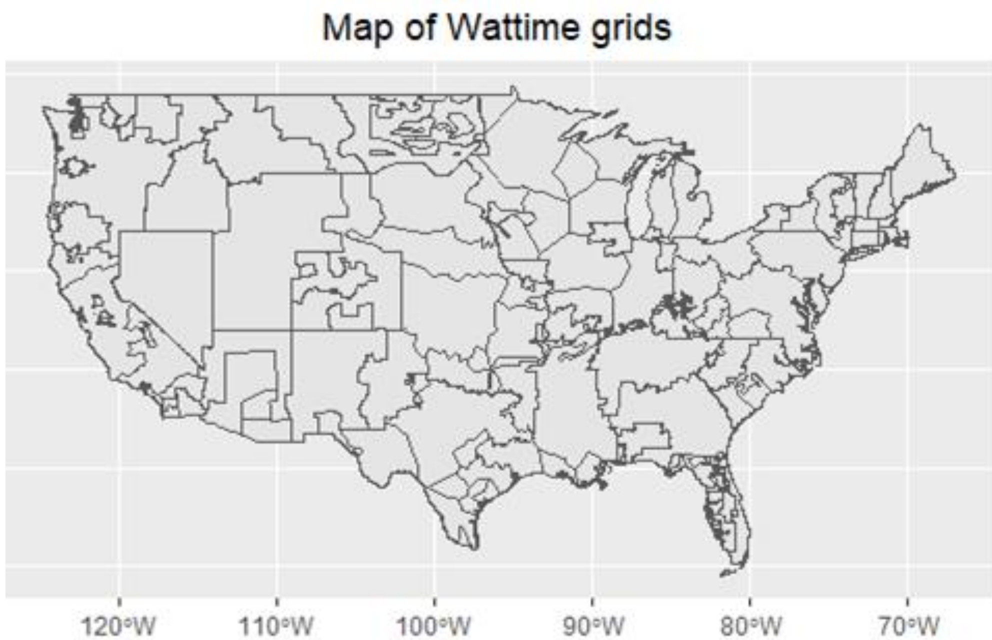

Figure 1:Map of Wattime Balancing Authorities.

While the data from Wattime shows a snapshot of present-day marginal emissions and the potential impact from replacing NG and electric resistance heating with AHP units presently it does not provide insight into the future effect. Wattime provides short-run marginal emissions data which makes projections of emissions based on today's grid resources. To account for potential changes in the mix of resources on the grid in the future as a result of planned generation resource additions, renewable portfolio standards, changing economics of renewables, etc. we use Cambium data from NREL (Gagnon et al., 2022). Cambium uses multiple resources to create hourly simulated data sets estimating long-run marginal emissions rates

(LRMER). Cambium simulated LRMER data uses projected changes to the electric grid and the influence of incremental changes to electricity demand on the structure of the grid to create estimates for emissions rates in the United States under different scenarios. Of the five scenarios modeled we use the mid-case scenario that assumes moderate technology cost reductions, mid-level default assumptions for demand growth, system cost, and fuel prices. The data we use has been levelized which involves taking an average across a range of years but with a greater weight on near-term years. Using data from Cambium provides a longer-term projection of the impact of costs and emissions from adopting AHP units in the residential sector.

Heat Pump Model

The COP of heat pumps depends on the temperatures and heat transfer conditions at the heat source, the heat sink, the refrigerant and design of the unit. In general, one of several refrigerants is used in a closed loop with a compressor, condenser, expansion valve and evaporator. As the refrigerant moves into the environment to be heated it is compressed and the temperature of the gas rises well above the desired indoor temperature. As it enters the condenser inside of the building the hot gas refrigerant condenses into a fluid giving off heat to the cooler inside air. When the refrigerant leaves the building, it passes through an expansion valve into the lower pressure environment of the evaporator. Refrigerants used in AHP units have boiling points lower than outside air temperatures allowing them to boil in the evaporator absorbing heat as it changes state into a gas. From the evaporator it enters the compressor, and the cycle begins again. The theoretical maximum COP for an ideal Carnot cycle can be found with the following equation.

$$COP_{AHP} = \frac{T_H}{T_H - T_C}$$

T_H = Setpoint temperature

T_C = Outdoor air temperature

Where T_H is the inside temperature and T_C is the outdoor air temperature, both temperatures are in Kelvin or Rankine. In reality, heat pumps operate at a much lower COP than the theoretical limit due to unavoidable inefficiencies. Technological improvements in refrigerants, improved compressors, variable speed fan motors and improved insulation for internal components have made modern heat pumps more efficient than their predecessors current technologies still govern efficiency. A more realistic equation for real-life operation would be:

$$COP_{AHP} = \frac{T_H}{T_H - T_C} \times C_p$$

Where C_p is a coefficient unique to each heat pump, based on its design and the refrigerant used. For our research, we used a large database of available AHP models provided by the Northeast Energy Efficiency Partnership (NEEP) (*Northeast Energy Efficiency Partnership*, 2022). Manufacturers are required to provide COP ratings for their products at 47° F and 17° F. First the NEEP data was filtered for values that were regarded as unrealistic (e.g., COP values greater than ten and less than one). We then selected from this revised list several representative AHP models with median COP at 47° F values from the data set. Next, we used a formula to minimize the difference between C_p at 47° F and 17° F for each of the selected median COP models by changing the value T_H. This process gave us the value for C_p and the high temperature (T_H) of the refrigerant used in the selected AHP models. We then selected the model with the least difference between the two coefficients to use for our values, giving a functional equation that produces a COP value to be used in the analysis. The representative model used is the Dave Lennox signature XP25 series 3-ton heat pump giving us the following values for our equation.

$$COP = \frac{128.9°F}{128.9°F - T_C} \times .566$$

T_C = ambient outdoor air temperature

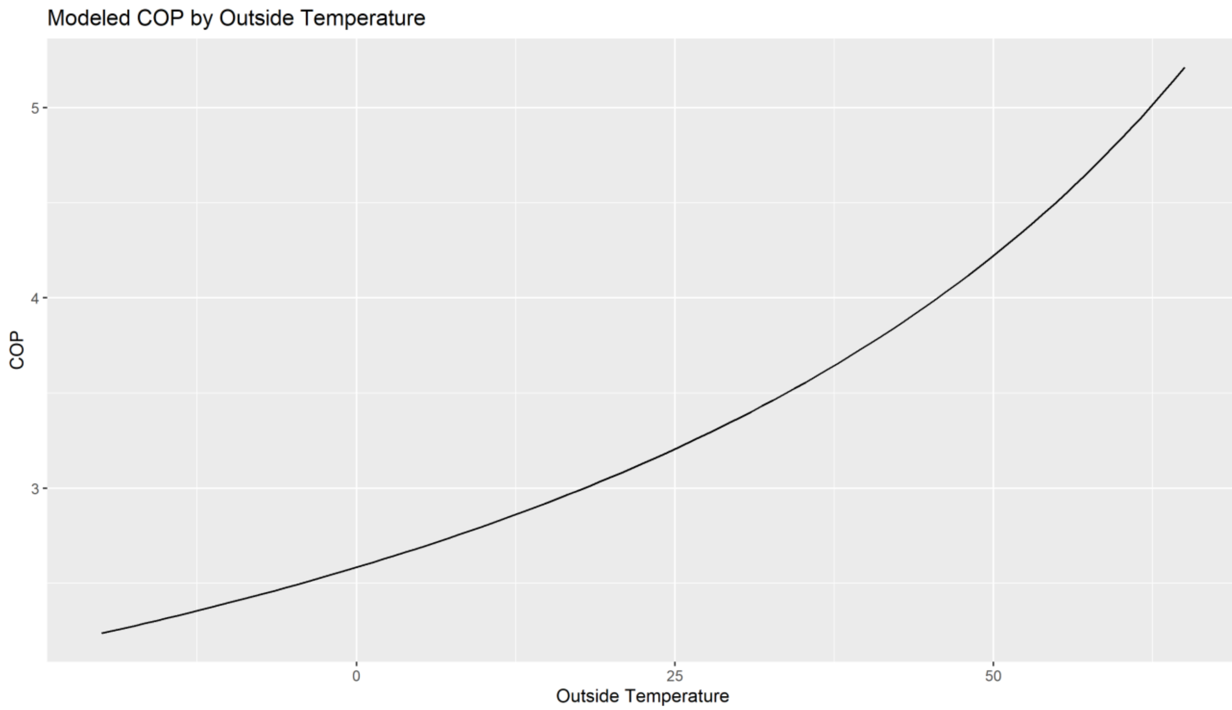

Figure 2: COP curve for Lennox AHP unit. Temperature in fahrenheit.

Weather Data

To determine the ambient outdoor temperature we used data from NREL's National Solar Radiation Database (NSRDB) (Sengupta et al., 2022). NSRDB's data is modeled with observations from geostationary satellites and meteorological data from weather stations. Although this data is typically used to estimate production for solar panel installations it includes temperature data at half-hourly time steps. Historical data is available going back more than 25 years. In order to match the emissions data, 2019 temperature data was used. To match the marginal emissions data the temperature data was aggregated to an hourly mean temperature from half hourly recorded temperature values. NSRDB's data covers the entirety of the United States with a geographic resolution of $4km^2$. As the grids in both Alaska and Hawaii are stand alone and significantly different than those in the contiguous United States, both states have been omitted from this study. A total of 522,318 points are included in this data set. A metadata set is used to index these sites to latitude and longitude points and includes a population figure for each site. The population provided in the metadata set was not in agreement with 2019 U.S. population estimates so each of the 522,318 points were multiplied by a scaling factor so that state populations in the metadata set matched state population data from the United States Census Bureau (USCB) (United States Census Bureau, 2019b). Only 5 states in the NREL metadata set had populations in excess of 2019 USCB estimates with none of those five showing populations that were larger than USCB reported populations by more than 3%. 27 states had population estimates less than 5% below USCB estimates, 8 states had population estimates more than 10% below USCB estimates with the greatest divergence being WA. with 15%. The resulting population data is divided by 2.6, an estimate of average residents per home from the USCB, and the resulting number of homes was used to multiply the emissions and cost data for each point as an estimate for total emissions and cost for all the households in each point.

Building Model

To calculate the amount of heat that escapes through the exterior components of the building we start with the thermal resistance value of its components. Resistance values can be added in series so that the total R-value of a component that has multiple layers is the sum of all its layers' individual R-values. Thermal transmittance, or U, is the inverse of this R sum calculated individually for all the separate envelope components of a building. UA is the U value for any given component multiplied by the area of that component. For example, the UA value of a floor would be the U value of the floor multiplied by the square footage of the floor. The heating degree hours (HDH) is found by subtracting the outside ambient temperature from an assumed balance point temperature of 65° F. In the cases where the ambient temperature is above 65° and $\boldsymbol{\Delta}$°F is negative, HDH is set to zero as no heating is required.

