Title

Consumer Impacts of A Clean Energy: Climate and health benefits from electrifying residential space and water heating

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Acronyms and Abbreviations

AERs	Average emission rates
ASHP	Air-source heat pump
AVERT	AVoided Emissions and geneRation Tool
HPWH	Heat pump water heater
LRMERs	Long-run marginal emission rates
SCC	Social cost of carbon
SRMERs	Short-run marginal emission rates

This paper is an overview of a series reports on **Consumer Benefits of Clean Energy.**

Clean energy offers many benefits to consumers, including reducing consumers' electricity bills, lowering total electricity system costs, and providing health and resilience benefits. States can accelerate consumers' access to these benefits with policies that support energy efficiency, demand flexibility, renewable energy and storage. Berkeley Lab developed a series of briefs that explore the consumer benefits of clean energy, and identify actions states can take to promote them.

1. ***Contribute to a least-cost electricity system*** by using low-cost resources such as end-use efficiency, demand flexibility, behind-the-meter solar PV and storage, and utility-scale renewable energy.
2. ***Greenhouse gas emissions reductions and improved outdoor air quality*** from consumers shifting their home energy consumption from direct combustion of natural gas to efficient electric appliances, taking into account increased electricity generation due to demand growth.
3. *Improved resilience* of homes to grid outages due to installation of BTM solar PV coupled with storage.

Together, these briefs highlight how investments in clean energy technologies can provide benefits to all electricity system customers – not just those who invest in these technologies for their homes. The series also outlines options that state policymakers can pursue to facilitate the beneficial outcomes discussed.

Download the reports here.

Executive Summary

Combustion of fossil fuels, whether locally to heat a house or at a power plant to generate electricity, produces greenhouse gases and air quality pollutants with negative health impacts. While electrification is commonly seen as the most viable pathway to reduce emissions from residential space and water heating, the climate and air quality impacts of electrification depend on the trade-off between reduced residential emissions on one side and increased power sector emissions on the other (until the vision of a fully decarbonized electric sector is achieved). In this paper we address this trade-off, asking: In the contiguous United States, what are the net climate and health impacts of switching a portion (1%) of fossil fueled residential space or water heating to heat pumps? Electric heat pumps also provide efficiency benefits over electric resistance heating, a benefit that was not studied here.

We study outdoor air pollution impacts from heat pump water heaters (HPWHs) and air-source heat pumps (ASHPs). Because ASHPs are available today in a wide variety of efficiencies, we study a minimum efficiency and a very high efficiency ASHP. Due to modeling constraints, the minimum efficiency ASHPs do not meet Energy Star requirements and thus would not be eligible for Inflation Reduction Act (IRA) incentives.

We compare the electricity use and associated emissions across the lifetime of a heat pump to the emissions that would have occurred over the same timeframe from a fossil fueled appliance. We assess the impacts on a dollar basis, using the social cost of carbon to estimate the dollar value of avoiding carbon dioxide (CO_2) emissions, and a set of air quality and health models to find the dollar value of avoiding the emissions of ammonia, nitrogen oxides, particulate matter, and sulfur dioxide. Through this approach we compare the impact of different pollutants being emitted in different locations. For example, in contrast to combustion in residential homes, power sector emissions are often located far from urban areas and released well above ground level. These differences in the location of emissions can affect the quantity of air pollution to which the population is exposed, a feature that our approach addresses.

To perform this analysis we use publicly available datasets and tools: a ResStock data release from the National Renewable Energy Lab (NREL) for spatially and temporally resolved fuel and electricity consumption in both the baseline and electrified cases; the AVoided Emissions and geneRation Tool (AVERT) from the Environmental Protection Agency (EPA) for emissions in the first years of the equipment's life; the Cambium dataset from NREL for emissions farther in the future; and the Estimating Air pollution Social Impact Using Regression (EASIUR) model from the Center for Air, Climate, and Energy Solutions (CACES). One particularly important methodological decision is around the appropriate type of emission factors to use for the electricity sector. We use short-run marginal emissions at the beginning of the equipment's life to represent the marginal changes in emissions before the electricity system has adapted to the new load and average emissions for the remainder of its life to account for changing conditions. We consider a mid-case rather than an ambitious decarbonization scenario.

There are substantial lifetime benefits to displacing even 1% of residential fossil fueled water and space heating in the contiguous U.S. with heat pumps. Replacing 1% of residential water heaters with HPWHs produces $1.5 billion in lifetime benefits and replacing 1% of residential space heating with ASHPs produces $7.0 billion or $3.1 billion for very high or minimum efficiency, respectively (Figure ES-1)[1]. These totals represent an average public benefit of $2,000, $9,200, and $4,100 per household that replaces fossil fueled appliances with HPWHs, very high efficiency ASHPs, and minimum efficiency ASHPs, respectively. These public benefits are similar to, or for very high efficiency ASHPs larger than, available incentives. Roughly, climate benefits account for 80% of net benefits and health benefits account for the remaining 20%. Installing HPWHs and very high efficiency ASHPs creates substantial improvements to both climate and air quality impacts. Installing minimum efficiency ASHPs produces climate benefits and relatively small air quality benefits.