The basic equation is listed below.

$$Q = \sum UA_{total} \times HDH$$

Q = energy loss in BTUs

U = $\frac{1}{R}$ for each component in units $\frac{BTU}{(hr \cdot \text{ftx}^2 \cdot F^{\circ})}$

A = area of each component in ft^2

UA_{total} = $\sum UA_{components}$ e.g. UA_{floor}+UA_{wall} …etc

HDH = $\Delta°F \times 1\ hour$

Although the ResStock data includes values for infiltration that are later used to calculate the heat lost through the unintended loss of heated air through the envelope, there is no single source of specific or averaged UA values for the existing housing stock, multiple avenues for deriving area-based averages were explored. The first attempt at deriving UA values for U.S. residential building stock comes from a database of 27,000 simulations previously run by ResStock from across the nation. The models in these simulations are tailored to reflect the building method and form of housing units from the geographic areas in which the simulations are run. The individual components and characteristics of ResStock's building models are assigned to each model based on a hierarchy of archetypes. For example, the first archetype is location which dictates the proportion of houses that are assigned a certain vintage. Vintage and location then dictate the proportion of houses that are assigned a heating fuel type and so on. In total there are 6,000 conditional probability distributions derived from a dozen data sources used to assign characteristics to the models in proportions representative of a given location's building stock. Table One is a breakdown of archetypes and dependencies ResStock uses.

	Characteristics	Dependencies: *Location*	*Vintage*	*Heating Fuel*	*Usage Level*	*Daytime Use*	*Floor Area*	*Number of Stories*	*Found. Type*	Data Sources: 2009 RECS (EIA 2012)[10]	NAHB[11 12 13 14]	IECC 2009[15]	RBSA (NEEA 2012)[16]	Ritschard et al. 1992[17]	American Community Survey[18]	Labs et al. 1988[19]	Chan et al. 2012[20]	Wenzel et al. 1997[21]	Lucas and Cole 2009[22]	Eng. Exp. & Calibration	Geographic Resolution	# of Options
Meta	*Location*																				TMY	216
	Vintage	✓													•						C	7
	Heating fuel	✓	✓							•											C	6
	Usage level																			•	U.S.	3
	Daytime use																				U.S.	2
Geometry	*Floor area*	✓	✓							•											R	6
	Number of stories	✓	✓				✓		✓	•											R	3
	Foundation type	✓									•					•					48	5
	Attached garage	✓	✓				✓			•											R	2
	Orientation																				U.S.	4
Envelope	Window type	✓	✓							•		•								•	R	5
	Wall insulation	✓	✓								•			•							R	8
	Attic insulation	✓	✓								•		•								R	7
	Foundation insulation	✓	✓								•									•	R	5
	Air leakage	✓	✓				✓	✓	✓								•			•	R	12
Equipment	Heating system type	✓	✓	✓						•	•										R	6
	Heating system efficiency	✓	✓								•							•		•	R	10
	Cooling system type	✓	✓							•											R	7
	Cooling system efficiency	✓	✓								•							•		•	R	7
	Duct insulation, tightness	✓	✓						✓			•							•	•	U.S.	5
	DHW system type	✓	✓	✓						•											R	5
	DHW system efficiency																	•		•	U.S.	3
	Cooking type	✓	✓	✓						•											R	10
	Clothes dryer type	✓	✓	✓						•											R	10
Occupancy	Heating, cooling set	✓				✓				•											TMY	3
	Cooking usage				✓	✓														•	U.S.	3
	Clothes dryer usage				✓	✓														•	U.S.	3
	Lighting, appliances,				✓	✓				•										•	U.S.	3

Figure 3: ResStock hierarchy of dependencies.
From (Wilson et al., 2017)

As the data provided by ResStock includes only character descriptions of relevant exterior components (e.g. double pane window with air gap) R values were assigned from existing measurements and assumptions found elsewhere. Where possible all building components, wall, ceiling, fenestration and roof R-values were taken from values available in the 2018 ASHRAE handbook (ASHRAE, 2018). For wood stud framing a framing factor of 0.20 was assumed for walls, accounting for typical wall framing practices and the extra thermal bridging from king studs, cripples and headers found around doors and windows. For floors, ceilings, and cathedral ceilings a framing factor of 0.094 was used assuming a standard framing practice of 16-inch centers between members. Although more modern advanced framing standards use 2 ft. centers and this spacing is becoming more common, most buildings in the ResStock data set are older, therefore traditional framing methods are assumed. Nominal stud size and depth used in calculations are consistent with standard framing practices with regard to the depth needed to accommodate cavity-fill fiberglass batt insulation at R-values specified by the ResStock data set.

In the case of slab on grade foundations, we use an equivalent to U called F-factor. As most of the heat lost from a slab foundation is lost through the perimeter of an unheated slab travels through a modest amount of dirt and then into the air, insulation is typically only applied vertically on the exterior of the footing and sometimes horizontally underneath the first 2 feet of the slab. Due to the minimal amount of heat loss through the floor of the slab, and the need-to-know soil temperature to quantify floor heat loss, only the perimeter heat loss is accounted for in this study. Radiant floor heating slabs are a relatively new practice in buildings and were not accounted for in the ResStock data set, so they are not represented in this method of calculating UA. For all slab insulation types specified in the data a corresponding F-factor was taken from ASHRAE (ASHRAE, 2018). No value for perimeter was given in the data set so a perimeter measurement was derived by dividing the total surface area of the heated exterior walls by the number of stories and then dividing the resulting number by eight feet, the standard height of a residential wall. The equation for heat lost through a slab is included below.

$$q = F_2 \times P_b \times (T_i - T_o)$$

q = rate of heat loss in $\frac{BTUs}{hour}$

F_2 = F-factor

P_b = Perimeter of slab foundation

T_i = Temperature indoors

T_o = Temperature outdoors

Although much has been written about calculating heat loss through basement walls and it is still a topic of debate the calculation methods for slab on grade floors and basement walls are those used by Big Ladder Software (Big Ladder Software, 2014) as they are comparatively simple and do not require ground temperature data, which is impractical for a study of this geographic size. To arrive at an R value of the soil for the entire subterranean basement, soil R values by depth in feet were taken from (ASHRAE, 2018). The total UA of the basement wall is the sum of each value multiplied by the perimeter of the building. For example, a basement with a depth of six feet would have six different UA values, one for each foot below grade. These six separate values are then summed to arrive at a total UA value for the basement.

$$\sum_{i=1}^{n} U_i \times P = U_1 \times P + U_2 \times P + \ldots + U_n \times P$$

i = increment of depth in feet

n = total basement depth in feet

P = Perimeter of building

Infiltration is the unintentional introduction of outside air into a building through cracks and air gaps in the building envelope and the use of doors generally measured in air changes per hour (ACH), a measure of how many times in an hour it takes for the heated interior volume of the building to escape through the envelope and be replaced by exterior air. In practice, this number is determined through a blower door test during which a calibrated fan is installed in an otherwise sealed window or door. When the fan is turned on a pressure difference is created between the outside and inside of the building and the fan speed is adjusted to maintain a pressure of negative 50 Pascals inside. As the fan is calibrated the volume of air traveling through it at any given speed is known and recorded as CFM50. CFM50 is used with the known volume of the house to arrive at the air changes per hour at 50 pascals (ACH50). A rule of thumb used in the industry is to divide ACH50 by 20 to arrive at a measure for steady state pressure air exchange. This actual number varies greatly for different buildings largely due to local meteorological conditions (Ji et al., 2022) however, it is the method most widely used in the industry and the method used in this study. The volume of the interior heated space is found by multiplying the conditioned floor area by the standard residential wall height of 8 feet with the full heat loss due to infiltration equation listed below.

$$q_{inf} = 0.018\frac{BTU}{ft^3} \times n \times V \times (T_i - T_o)$$

n = ACH value

V = Volume of building

T_i = Temperature indoors

T_o = Temperature outdoors

The model data includes an assignment to one of the seven climate zones identified by the Office of Energy Efficiency & Renewable Energy (EERC) Building America program (U.S. Department of Energy, 2010). A map of these climate zones is provided in figure 4. Using the model database, a mean UA value for each of the seven different climate zones was calculated and used in conjunction with hourly temperature data to estimate the heat loss in our calculations.

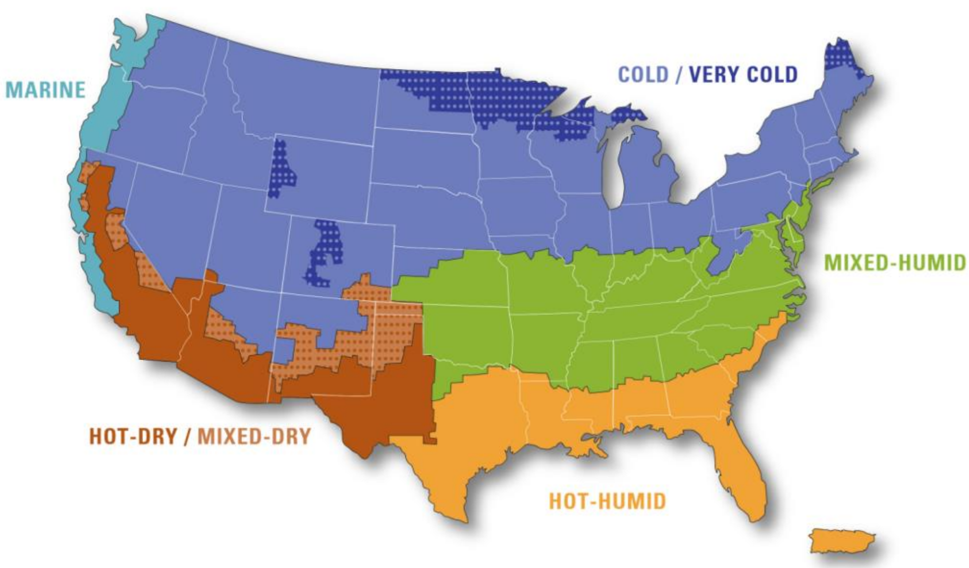

Figure 4: Buiding America Best Practices map of climate zones. From (Wilson et al)

When calculations for heat loss were run using the derived average UA values using this method results were compared to EIA 2015 average home heating energy estimates (U.S. Energy Information Administration, 2015) and it was concluded that the UA values were excessively high as the heating energy use totals for just the homes using NG heating were higher than the total energy use for homes in some of the climate regions.

Climate Zone	Mean UA
Cold	830
Hot-Dry	629
Hot-Humid	689
Mixed Dry	747
Mixed Humid	796
Very Cold	797
Marine	745

Table 1: Mean UA values derived from ResStock data set.

Individual component contributions to total UA were examined to make sure no one component was responsible for the excessively large values. Although some components did contribute disproportionately, even removing individual components entirely did not produce results that were reasonable. For example, basements contributed disproportionately to the overall UA but when averages were taken without basements included at all the resulting UA values still produce unreasonable results. Why this method produced such high UA values is unknown. As there are no actual UA values in the ResStock data set it could be hypothesized that the recorded building component descriptions provided do not agree with values taken from other sources. As descriptions of construction type provided by ResStock were very limited many assumptions about framing, floor and roof construction had to be made which undoubtably contributes to error. ResStock runs individual simulations that are far more complicated than the method used in this study. The process by which the EnergyPlus code calculates values might be significantly different than the method used here.