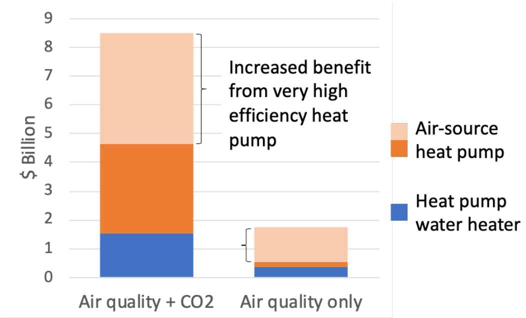

Figure ES-1. Present value of net lifetime public benefits of displacing 1% of fossil fueled water heating and space heating consumption with heat pumps. The air quality pollutants included are NH_3, NO_x, ozone, $PM_{2.5}$, and SO_2 in outdoor air.

The benefits vary widely by region (Figure ES-2). For example, each household that electrifies space heating with a minimum efficiency ASHP in New England provides $11,300 in public benefits but only $1,200 in the Midwest. While the sum of climate and air quality impacts is positive for all 14 study regions for all heat pump types, electrification with minimum efficiency ASHPs leads to health penalties in 5 regions. In contrast, electrification of water heating and space heating with very high efficiency ASHPs provides health benefits in all regions.

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[1] The performance requirements for IRA incentives are similar to our minimum efficiency case (i.e., the minimum efficiency ASHPs are just below IRA incentives performance requirements, but are conservatively representative of the impact of adoption of IRA-incentivized ASHPs).

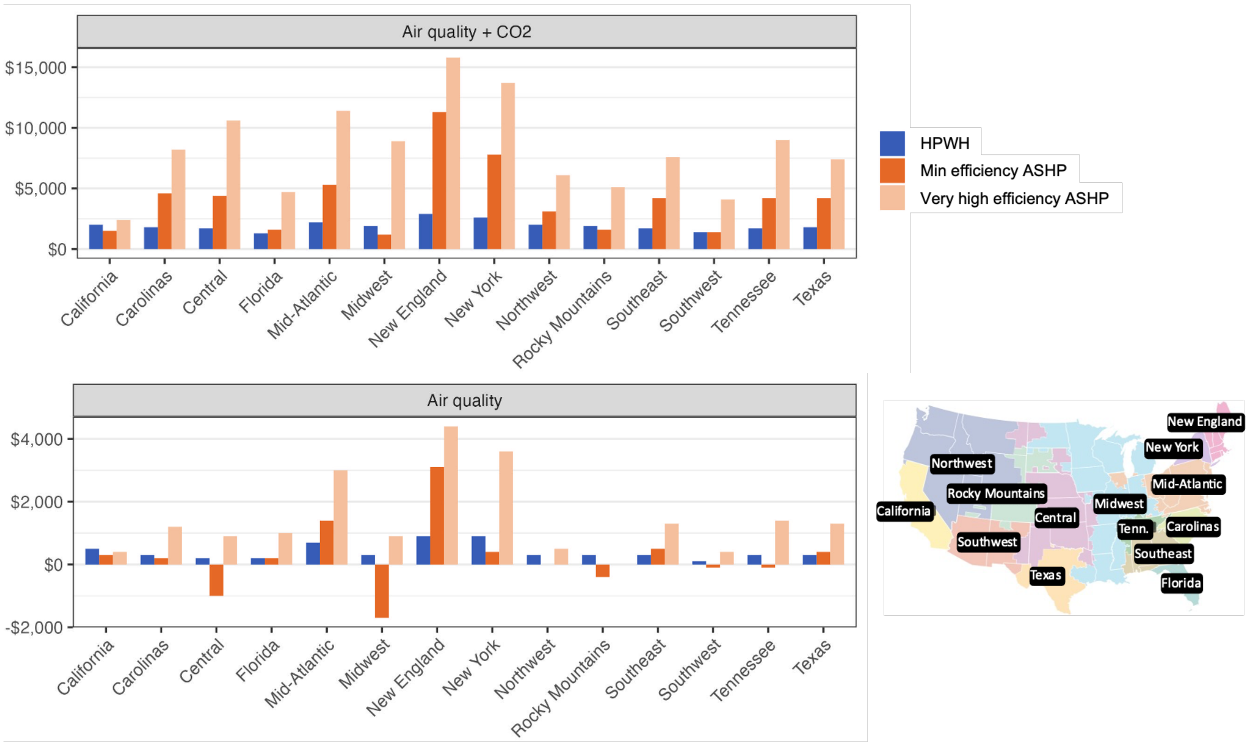

Figure ES-2. Present value of lifetime public benefits and costs per household electrifying fossil fueled water heating and space heating consumption with heat pumps by AVERT region.

For the contiguous U.S., we find that there is a net positive impact from residential water and space heating electrification. More damages are avoided by eliminating combustion associated with existing appliances than are caused by generating the electricity to power the heat pumps that replace them. However some regions see net costs for public health from electrifying space heating with minimum efficiency ASHPs with today's grid. One option to ensure *both* climate and health benefits in all regions would be to increase efficiency requirements in selected regions. Other options include reducing emission rates from existing power plants through emission controls.