The next method explored for deriving UA values was to reverse engineer them from energy use data. ResStocks model simulation data includes data for energy use for heating as well as efficiency of the primary heat source. Knowing the end use energy for heating and the average heating degree days in different geographic areas we can solve for UA in the heat loss equation. By looping through the NSRDB data, with the previously described calculation provided, we find an HDH value for each point in the data set. This value was then multiplied by the number of residential structures at each point. Creating a total HDH value representing all the HDHs serviced for each point. These values were then summed up by BAC climate zone and divided by the total number of residential structures in each zone to arrive at an average home HDH value for each zone. Residential end-use heating data was multiplied by the efficiency of the primary heating equipment for each model to produce a heat demand value and an average heat demand value could then be calculated for each of the seven climate zones. When calculations were run using the below, much lower UA values, they did not match the EIA's average energy use data but did produce much more sensible heating energy use values.

$$HHDH_{total} = HDH_{point} \times Houses$$

$$HDH_{BACmean} = \frac{\sum HHDH_{BACtotal}}{\sum Houses_{BAC}}$$

$$q_{delivered=} q_{total} \times E_{primary}$$

$$q_{BACmean} = \overline{q}_{BACdelivered}$$

$$UA_{BACmean} = \frac{q_{BACmean}}{HDH_{BACmean}}$$

BAC Climate Zone	Mean UA Value
Cold	352
Hot-Dry	192
Hot-humid	340
Marine	209
Mixed-Dry	394
Mixed-Humid	457
Very Cold	316

Table 2: Average UA values derived from ResStock data.

Although the values produced from this data set are closer to those reported by the EIA there were still some significant discrepancies and the range of UA values across the climate regions were still significantly larger than anticipated producing energy use values higher than the values reported by EIA. It seems counterintuitive to see higher UA values in colder climates as one would expect more insulation and higher R values for all components. This discrepancy can partially, if not completely, explained by the fact that colder climate homes are generally larger than warmer climate homes (Debs & Metzinger, 2022).

The last avenue explored for deriving mean UA values was to directly use the 2015 EIA estimates for average home heating energy use and the number of homes in each of the census districts and the above methods for calculating a mean UA for each census district. Census district level was used as the data for home appliances is more complete than BAC climate zone data. TMY data downloaded from the NSRDB showed obvious flaws and the new TMY data sets are no longer accessible through the API. Although imperfect, 2019 real temperature data from NREL was used to calculate this last set of UA values and these are the values used in the final calculations.

Census District	Mean UA Value
West South Central	323
Mountain	231
Pacific	216
West North Central	276
East North Central	345

East South Central	278
South Atlantic	349
Middle Atlantic	355
New England	360

Table 3: Average UA by census region.

With all the relevant data in place the code was written to calculate several values for each of the 8760 hours in 2019 at each of the 522,318 weather data points that make up the contiguous United States.

$$HDH = 65°\mathrm{F} - T_{hourly}$$

When the hourly temperature is over 65 °F an HDH value of zero is substituted representing no heating demand.

$$COP = \frac{128.9°R + 459.67°R}{128.9°R - T_{hourly}} \times C_p$$

$$BTU_{demand} = UA_{census} \times HDH$$

$$kWh_{AHP-demand} = \frac{(BTU_{demand} \times \frac{1\ kWh}{3412\ BTU})}{COP}$$

$$kWh_{res-demand} = (BTU_{demand} \times \frac{1\ kWh}{3412\ BTU})$$

$$G_{cf} = BTU_{demand} \times \frac{1\ cubic\ foot\ gas}{1050\ BTU} \times \frac{1}{Efficiency_{furnace}}$$

$$Cost_{gas} = G_{cf} \times \frac{State\ Gas\ Price_{1000\ cf}}{1000\ cf}$$

$$Cost_{AHP-kWh} = kWh_{AHP-demand} \times \frac{\$\ cost}{kWh}$$

$$Cost_{res-kWh} = kWh_{res-demand} \times \frac{\$\ cost}{kWh}$$

$$lbs\ CO_{2_{gas}} = G_{cf} \times \frac{.12096\ lbs\ CO_2}{cubic\ foot\ gas}$$

$$lbs\ CO_{2_{AHP}} = MER \times kWh_{AHP-demand}$$

$$lbs\ CO_{2_{res}} = MER \times kWh_{res-demand}$$

For hours when: $lbs\ CO_{2_{AHP}} < lbs\ CO_{2_{gas}}$ and $Cost_{AHP-kWh} < Cost_{gas}$

$BTU_{cheaper-cleaner} = BTU_{demand}$

$lbs_{cheap-clean} = lbs\ CO_{2_{gas}} - lbs\ CO_{2_{AHP}}$

$Cost_{cheap-clean} = Cost_{AHP-kWh} - Cost_{gas}$

For hours when: $lbs\ CO_{2_{AHP}}$ < $lbs\ CO_{2_{gas}}$ and $Cost_{AHP-kWh}$ > $Cost_{gas}$

$lbs_{expesive\text{-}clean}$ = $lbs\ CO_{2_{gas}}$- $lbs\ CO_{2_{AHP}}$

$Cost_{expensive\text{-}clean}$ = $Cost_{AHP-kWh}$ - $Cost_{gas}$

C_p: Unitless coefficient used to adjust theoretical Carnot Equation with a value of .566.

G_{cf}: Cubic feet of NG needed to supply heat in a given hour.

$Efficiency_{furnace}$: Lowest forced air NG furnace efficiency allowed through the Energy Star program, a value of 90%

MER: Marginal Emissions Rate provided by Wattime™ in lbs. CO_2 per kWh

The value for lbs. CO_2 per ft^2 is taken from EIA (U.S. Energy Information Administration, 2022b) with no assumed value for leakage at the homesite.

State natural gas prices taken from EIA (U.S. Energy Information Administration, 2022).

A table of the above values was made for each point. The values for each of the 8760 hours of 2019 are summed to provide yearly values. As the calculations above represent all the individual residential units across the entire Contiguous United States, and not every house has a NG forced air furnace or electric resistance heater, the values were adjusted by multiplying them by the fraction of homes that do have those primary heating systems. EIAs housing RECS (U.S. Energy Information Administration, 2015) space heating data was used to adjust the data at the census district level. This method assumes a homogeneous single family housing stock at each location with the proportion of appliances provided by EIA evenly distributed across them. The real distribution might vary by housing type greatly. The resulting data is used to provide estimates for cost and CO_2 emissions reductions that can be achieved by replacing existing furnaces and resistance heaters with AHP technology.

Census Region	Total Homes with Heating	Homes with NG Heating	Homes with ER Heating
New England	5.6	1.2	1.4
Middle Atlantic	15.4	5.6	1.7
East North Central	18.1	11.9	3
West North Central	8.3	5.5	1.5
South Atlantic	21.6	5.2	7.5
East South Central	7.2	1.5	2.8
West South Central	13.3	4.7	6.2
Mountain	8.4	4.6	1.6
Pacific	15.3	7	4.4

Table 4: Census Region and Heat Source (millions of homes).

Marginal Abatement Cost Curves

One of the tools used to present the findings of this analysis is Marginal Abatement Cost Curves (MACCs). MACCs are widely used tools to visually present the associated cost and savings, per unit of GHG, of implementing a technology that has the potential to reduce emissions and compare them to the base case of business-as-usual. Typically presented as a cost function, plotting the cost per unit of implementing any number of measures and presented here in the form of dollars per tonne. In studies of CO_2 abatement, it has been found that significant reductions can be attained with negative costs (Almihoub et al., 2013) showing that there is room to reduce emissions while increasing the profitability of companies, or in the case of this research, deliver net savings to the occupant.

Literature provides insight into many methods of constructing MACC and their potential limitations(Almihoub et al., 2013; Ibrahim & Kennedy, 2016; Kesicki & Ekins, 2012). As with any tool used to estimate the effect of future scenarios, MACCs are only as good as the data that is used in their generation. Although MACC can include scope 3 emissions (indirect emissions that happen in a given value chain) attempting to quantify CO_2 emissions from manufacturing processes, transportation, etc. this research focuses solely on scope one and two emissions (direct emissions and emissions from bought utility services). Considered in this research are the annualized capital cost of replacing both electric resistance heaters and NG furnaces with AHP units. A 3%

discount rate based on inflation is assumed, installed costs and lifetime in years is based on EIA literature (U.S. Energy Information Administration, 2018). Adjustments were made as the EIA literature was based on 2015 prices. Modern unit prices were sourced from online retailer Home Depot and an assumed billable rate of $80/hr and ten hours of work for installation. In reality these prices vary significantly by location, season and year. No accounting for AHP incentives in the recent Inflation Reduction Act were included. The basic equation for discerning the cost of CO_2 is as follows.

$$MAC = \frac{Cost_{project} - Cost_{base} + Cost_{annual}}{CO_2base\ - CO_2project}$$

MAC= Marginal Abatement Cost in $/tonne CO_2

$Cost_{project}$ = Cost of electricity for AHP in $

$Cost_{base}$ = Cost of NG used by furnace in $

CO_2base = CO_2 produced from NG combustion in metric tons

CO_2project = CO_2 produced from electricity generation

C_{annual} = Annualized installed cost difference (AHP – NG)

Heating Type	Installed Cost	Lifetime in years	Annual Maintenance	Amortized Annual Total	Annual Cost Difference
AHP	$5900	15	$100	$654.77	-----
NG	$5600	20	$100	$545.82	$108.95
ER	$4337	20	$40	$331.51	$323.26

Table 5: Annualized cost of heating systems.

Results

Looking first at the results using the Cambium data for, and the sequence of equations outlined in the methodology section for calculating emissions, we find that 3.7 million out of 51.7 million homes could reduce their emissions by 3 million tonnes annually with a savings of $117 million, an average savings of $39 per tonne, if they replaced NG with AHP. Another 48 million homes could reduce emissions by 55.8 million tonnes at a cost of $7.5 billion averaging to $134 per tonne. In total 99.7% of gas heating demand could be delivered with lower carbon emissions if AHPs were used instead. For electric resistance heaters, 99%+ of 34.1 million homes could reduce their carbon footprint with an economic benefit. In total switching from electric resistance heating to AHP units would reduce emissions by 61.4 million tonnes while saving 27 billion. Together this amounts to a total reduction in CO_2 emissions of 84.1 million tonnes and a savings of $28.7 billion. If we add the 11.8 million homes already using an AHP unit reported in to the sum of those that could save money 57.7% percent of all US homes using NG or ER for heating could save money, while reducing emissions, over the lifetime of their heating system is they replaced it today with an AHP. As the data from Cambium is levelized over the 15-year lifetime of the AHP unit, it represents a more accurate assessment of the mitigation potential of an AHP unit deployed today.

Using the Wattime emissions data, which gives us a look at mitigation potential as of 2019, we find that 3 million out of 51.7 million homes using NG furnaces in the United States could reduce their CO_2 emissions, while saving money, by switching from a NG-forced air furnace to an AHP unit. Another 38.8 million households could reduce emissions with an added cost. For electric resistance heating, 28.7 out of 34 million homes using resistance heating could achieve reduced emissions and an economic benefit from switching to an AHP unit. Of note is that all 34 million ER heated homes pay cheaper energy prices annually with AHP and AHP only becomes more expensive when annualized capital costs are included. In total this represents 36.9% of all 85.9 million U.S. homes using gas or electric heat. If we add to this the 11.8 million homes reported in the 2015 RECs as already using a heat pump, we have a total market share of 50.6% of homes that are having or could have a positive economic benefit from switching to AHP heating today.

In total 1.1 million tonnes of CO_2 could be saved annually with an economic benefit of $92.4 million or $84 average per tonne savings from switching NG heating to AHP. 17.4 million tonnes could be saved at an added cost of $5.4 billion or $310 per tonne average cost. While this seems high on the surface it should be noted, as is apparent in the MACC graphs that follow Figure 9 - Figure 12, that a smaller number of tonnes are disproportionately expensive and the price per tonne starts to grow exponentially towards the end of the dataset. With an assumed high-efficiency rating of 90% for NG furnaces, these numbers likely underestimate significantly the savings potential of AHP deployment. When looking at electric resistance heat replacement we find that 106.7 million tonnes CO_2 could be saved, with a net economic benefit of $17 billion at an average savings of $159 per tonne. Another 4.3 million tonnes could be saved at a cost of $791 million at an average cost of $184 per tonne.

These numbers exceed the more geographically constrained, but very similar work of Deetjen et al., (2021) who found that 16.7 million single family homes, or 21%, could benefit economically and in total 160 million tonnes CO_2 equivalent could be saved but with a net cost of 25.2 billion dollars. Although as previously mentioned, Deetjen et al., (2021) limits their study to 400 individual house models, excluding apartments and other forms of multifamily housing units while using a different method of modeling than used here. Included in the Deetjen et al., (2021) study is the cost of health damages which start to “skyrocket” in areas exposed to criteria air pollutants from power plants. Higher AHP adoption rates produce more criteria air pollutants in their model. Deetjen et al. (2021) monetize SO_2, NO_x, and fine particulate emissions ($PM_{2.5}$) according to methods developed by (Heo et al., 2016). No monetary number for health damage costs are included in this study, contributing to the discrepancy in results.

Of note is that both the Wattime and Cambium data results use 2019 energy prices and the actual costs and saving numbers will change as energy prices change. Table 7 compares the values from analysis of the Wattime data and Cambium data for the instance of moving from NG or resistance heating to AHP. Units for emissions are in millions of tonnes, dollar amounts are in millions. “Cheaper” and “expensive” refer to emissions reductions which either save the end user money or add cost.

Values	**Cambium**	**Wattime**
Percent of BTU demand delivered with reduced emissions and lower energy cost (NG)	34.1%	33.8%
Percent of BTU demand delivered with reduced emissions but higher energy cost (NG)	65.8%	33.69%

CO_2 reductions with reduced costs (NG)	3	1.1
CO_2 reductions with higher cost (NG)	55.8	17.4
Energy cost savings from "cheaper" reduced emissions (NG)	$117	$92.4
Energy cost from "expensive" reduced emissions (NG)	$7,544	$5,400
CO_2 reductions with reduced cost (Resistance)	58.8	106.7
CO_2 reductions with higher cost (Resistance)	2.5	4.3
Energy cost savings from "cheaper" reduced emissions (Resistance)	$16,955	$17,000
Energy cost from "expensive" reduced emissions (Resistance)	$790.7	$791
Total CO_2 emissions saved at lower cost	61.8	107.8
"Cheaper" energy cost savings total	$17,071.6	$17,092.4
Total CO_2 emissions saved at higher cost	58.3	21.4
"Expensive" energy cost total	$8,335.4	$6,191
Net CO_2 reduction (NG and resistance)	120.1	129.2
Net dollars saved (both NG and Resistance)	$8,736.2	$10,901.4

Table 6: AHP vs.NG furnace, reduced emissions and associated costs. Emissions in millions of tonnes CO_2, dollars in millions.

Figure 5 shows the geographic distribution of the percentage of NG heating demand that can be delivered with a net reduction in emissions using 2019 Wattime emissions data. In figure 5 mild climates and coastal regions show the greatest potential for CO_2 mitigation through heat pump deployment. In these locations, winter temperatures are warm enough to support a high COP and more efficient performance of AHP units. Also visible in figure 5 are delineations of different grids, illustrating the role that different generation sources play on the MOER of the different grids. Unsurprisingly the benefits of heat pump adoption are diminished in colder, more northern, and interior climates.

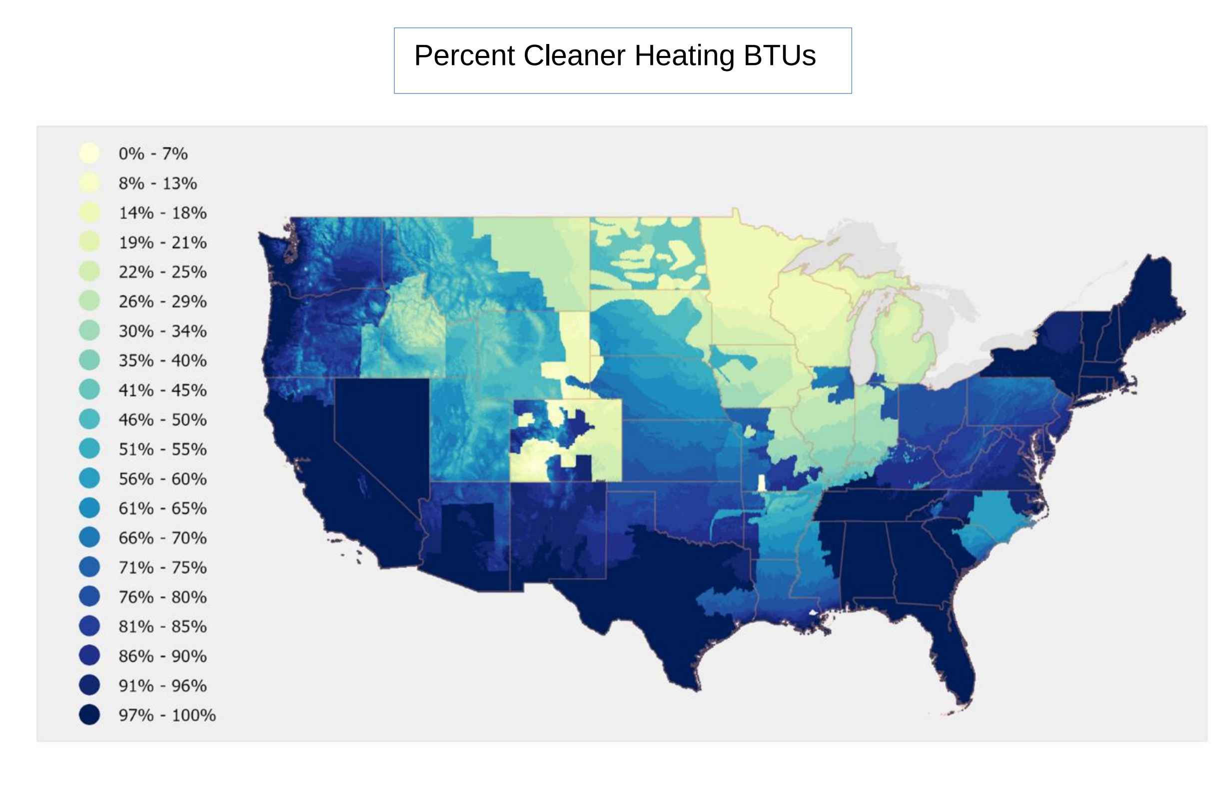

Figure 5: Percent of BTU heat demand that can be delivered by AHP deployment with lower carbon emissions using Wattime data.

In figure 6 we see the same map using Cambium data which better represents the lifetime emissions potential for replacement of NG heating with AHP. In this map the lowest value for heating BTU percent that can be delivered with lower emissions by AHP is 97.8%. With a total percentage of BTUs delivered by AHP at 99.9%. If the grid mix of generation resources changes as predicted by NREL's base case scenario than heat pumps deployed today will reduce emissions over their lifetime everywhere in the United States.

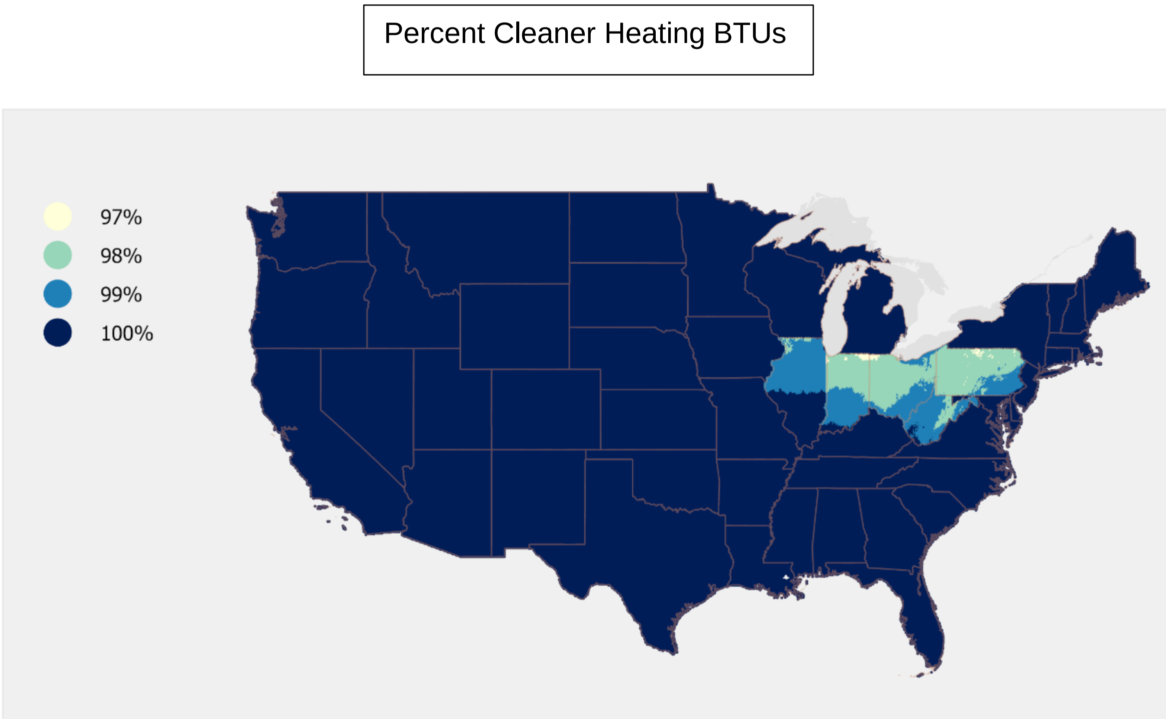

Figure 6: Percent of BTU heat demand that can be delivered by AHP deployment with lower carbon emissions using Cambium data.

Figure 7 shows the percentage of heating BTUs that can be delivered with reduced emissions and cost savings using 2019 Wattime emissions and 2019 energy price data. It has much in common with figure 5 but shows that not all heating BTUs that could be delivered with reduced emissions in 2019 could also be delivered with residential cost savings. Geographically located trends are similar in both maps re-inforcing the conclusion that geography and weather currently play a strong role in both emissions reduction potential and the economics of AHP deployment.