Additional policy implications include:

- In all regions, policies supporting electrification with HPWHs and minimum efficiency ASHPs provide climate benefits, but higher efficiency ASHPs provide greater climate benefits.
- In some regions, increasing efficiency requirements for ASHPs beyond minimum efficiency is needed to provide air pollution benefits under current grid conditions.
- Climate benefits of ASHPs and HPWHs are positive under a mid-case decarbonization scenario.

When evaluating the air quality impacts of policies that promote heat pumps, the short run marginal emission rates should *not* apply across the life of the appliance, but only at the beginning of an appliance's lifetime. Using the short-run emissions marginal emissions rates to assess such policies will result in significant underestimates of the climate and air quality benefits that will be realized over the full lifetime of the equipment.

1. Introduction

Combustion of fossil fuels in residential buildings contributes 7% of United States greenhouse gas emissions (EPA 2024), and electrification of space and water heating activities is commonly seen as one of the most viable pathway to decarbonization this sector. The most prominent policy instrument to date was incorporated within the Inflation Reduction Act (IRA), providing several types of residential electrification tax credits and rebates. As one example, low- and moderate-income households can receive up to $8,000 for a heat pump and $1,750 for a heat pump water heater.[2] Further, heat pump technology has been advancing rapidly, with more options, such as low power, high efficiency, and cold weather configurations, being recently introduced to the market. With the new incentives and greater market options, heat pump deployment may increase substantially. In the Rapid Energy Policy Evaluation and Analysis Toolkit's conservative scenario, which includes existing policies such as IRA but no additional legislation, heat pumps will grow from 11% to 31% of residential heating equipment by 2050 (REPEAT 2024)[3].

Whether locally to heat a house or at a power plant to generate electricity, combustion of fossil fuels produces a variety of air quality pollutants with negative health impacts in addition to greenhouse gases. Until the vision of a fully decarbonized electric sector is achieved, the climate and air quality impacts of heat pumps depend on the trade-off between reduced residential emissions on one side and increased power sector emissions on the other. Analysis by Vaishnav et al. (2020) and Deetjen et al. (2021) suggests that switching out fossil fueled space heaters for heat pumps would, on balance, decrease CO_2 emissions in most locations in the United States, but increase air pollution across a number of locations. Wilson et al. (2024) also find wide-spread CO_2 emission benefits across the United States, but do not assess air quality impacts. As described below, our paper complements that past work by covering the full U.S. residential building stock, examining three electrification technologies, and using a different method for calculating future emissions.

However, this is a dynamic space – heat pump technology has advanced and electric sector emission rates have changed dramatically over the past decade, and are likely to continue to change over the coming years. The magnitude of the impact, and potentially the direction of the impact (positive or negative), can be sensitive to input data sources and methodological choices within the analysis. Therefore, one goal with this analysis is to address these key methodological choices and understand the sensitivity of climate and air pollution impacts to these choices.

The overarching analytical question we address in this paper is: What are the net climate and health impacts of switching a portion (1%) of fossil fueled residential heating (or residential water heating) to heat pumps? We assess this turnover rate of 1% per year because it roughly matches estimates (such as the above REPEAT estimate) for turnover by 2050. To assess the impacts of this level of turnover we

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[2] For more information, visit www.energy.gov/save.

[3] The REPEAT Project analyzes the impacts of federal energy and climate policies and their role in progress towards net-zero emissions.

examine the electricity use and associated emissions across the lifetime of a heat pump and the outdoor emissions that would have occurred over the same timeframe from a fossil fueled appliance. We compare the impacts on a dollar basis, using the social cost of carbon (SCC) to estimate the dollar value of avoiding CO_2 emissions, and a set of air quality and health models to find the dollar value of avoiding the emissions of other pollutants. Through this approach we are able to compare the impact of different pollutants being emitted in different locations. For example, in contrast to combustion in residential homes, power sector emissions are often located far from urban areas and released well above ground level. These differences in the location of emissions can affect the quantity of air pollution to which the population is exposed, a feature that our approach is able to address.

In this paper, we explore three critical methodological questions: 1) What is an appropriate approach to estimate electric sector emissions over the course of the lifetime of the heat pump? 2) What is the impact of varying heat pump efficiency parameters? And 3) What are the emission rates of existing combustion-based heaters? By carefully assessing these methodological questions we are able to derive important, policy-relevant conclusions about what underlying factors drive heat pumps to produce air pollution health and climate benefits or penalties.

To estimate the electric sector emissions caused by increased heat pump adoption we draw an important distinction between different types of emission rates and their appropriate applications. Short-run marginal emission rates (SRMERs), commonly referred to as marginal emissions rates, represent the change in operational emissions that occur concurrently with new, unplanned demand. We use SRMERs to assess the emissions impact of an appliance during its first three years of operation. We assume that after the fifth year of operation, electricity demand from a heat pump is no longer unplanned for and therefore that SRMERs are no longer appropriate for assessing its impact. Instead we apply average emissions rates (AERs), or the total amount of emissions divided by the total electricity consumption, for the remainder of the equipment's life with a transition period in the fourth and fifth years of operation. The switch between types of emissions rates is an important characteristic of our approach and is different from prior efforts that applied declining SMRERs to heat pump electricity through their entire lifecycle (Vaishnav et al. 2020 and Deetjen et al. 2021). We also explore the sensitivity of the results to using long-run marginal emission rates (LRMERs) instead of AERs. LRMERs are meant to account for the impact of new demand on the evolution of the electricity supply over time, in addition to the emissions associated with an increase in electricity demand. LRMERs are developed using electric sector capacity expansion models, discussed further in Gagnon and Cole (2022).

To estimate the residential emissions associated with fossil-based heating, we reviewed literature on emission rates from fossil fueled heating equipment. In addition to assessing literature on natural gas and propane fired heaters, we examined fuel-oil based heaters, focusing on sulfur content and its interaction with emission rates of particulate matter. The results of this review are presented in Appendix A.

Finally, we also examine two efficiencies of space heaters: a minimum efficiency unit, which is close to but does not meet the equipment standard for IRA incentives, and a very high efficiency one which represents the best that is available on the market (EPA 2022; Appendix C). Because heat pumps warm the indoors by moving heat in from outdoors, their capacity to provide heat decreases at low outdoor temperatures. When they cannot meet the full heating demand, we model electric resistance backup supplying the remainder. This capacity to provide heat at low temperatures is a primary difference between the two efficiencies of heat pump – the very high efficiency units have a higher capacity at low temperatures and therefore do not rely on electric resistance backup as often. Consequently, the difference in efficiency has a larger impact in cold climates than warm ones.

Our study includes all counties in the contiguous U.S. and multifamily as well as single family homes. We focus on electrification and, importantly, do not include homes with electric resistance space or water heating.[4] We do account for the instances when installation of an air source heat pump (ASHP) would replace a lower efficiency air conditioner, thus lowering air conditioning energy use. We also consider instances when installation of an ASHP would add air conditioning capability (i.e., for homes that do not currently have air conditioning) and would thus add to electricity demand. We study outdoor air pollution from power plants and from fossil fueled space and water heaters – we do not consider the impacts from poor indoor air quality, for example from incorrectly vented appliances. Although there are other residential fossil fueled end uses, primarily stoves and clothes dryers, we only study space and water heating because they account for at least 95% of residential natural gas and fuel oil consumption (ResStock). We also include estimates of the impact of methane and refrigerant leakage and compare those estimates to the CO_2 benefit estimates.

2. Methodology

We take three main steps to calculate the change in damages from electrification:

1. For the fossil baseline and electrified appliances, we estimate hourly electricity consumption and on-site fuel usage using ResStock[5] from the National Renewable Energy Laboratory (NREL).
2. We calculate air quality and CO_2 emissions for on-site fuel use and for electricity demand from heat pumps. For on-site fuel combustion we use constant emission conversion factors. For electricity consumption we use the AVoided Emissions and geneRation Tool (AVERT)[6] from the Environmental Protection Agency (EPA) and NREL's Cambium[7].
3. We estimate dollar damages based on emissions quantities and location. For air quality pollutants, we calculate health damages using the Estimating Air pollution Social Impact Using

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[4] The IRA incentives also apply to heat pumps that replace electric resistance space and water heating. These applications categorically provide climate and health benefits by reducing electricity demand; we only analyze the fuel switching applications where there is the tradeoff between local and power sector emissions.

[5] https://resstock.nrel.gov/

[6] https://www.epa.gov/avert

[7] https://cambium.nrel.gov/

Regression (EASIUR)[8] model from the Center for Air, Climate, and Energy Solutions (CACES). For CO_2, we calculate climate damages using the social cost of carbon (SCC).

2.1 Energy consumption

We use ResStock to estimate the energy consumption for water heating and space conditioning. ResStock provides a database of simulated end use load profiles from 450,000 EnergyPlus building energy models of dwelling units that statistically represent the residential building stock of contiguous U.S. Each of the 450,000 models is run for a baseline set of characteristics and then adjusted and rerun to represent a variety of potential efficiency and electrification upgrades. We use the energy consumption and electricity load shapes from the baseline results and three of the upgrade scenarios: (i) heat pump water heater, (ii) minimum efficiency for the heat pump with electric backup, and (iii) high efficiency heat pump with electric backup.[9]

We include dwelling units that have natural gas, fuel oil, and propane equipment for water or space heating in the baseline. For both end uses, more than 80% of the sample have natural gas (Table 1). Fuel oil space heating is heavily concentrated in New England, New York, and Pennsylvania. Although those states contain only 20% of the dwelling units we study, they contain 80% of the dwelling units with fuel oil space heating.

Table 1. The type of fuel used (by number of dwelling units) for water heating and space heating in the baseline.

	Water heating	Space heating
Natural gas	89%	84%
Fuel oil	4%	8%
Propane	6%	8%

Consistent with ResStock, we assess a heat pump water heater (HPWH) with a uniform energy factor (UEF) of approximately 3.4. This is in line with the minimum Energy Star performance required for IRA incentives (3.3 UEF). We also follow ResStock's lead by examining two efficiencies for air source heat pumps (ASHPs): a minimum efficiency case which represents the appliance standard (15 SEER, 9 HSPF), and a very high efficiency case (24 SEER, 13 HSPF for dwelling units with ducts)[10]. IRA incentives require a level of performance that slightly higher than but close to the minimum efficiency case. See Appendix C for a list of heat pump efficiencies, including minimum federal standards and IRA incentive requirements. We assume that space heating is completely electrified, so the backup heating fuel is electricity.