Percent Cheaper and Cleaner BTUs

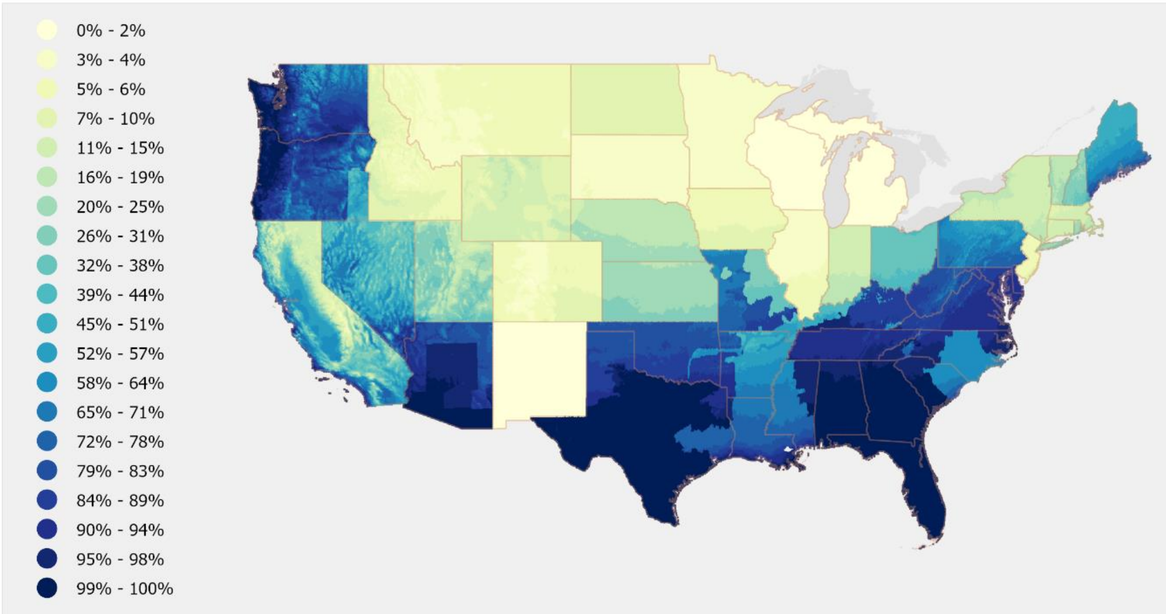

Figure 7:Percent of BTU heat demand that can be delivered by AHP deployment with lower carbon emissions and cost savings. Wattime data.

Figure 8 shows the same results only with Cambium data reflecting the potential for emissions reductions and cost savings over the lifetime of an AHP unit. Compared with figure 7, we see a greater geographic area and higher percentages of BTUs that can be delivered with reduced emissions and cost savings. Of note is that this analysis was done with 2019 energy prices and current capital cost differences between AHP and NG heating units. Changes that increase the cost of residential natural gas more than electricity and especially changes that reduce the installed cost of AHP units will change the results of this analysis significantly.

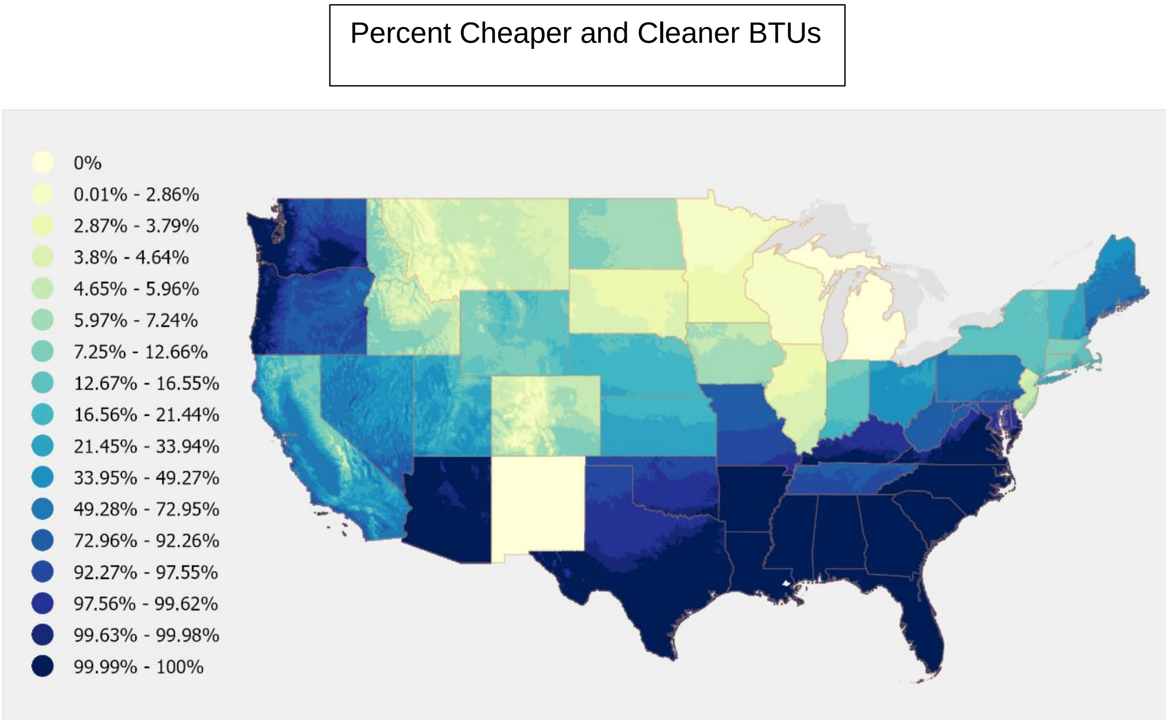

Figure 8: Percent of BTU heat demand that can be delivered by AHP deployment with lower carbon emissions and cost savings. Cambium data.

When looking at the MACC for NG replacement the first thing that stands out is the effect of adding amortized cost to the energy cost. Figures 9&10 both show the results based on energy prices alone while figures 11&12 include the added difference in amortized capital cost of AHP and NG units. Both sides of the curve show a trend towards exponential growth which is exacerbated on the expensive right side of the curve when amortized costs are included. Including the most extreme values on the right side made the graphs uninterpretable so a small number of extreme values were set much lower to produce the graphs presented below. Although the area above the curve for negatively priced emissions is similar between the two data sets, the right side representing positively priced emissions shows a much more gradual rate of increase without a movement to exponential growth in cost for much more of the curve. Cambium data shows a slower rate of change across the more expensive side of the graph representing a more uniform distribution of cleaner generation assets than we have today as well as a cleaner grid overall.

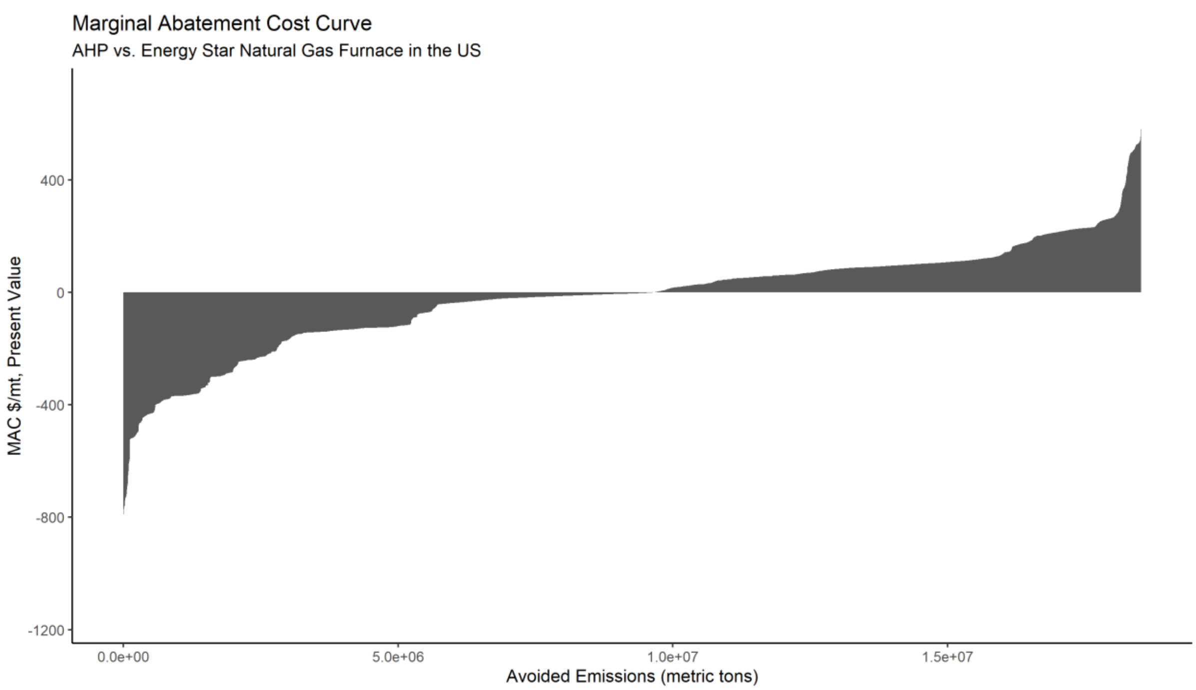

Figure 9: Marginal Abatement Cost Curve for all NSRDB weather point homes using NG heating, no added amortized cost of AHP system, Wattime data.

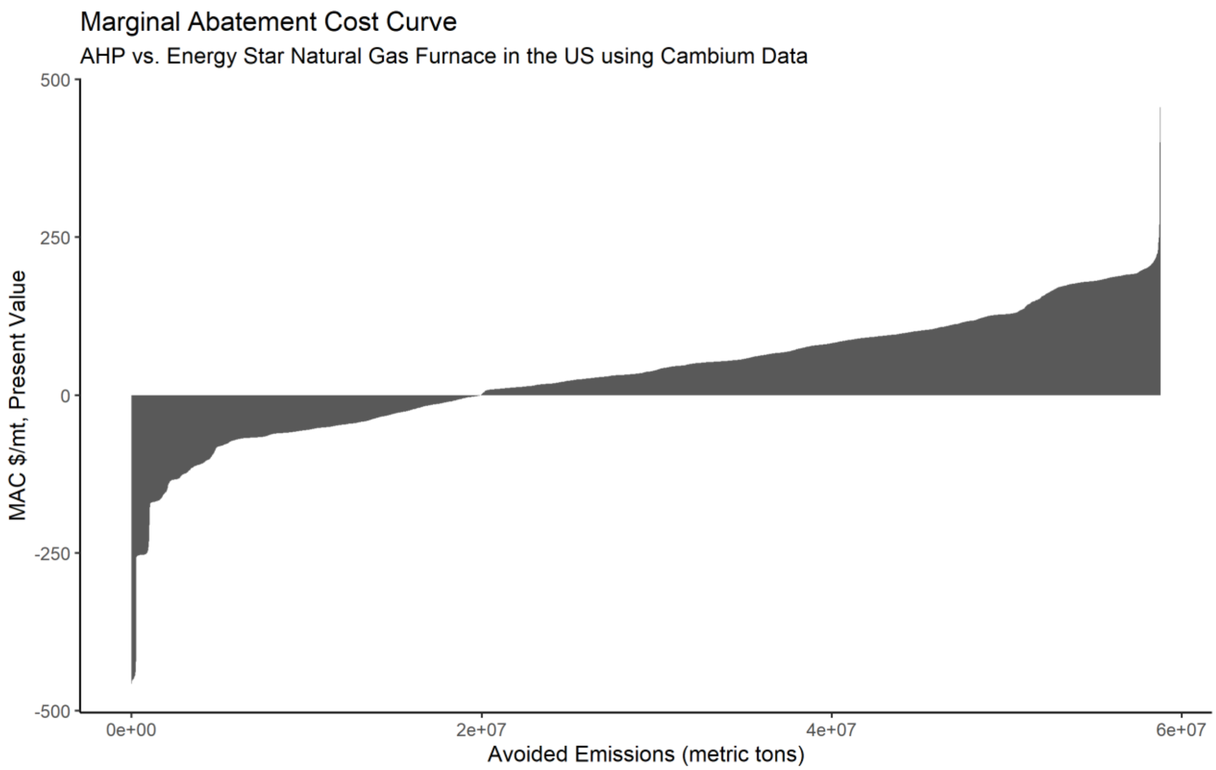

Figure 10 Marginal Abatement Cost Curve for all NSRDB weather point homes using NG heating no amortized cost of AHP system, Cambium data.