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[8] https://www.caces.us/easiur

[9] The ResStock team periodically releases new results with modeling improvements and additional efficiency and electrification measures. We use the 2022.1 data release.

[10] For the approximately 30% dwelling units without ducts, the heat pump was slightly more efficient – 29.5 SEER, 14 HSPF.

Because ASHPs provide both heating and cooling, we consider the change in electricity consumption for both those end uses. In the 20% of cases where there was no air conditioning in the baseline, this increases both health benefits through the addition of cooling as well as the incremental electricity consumption from electrification. In many cases, however, the cooling efficiency of the modeled heat pumps is greater than the baseline air conditioners, so it reduces the incremental electricity consumption from electrification.

Following the Energy Information Agency (EIA) assumptions,[11] we use a 15 year expected useful life (EUL) for both HPWHs and ASHPs.

2.2 Emissions

In the main analysis we consider CO_2 and five air quality pollutants: NH_3 (ammonia), NO_x (nitrogen oxides), ozone, $PM_{2.5}$ (particulate matter), and SO_2 (sulfur dioxide). This section describes our data sources and methods for converting electricity and fuel consumption into emissions.

2.2.1 Appliance emissions

We base our emission factors for direct combustion of fossil fuels in furnaces and water heaters on EPA's AP-42 and update them with more recent research from Brookhaven National Laboratory (EPA 1995; McDonald 2009). McDonald found that $PM_{2.5}$ emissions from residential fossil fueled heaters were reduced by about 99% compared to AP-42. Other emission rates were found to be similar between the sources, except for SO_2 emissions from ultralow sulfur fuel. In 2023, 93% of the fuel oil stock in the U.S. was ultralow sulfur, so we use emission factors for ultralow sulfur fuel oil.[12] Table 2 shows the emission factors we use for direct combustion of fossil fuels in space and water heaters. See Appendix A for details.

Table 2. Air quality emission factors for combustion of fossil fuels in residential furnaces and water heaters. * indicates that the EPA AP-42 value was updated based on McDonald (2009).

	Natural gas ($lb/10^6$ scf)	Fuel oil ($lb/10^3$ gal)	Propane ($lb/10^3$ gal)
NO_x	94	20	13
$PM_{2.5}$	0.076 *	0.02 *	0.007 *
SO_2	0.6	0.216 *	0

2.2.2 Power system emissions

We model the power system emissions differently depending on the time elapsed from installation of a heat pump. For the first three years of operation, we use short-run marginal emission rates (SRMERs) calculated with EPA's AVERT. After the fifth year of equipment operation, we use average emission rates (AERs) from NREL's Cambium to reflect the change in infrastructure. For the fourth and fifth years

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[11] https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/appendix-a.pdf

[12] https://www.eia.gov/dnav/pet/pet_sum_sndw_dcus_nus_w.htm

of operation, we interpolate between the two types of factors. By using SRMERs for the first years of the equipment's life, we are assuming that the increased load from electrification was not included in utility forecasts or used to plan the current grid structure. As the push to electrify continues, it may be more appropriate to assume that utility forecasts include electrification, in which case long-run marginal emission rates (LRMERs) should be used for the whole operating lifetime of the equipment (see below).

Short-run marginal emissions

SRMERs reflect the change in emissions caused by an additional load given today's grid and do not take into account any structural changes that the load might induce in the future. They also embed the assumption that the new load was not previously anticipated or planned for. They are appropriate for estimating the emissions from the first few years of a piece of equipment's operation.

We calculate short-run marginal emissions using EPA's AVERT. AVERT divides the contiguous U.S. into 14 grid regions (Figure 1). Given an hourly change in electricity load in a particular grid region, it models which generators will be modulated up or down based on historical measured data. It outputs the associated changes in county-level emissions of CO_2 and air quality pollutants. EPA recommends that the main AVERT module only be used for electricity consumption up to5 years in the future (EPA 2023a).

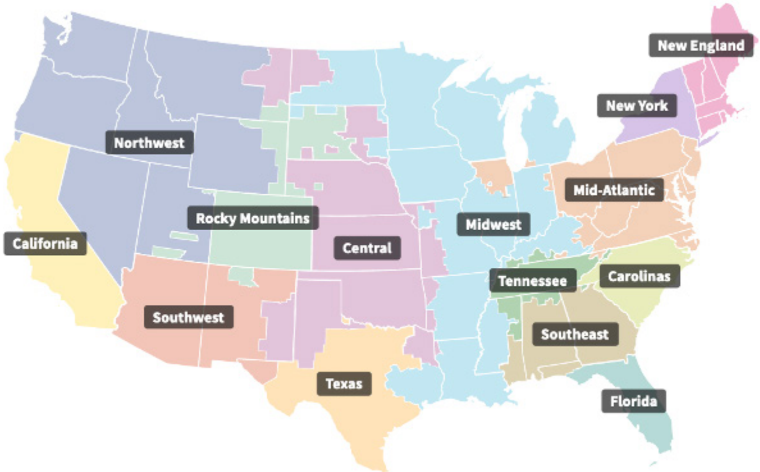

Figure 1. AVERT regions

Long-run marginal emissions

LRMERs reflect the change in emissions caused by an additional load, but they take into account structural changes to the grid caused by that load. For example, if a utility's forecasts include a new cooling load in the middle of the day, it might choose to build more solar. In this case, the SRMERs for the hot summer day would be much higher than the LRMERs for that same day because the LRMERs take the future solar into account.

Average emissions

Projections of AERs, or the total electricity produced divided by total emissions, also reflect changes in grid infrastructure. Because LRMERs are not available for air quality pollutants, we use AERs to account for those grid changes. We use the 2022 “mid” case from NREL’s Cambium, which includes IRA provisions, for NH_3, CO_2, SO_2, and NO_x emissions. Cambium does not estimate $PM_{2.5}$ emissions, so we assume that the ratio of $PM_{2.5}$ to SO_2 emissions from AVERT remains constant for the full lifetime of the equipment. Table 5 compares the results we get using AERs and LRMERs for CO_2 emissions.

2.3 Damages

To assess the damages caused by annual county-level air quality emissions we use EASIUR, a simplified air quality model and health impact model. Combined with data from epidemiological studies, EASIUR provides annual and seasonal county-level damages from morbidity and mortality for ground-level and high-stack emissions of air quality pollutants. For NO_x, $PM_{2.5}$, and SO_2 we use EASIUR damages derived from the Harvard Six Cities (H6C) epidemiological model (Lepeule et al. 2012). EASIUR does not contain damages caused by ozone from increased NO_x emissions; instead we use damage estimates from modeling performed by the U.S. Environmental Protection Agency for three regions (EPA 2023b, EPA 2023c). To evaluate ozone impacts on health we assess NO_x emissions that occur between May and October. EPA provides estimates of health damages from ozone exposure caused by NO_x emitted from the power sector, but does not provide per-ton damage estimates for residential natural gas heating. Instead we apply estimates of damages per ton of NO_x emissions from residential woodstoves.

For CO_2, methane, and refrigerants we use social costs (Rennert et al. 2022; Rennert and Prest 2022; EPA 2021).

We assume that the conversion between emissions and damages does not change over time. Because the damages depend on where people live, this implies that the geographic distribution of the population does not change substantially. This also assumes that there are not substantial changes in the existing background air quality because that would affect the chemistry that causes SO_2, NO_x, and NH_3 to turn into $PM_{2.5}$ as well as how NO_x emissions impact ozone formation.

We use a 2% discount rate for future damages (The White House 2024). We report all damages in 2022 dollars.

3. Results

We report our results in three main subsections. First, we compare the values of the three types of power sector emissions rates. In this section, we focus specifically on emission rates of CO_2 both for simplicity of discussion and also because the LRMERs are not available for other pollutants.

Second, we report results summed across the contiguous United States. Results in this second section do not necessarily represent the *typical* heat pump impact, but instead represent the summed impact of displacing 1% of fossil fueled water and space heating across all regions analyzed. Regions with higher populations will therefore have more influence on these national results. In this second section we also examine the sensitivity of this national result to the use of alternate emission factors and timings of the transition between types of factors, and the impact of methane and refrigerant leakage. The main results do not include methane and refrigerant leakage.

Third, we report results at each region individually. Results vary widely by region given many differences in weather, electricity generation sources, and existing dwelling and appliance characteristics. Thus it is important to examine the regional analysis, rather than simply assume the national results apply.

3.1 Comparison of different types of CO_2 emission rates

Figure 2 compares CO_2 emission rates of different types and sources. Consistent with Holland et al. (2022), the SRMERs (black) are the highest in every year, although they decline over time. The AERs (orange) are the lowest, and Cambium's estimate for 2022 matches EIA's recorded national average very closely. The LRMERs start out very similar to the AERs but do not decline as much as the grid decarbonizes. A key point here is that by 2030, the AERs and LRMERs are roughly 1/5th and 2/5th that of the SRMERs, respectively. The difference between the emission rates indicates that the use of SRMERs many years after an appliance is installed may produce biased estimates of electric sector impacts. Though there is also a large relative difference between the AERs and the LRMERs, the absolute difference between the two is smaller than the absolute difference between the LRMERs and the SRMERs. Further analysis of the impacts of choice between LRMERs and SRMERs is contained in the section entitled "Sensitivity to choice of electricity emission factors."