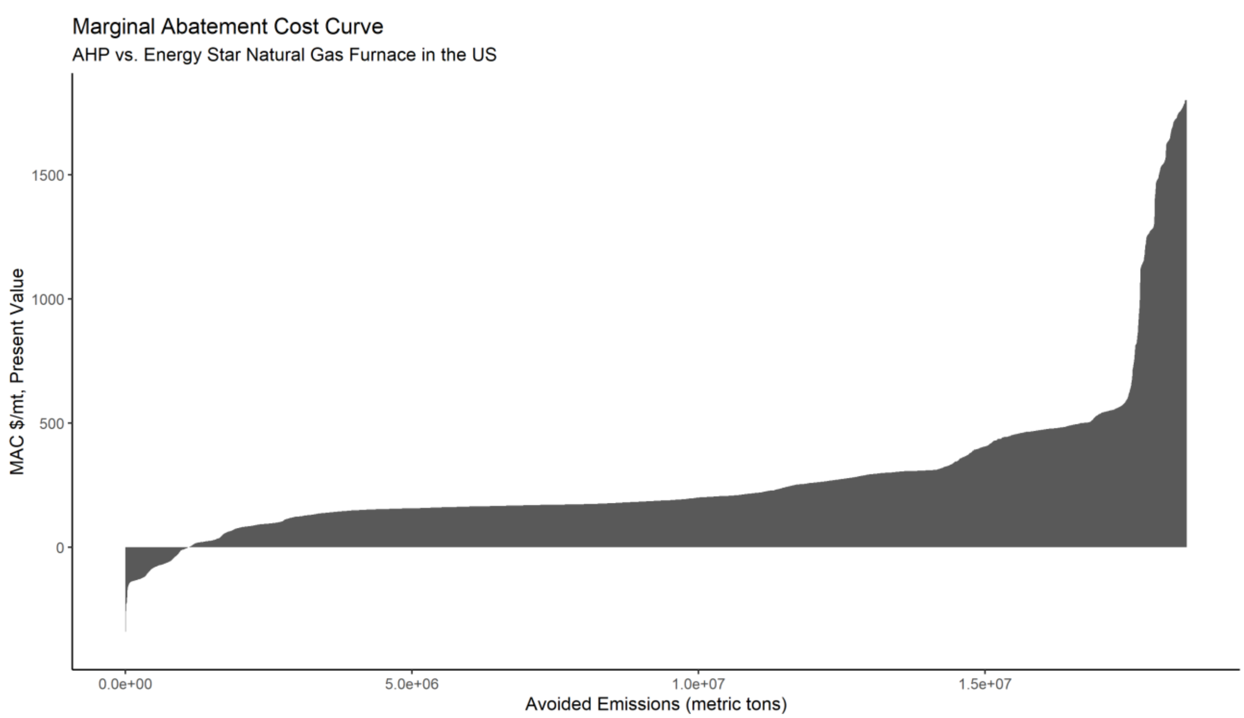

Figure 11: Marginal Abatement Cost Curve for all NSRDB weather point *homes using NG heating, Wattime data.*

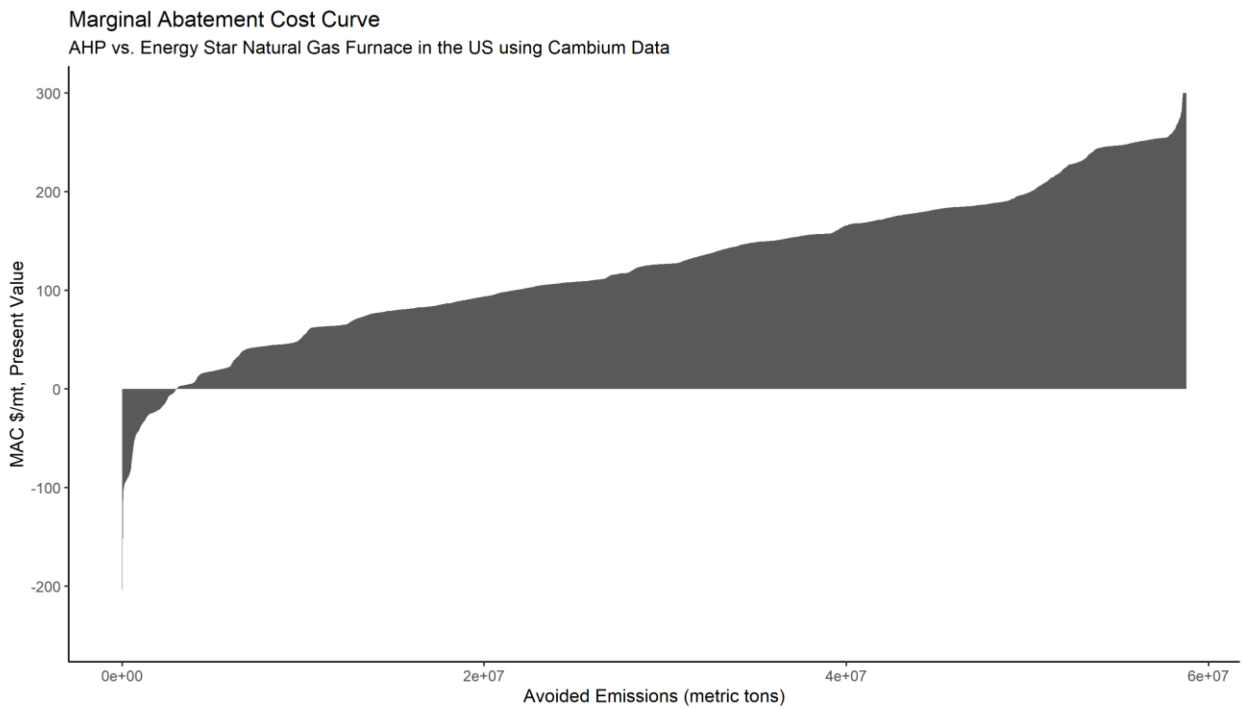

Figure 12: Marginal Abatement Cost Curve for all NSRDB weather point homes using NG heating amortized cost added, Cambium data.

Looking at the climate zone aggregated values in figures 13&14 adds further insight regarding local climate and the potential economic benefits of AHP deployment. When amortized cost is added all climate zones show a positive cost for CO_2 reduction. Although cold climates represent the greatest potential savings by volume, they also represent the second highest cost. Very cold climates show minimal emissions savings at a substantial cost. Using the Cambium data shows a great deal more CO_2 emissions that can be saved at a much lower cost for every climate zone. Where Wattime data gives us a snap shot of what would happen in the advent of replacing NG heating with AHP Cambium data gives us an idea of the mitigation potential over the lifetime of the

AHP unit. A caveat being that this analysis was done with 2019 energy prices for both Wattime and Cambium and does not consider future changes in either the cost of natural gas or electricity.

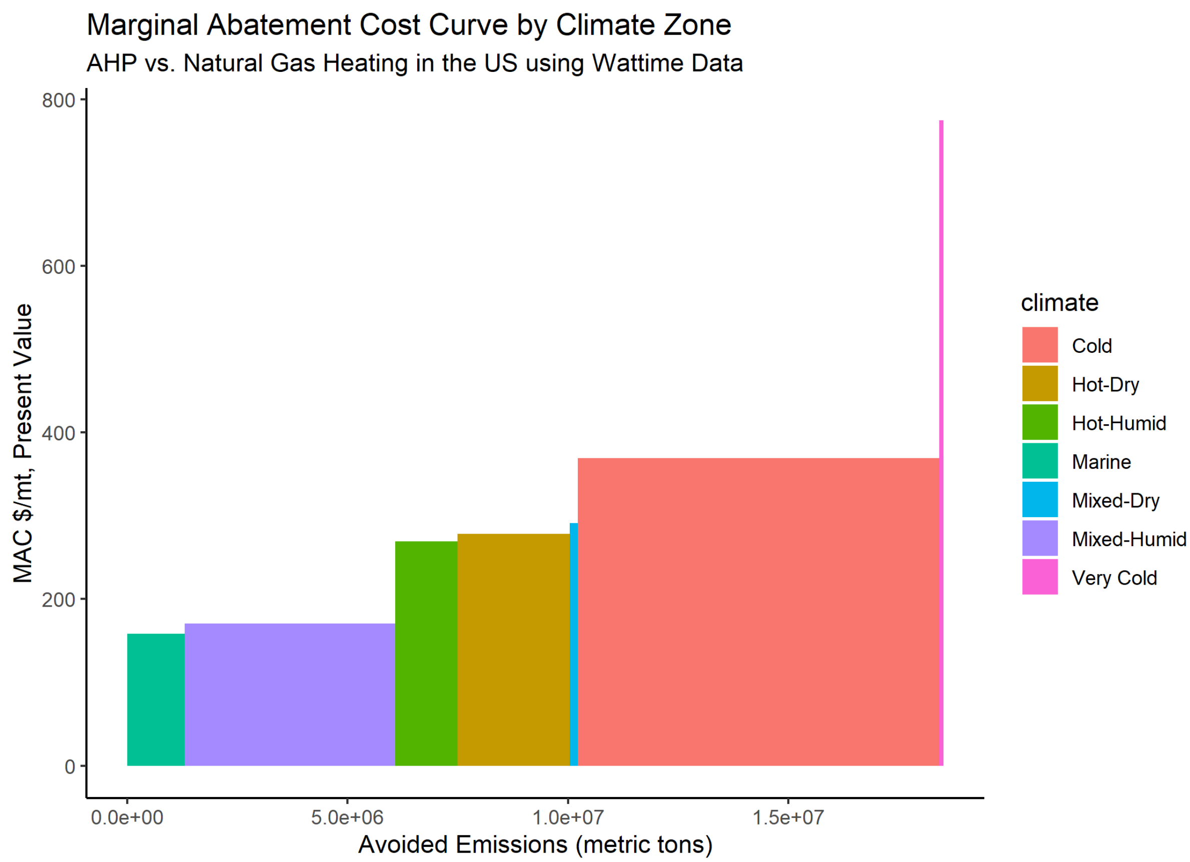

Figure 13: Marginal Abatement Cost Curve aggregated by climate zone NG heating with amortized cost of AHP system, Wattime data.