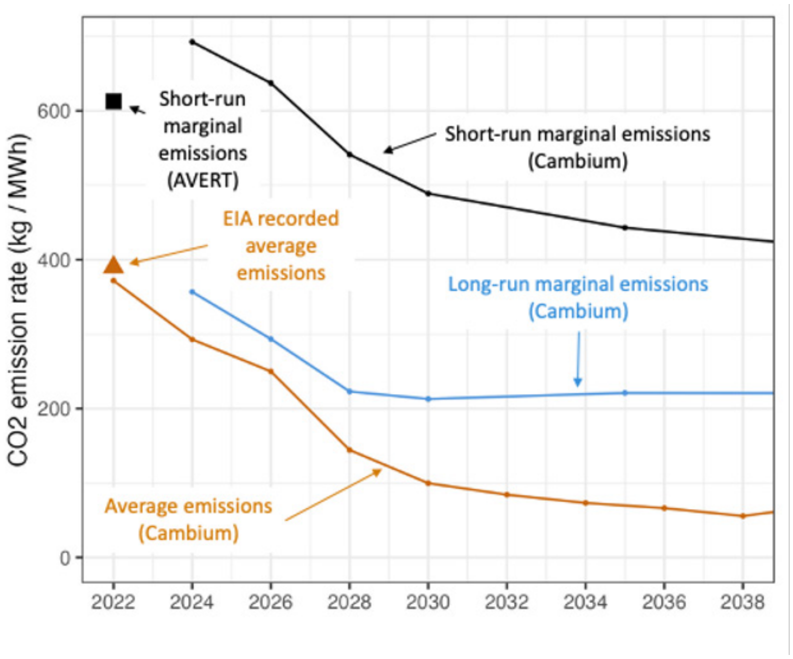

Figure 2. Comparison of average, short-run marginal, and long-run marginal emission rates for CO_2 from EIA, AVERT, and Cambium. In this plot, short- and long-run marginal emissions rates are calculated with the load shapes of all three heat pump types. See Appendix E for an analogous plot with the rates split out by each technology's load shape.

3.2 Contiguous United States

There are substantial lifetime benefits to displacing even 1% of fossil fueled water and space heating in the contiguous U.S. with heat pumps: $1.5 billion for water heating and $7.0 billion or $3.1 billion for very high or minimum efficiency ASHPs, respectively (Figure 3, Figure 4, Figure 5, Table 3). These totals represent an average public benefit of $2,000, $9,200, and $4,100 per household that replaces fossil fueled appliances with HPWHs, very high efficiency ASHPs, and minimum efficiency ASHPs, respectively. For the case of replacement of water heaters and deployment of very high efficiency ASHPs, there are substantial improvements to both climate and air quality impacts. For the case of minimum efficiency ASHPs, we find a lifetime improvement to CO_2 emissions, but only a small lifetime benefit to air quality.

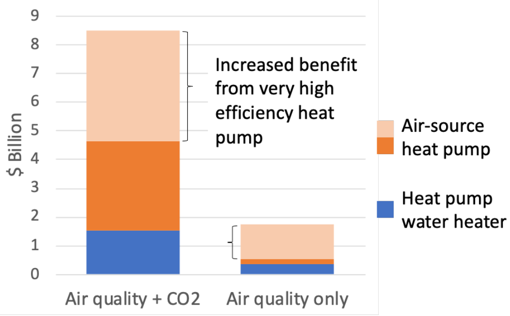

Figure 3. Present value of net lifetime public benefits of displacing 1% of fossil fueled water heating and space heating consumption with heat pumps. The air quality pollutants included are NH_3, NO_x, ozone, $PM_{2.5}$, and SO_2 in outdoor air.

As a proportion of total dollars, the damages and benefits are dominated by CO_2. On a lifetime basis, CO_2 accounts for approximately 70% of the damages and almost 80% of the benefits. That said, there are still net benefits only from the improvement to air quality: \$365 million for water heating and \$179-1,380 million for space heating, with the range reflecting minimum and very high efficiency heat pumps (Figure 4, Figure 5, Table 3).