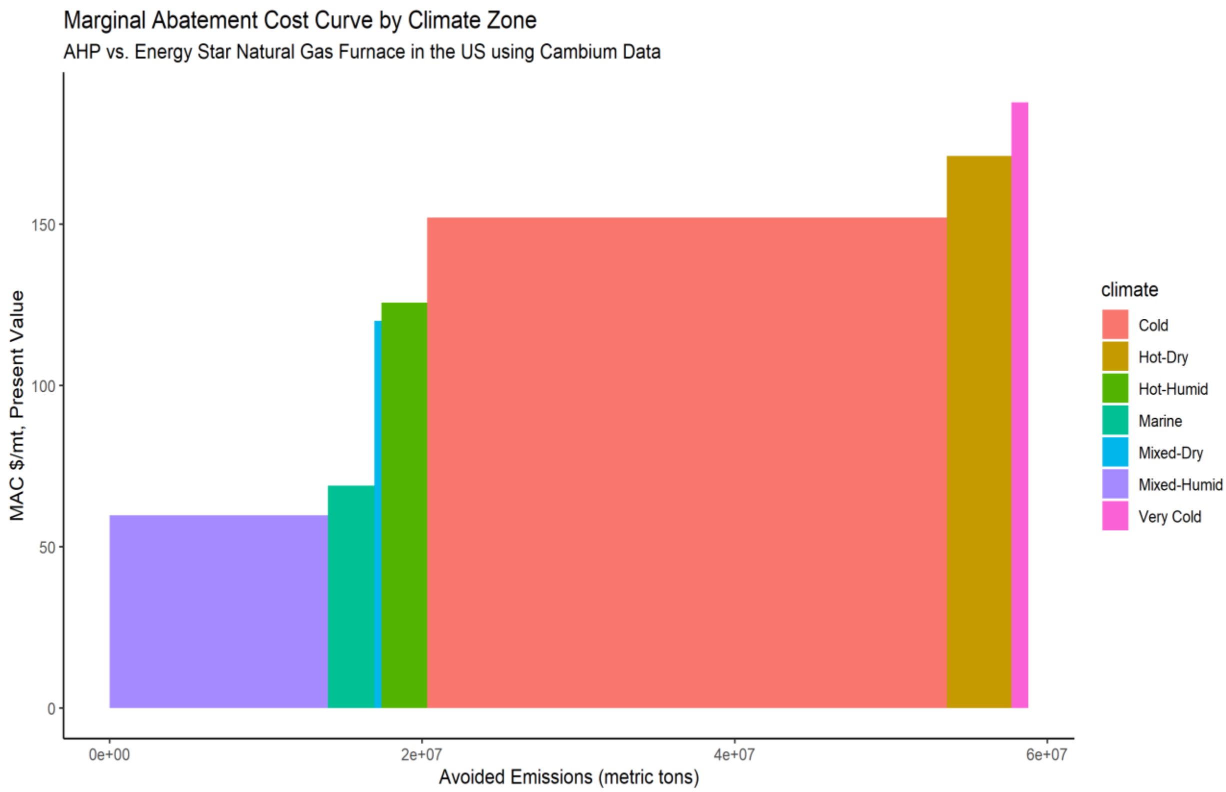

Figure 14: Marginal Abatement Cost Curve, aggregated by climate zone, NG heating replacement with AHP system, includes amortized cost, Cambium data.

In the case of electric resistance heat replacement with AHP units this study's results are in line with Deetjen et al., (2021) in that switching "almost always produces a clear benefit." In terms of energy cost, all homes included in this study could reduce their carbon footprint while realizing an economic benefit. Like the curve for the replacement of forced air NG by AHP units the curve for electric resistance heater replacement also shows a trend towards exponential growth on both sides signifying that in some areas the costs, or savings of AHP deployment can become massive. In contrast to NG replacement, we see a decrease in the amount of CO_2 mitigated when comparing the result produced with Cambium data compared to Wattime. As the grid becomes cleaner the amount of CO_2 saved per kWh of unused energy decreases. If the amount of carbon released from electricity generation decreases, without a price change in kWh, then the increase in both the cost and savings for a tonne of CO_2 will rise and this is what we observe when looking at results between the two datasets.

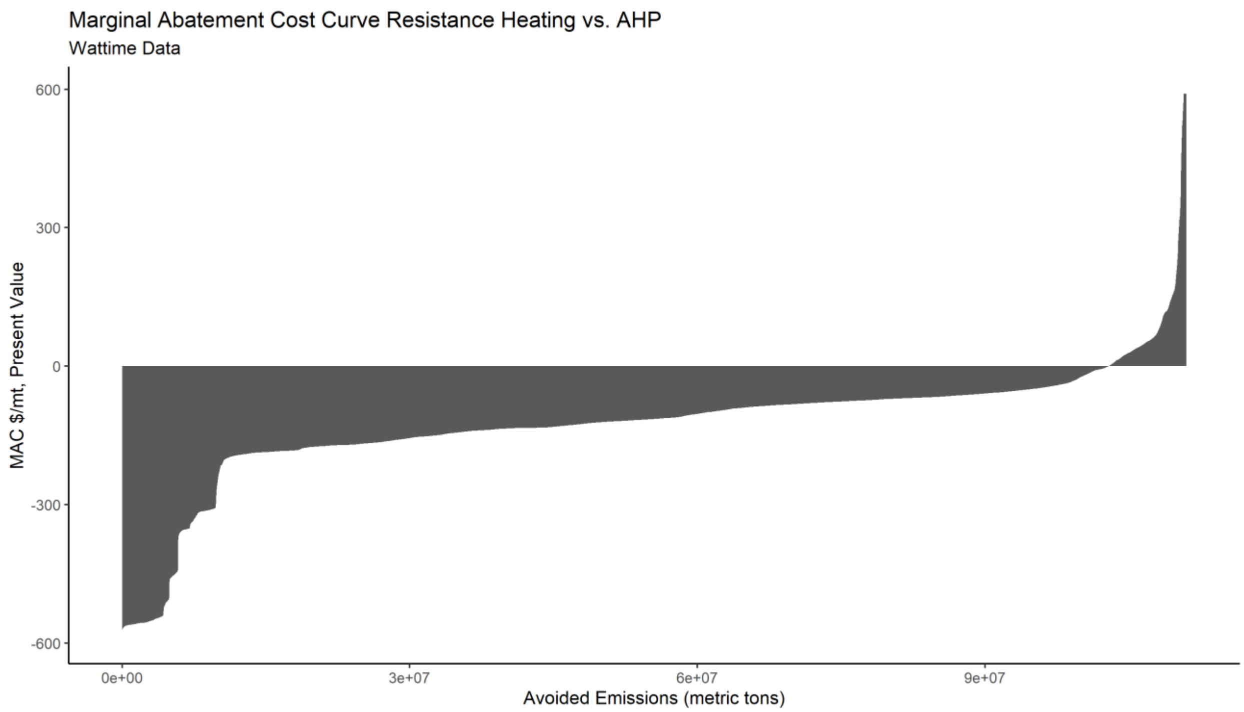

Figure 15: MACC for
resistance heating with amortized cost of AHP system, Wattime data.

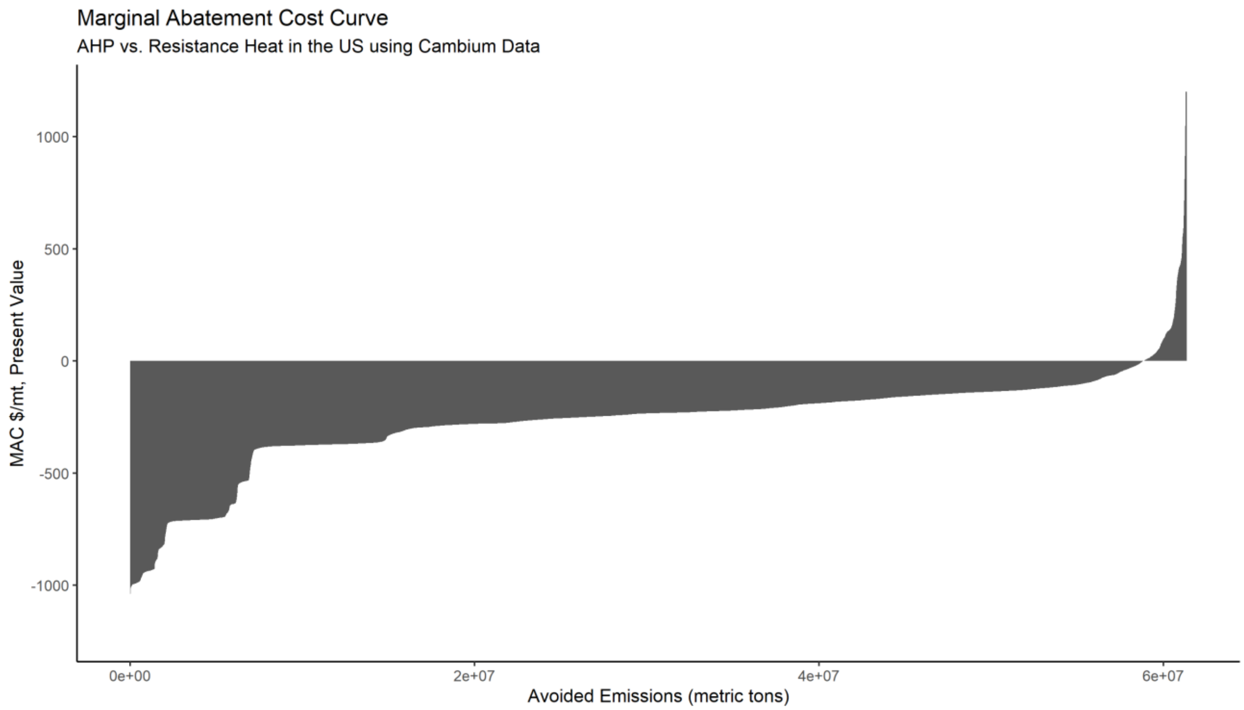

Figure 16: MACC for
ER with amortized cost of AHP system, Cambium data.

Results by climate zone in figures 12&13 show the benefits of replacing resistance heat with AHP aggregated by climate region a very different cost landscape from NG replacement. The greatest savings come from cold climates where the savings in energy cost delivered by AHP units, over many heating hours, eclipse the added amortized cost of an AHP unit. In contrast areas with little heating demand show very low savings or, in the case of hot-humid climates, an economic cost. Looking at just energy cost savings, there are no homes in the U.S. that would pay higher energy prices from replacing resistance heating with an AHP unit.

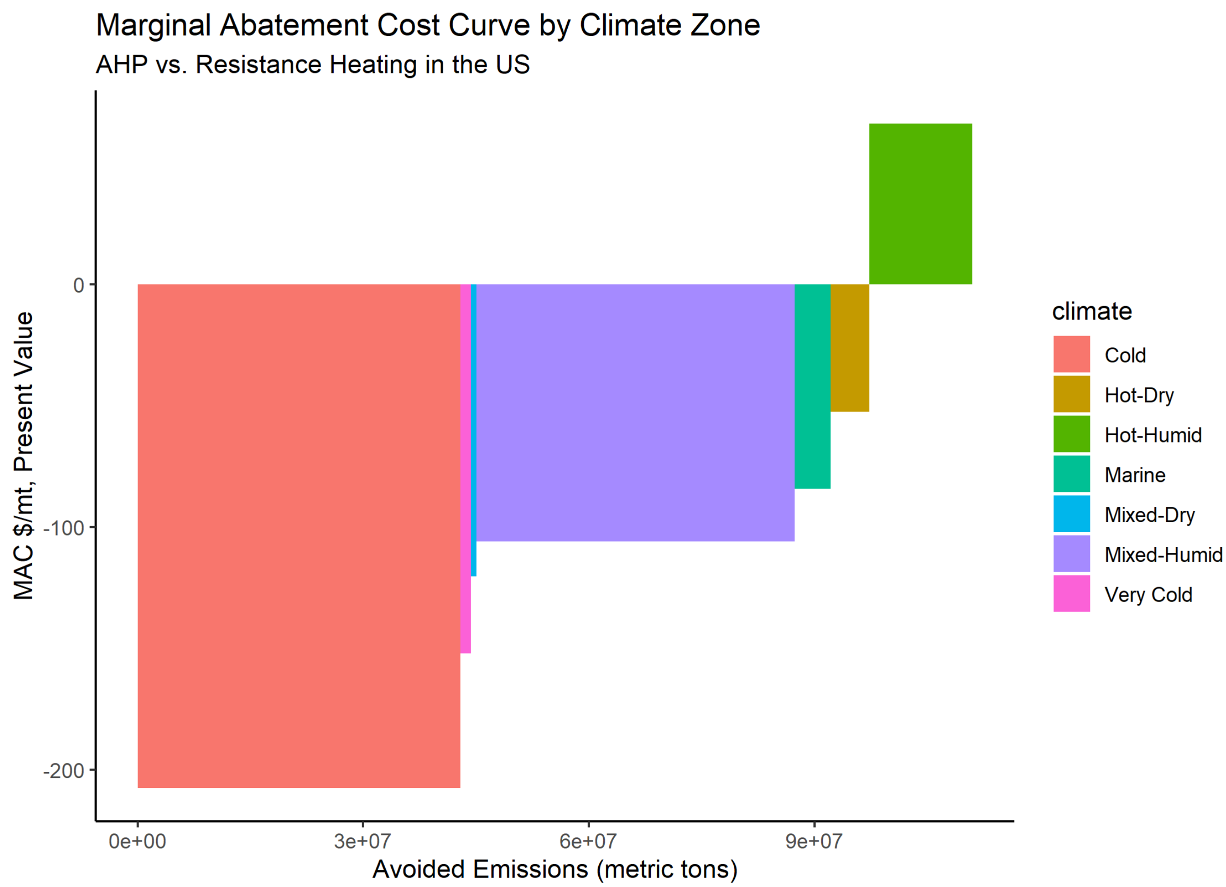

Figure 17: MACC ER with amortized cost of AHP system, Wattime data.

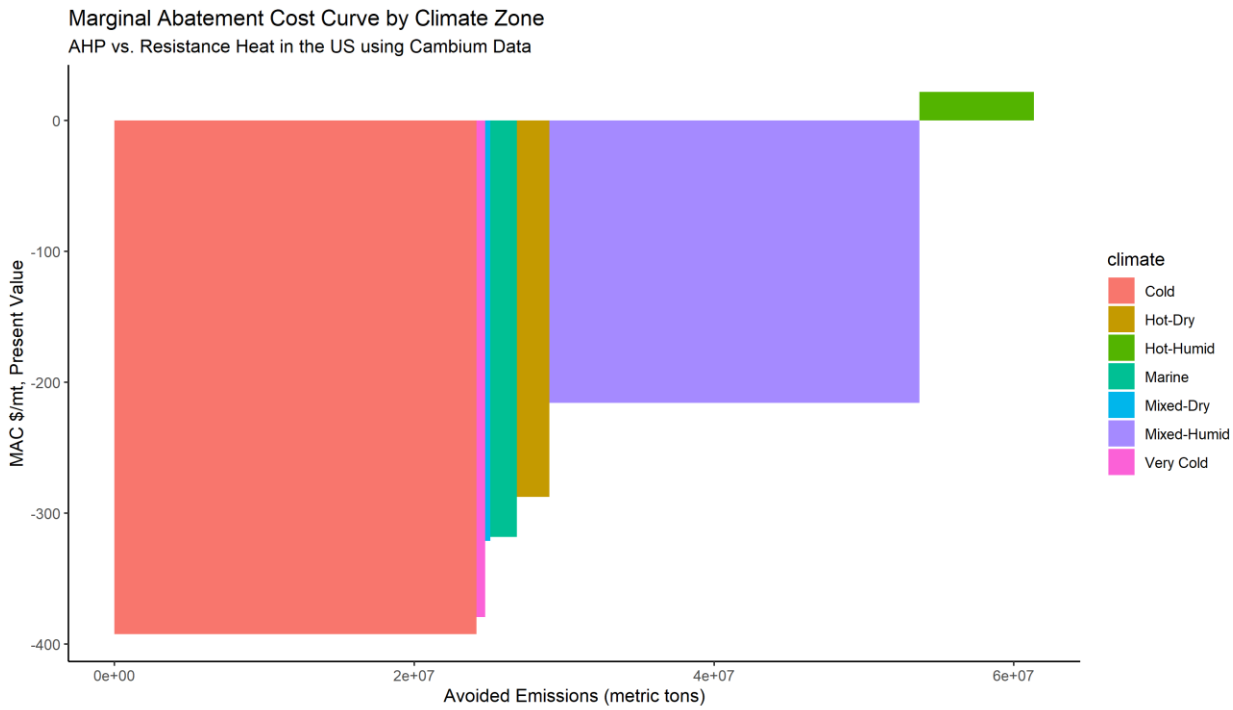

Figure 18: MACC ER
with amortized cost of AHP system, Cambium data

Discussion

Consistent with past work, this research also shows that increased AHP penetration can substantially reduce CO_2 emissions with the size of the benefits largely dependent on the climate and carbon intensity of the local grid (Vaishnav & Fatimah, 2020). We also find that for many households the adoption of AHP unit would provide an economic benefit. Past studies have called into question the feasibility of mass replacement of NG heating with AHP technology due to the increased electricity demand and constraints from the current grid, especially problematic in cold climates (Waite & Modi, 2020). This study suggests that if AHP adoption is limited to homes that can save money by doing so, the effect on peak demand in cold climates would likely be beneficial as most of the economic benefits also come with decreased electricity usage from the increased efficiency AHP units offer compared to ER heating.

Although this study provides a more geographically dispersed view of the economic and environmental benefits and costs from AHP adoption there are key limitations that future work could address. The model we use for building energy efficiency, while based on data from EIA, falls short in many ways. Using one value for UA and single values for the distribution of heating systems across the housing units in census districts does not capture the heterogeneity of either the housing stock or the distribution of systems across that stock. The prevalence of different heating systems across different housing types varies greatly (Goldstein et al., 2020) and the results of AHP replacement based on averaging all housing types together creates room for inaccuracy. Using such a simple model does not allow for relationships between local climate, various components and improved efficiency measures like weatherization to be accounted for in their relationship to AHP performance. A more thorough approach to modeling of the U.S. housing stock could provide insight for policymakers on what vintage and make of residential homes could provide the most benefit for AHP deployment.

Given that the amortized capital cost of AHP as a replacement for NG heating is such a limiting factor to its economics, future work to examine the relationship between efficiency measures and the savings that could be realized from downsizing AHP units and reducing the installed cost as a result could radically increase the geographic range where AHP units can be economically adopted. Particularly in colder climates where interventions that increase a home's efficiency, like weatherization, would have the greatest impact. Direct upstream or downstream incentives could also serve to greatly increase the number of homes where AHP units are economically superior. Future studies on how the incentives provided in the Inflation Reduction Act change the rate and economic benefit of AHP deployment would be worthwhile.

No accounting for the replacement of air conditioning systems (AC) with AHP was done in this study. Nor was any analysis done for the economics of AHP adoption in homes that have NG or ER heating with a separate AC system. Given that the only areas that showed positive abatement values for ER replacement are areas with low annual heating demand and high annual cooling demand, accounting for these potential savings would change the results. As the difference between an AHP unit and an AC unit is mostly a matter of adding a few valves, the cost difference between the two is low. Replacing an AC unit with an AHP unit at only slightly higher installed cost would provide a cheaper heating source for all those homes currently using ER heating and many using NG. In the case of NG heated homes that have AC, replacing the AC unit with an AHP unit could lead to decreased NG use or the early retirement of the system altogether. Further research to quantify these potential effects is warranted.

Though most of the heating in the U.S. is provided by either electricity or NG, excluding other sources from this study, such as fuel oil, propane, and wood, undoubtedly effects the findings in this paper. No accounting for fugitive emissions of

NG are included in this study which have been found to be significant in other studies (Alvarez et al., 2018). Direct and indirect CO_2 emissions are the only emissions considered in this paper. As such the effect on levels of other pollutants such as sulfur dioxide, nitrogen oxides, and particulates produced from electricity generation cannot be ascertained from this study. Absent from this work is any accounting for the effects of refrigerants used in AHP models that might eventually find their way into the atmosphere, through leaks, or at the end of the unit's serviceable life.

Conclusion

The results of this paper are generally in line with the conclusions of previous research: increased adoption of air source heat pumps would reduce CO_2 emissions and have a net positive economic effect. The magnitude of this effect varies greatly across the United States and, when looking at the results from Cambium data, would reduce emissions everywhere they are deployed. Although currently the replacement of NG with AHP technology produces positive abatement costs for most of the emissions that can be mitigated, this is largely a function of greater installed costs. Assuming equal installed costs for AHP and NG units and 2019 energy prices, roughly 90% of the potential CO_2 reductions would come with a maximum cost of $100 per tonne. This research provides several findings that could be used to inform future strategic economic and policy initiatives to increase AHP adoption.

- As the economic benefit of replacing NG heating with AHP varies greatly by geography, focus on mild and coastal climates first as this is where the individual economics are currently most favorable.
- With regards to electric resistance heating replacement, the mitigation potential and economic benefits are almost universal.
- Replacing ER with AHP heating in cold climates would provide the highest cost savings and 2nd highest CO_2 reductions of any of the climate regions. Reducing peak demand in areas of adoption with winter peaking would allow greater replacement of NG heating without requiring investments in capacity expansion.
- In the hot-humid environments of the southeast further research to evaluate the benefits of adopting a single heat pump unit to replace a dual heating and AC system could change the cost calculation of mitigation. Policy that would encourage the adoption of AHP over AC systems, such as upstream manufacturing incentives to produce only AHP units, could serve to increase production and phase out the use of existing NG for heating in dual system homes.
- Reducing emissions from electricity generation, on par with Cambium's predictions, will make the mitigation potential of AHP units universal.
- MACC curves in this study use 2019 energy prices, but projections for future electricity and NG prices show NG prices increasing at a greater rate than electricity (U.S. Energy Information Administration, 2022a). This trend will improve the lifetime economic competitiveness of AHP deployment.

- Although reducing electricity prices will help make AHP units more economically competitive, the deciding factor for much of the country is the higher price of a heat pump. A meaningful leveling of the price of heat pumps, when compared to NG heating would expand the geographic range and CO_2 mitigation potential of AHP. The heat pump rebate in the new IRA legislation will radically change the cost landscape as even homeowners that earn over 150% of the median income could see a max tax credit of 30% installed cost, up to $2,000, more than the cost difference between an AHP and NG system in this study. Lower income households can realize progressively higher rebates.

Although the potential for heat pump adoption to reduce emissions in the residential sector is significant the economic hurdles that exist today are also significant. While decarbonizing the grid will increase the potential for CO_2 mitigation it will not significantly change the economics of the situation. Although the incentives in the IRA will undoubtably play a large role in increasing the adoption rate of AHPs in homes many unaddressed challenges remain. Training the workforce and the general lack of skilled tradespeople, service upgrades for increased electric loads, the potential for incentives to promote the adoption of systems that are less than optimal, and general lack of belief that AHP technology can deliver sufficient heating in cold climates as well as fear of heat loss during power outages are just some of the remaining obstacles.

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