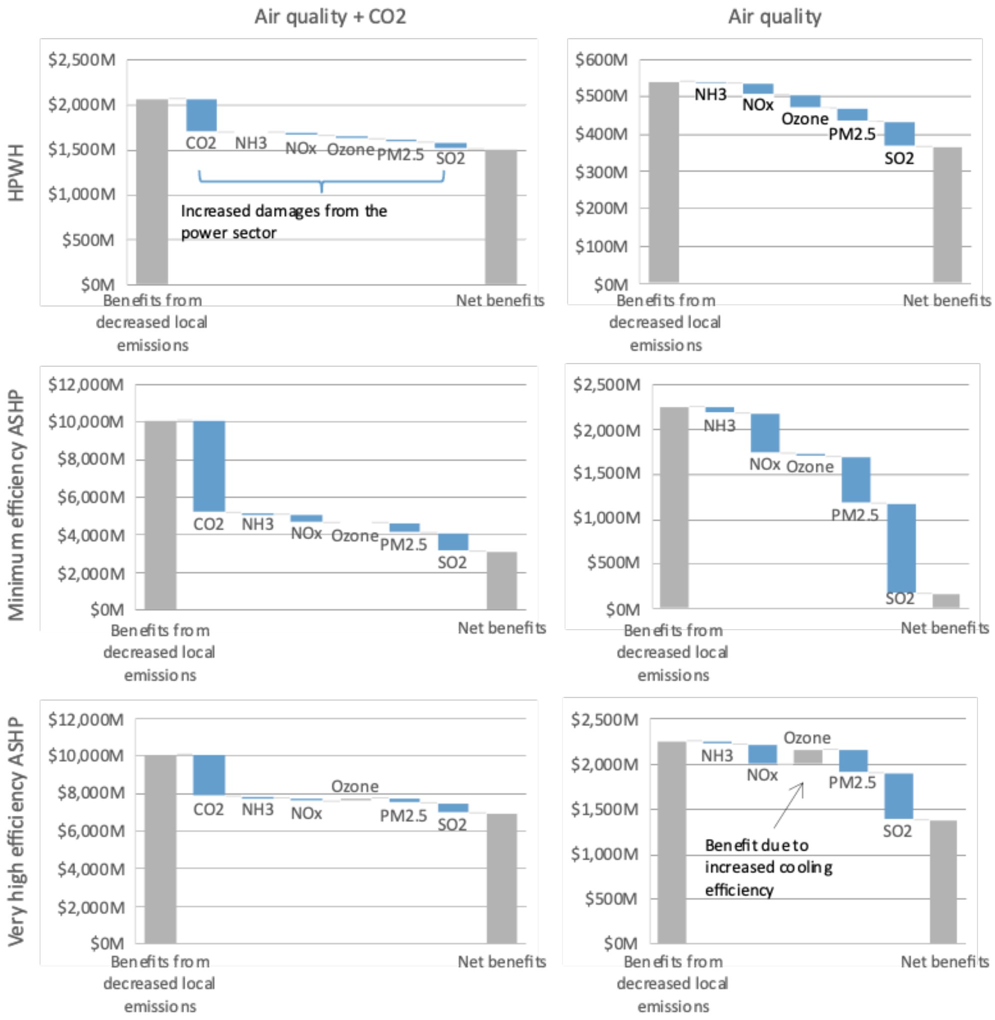

Figure 4. Present value of lifetime public benefits and costs of displacing 1% of fossil fueled water heating and space heating consumption with heat pumps. The lefthand panels include CO_2; the righthand ones only include outdoor air quality pollutants.

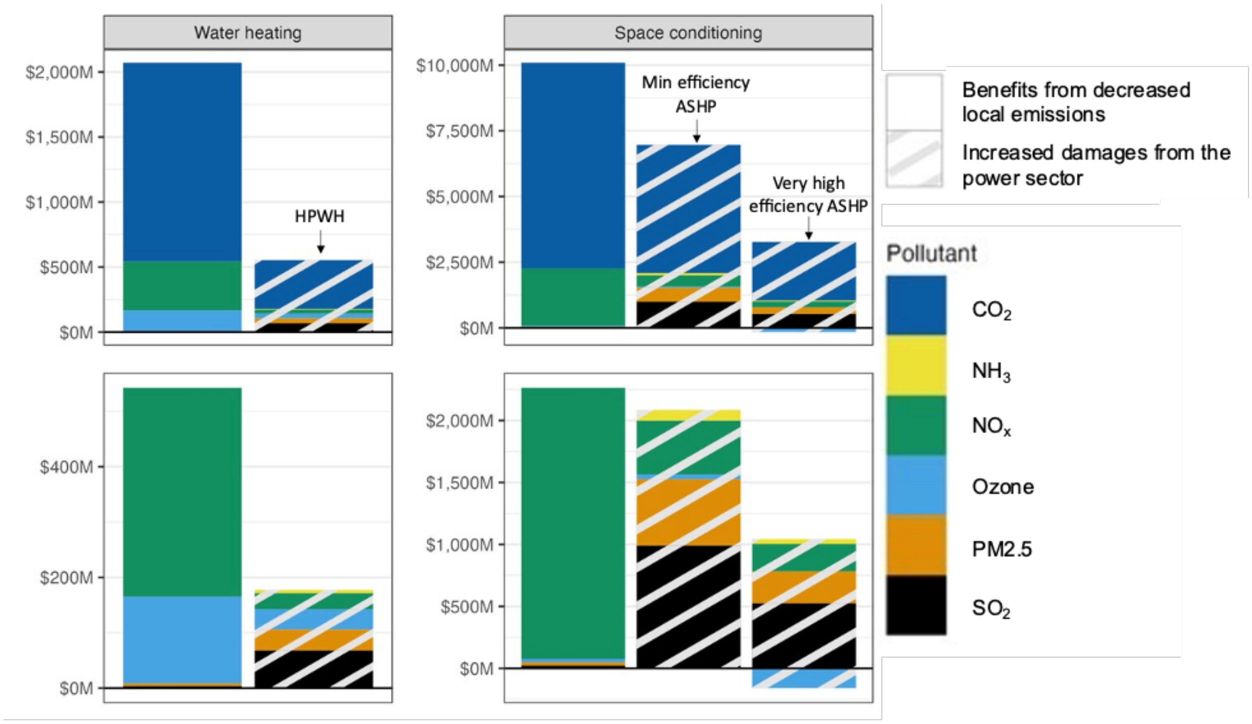

Figure 5. Present value of lifetime public benefits and costs of displacing 1% of fossil fueled water heating (left) and space heating (right) consumption with heat pumps. Solid bars indicate benefits from decreased local emissions; hashed bars indicate increased damages from the power sector. The top panels include CO_2; the bottom ones only include air quality pollutants. The negative hashed bar for the very high efficiency ASHPs is due to electricity savings from replacing less efficient air conditioners with higher efficiency cooling.

Table 3. Present value of net lifetime public benefits and costs of water or space heating electrification using heat pumps. The air quality pollutants included are NH_3, NO_x, ozone, $PM_{2.5}$, and SO_2 in outdoor air. Per household benefits represent the public benefit per household that electrifies.

	Displacing 1% of fossil fueled stock ($M)		Per household ($)	
	Air quality + CO_2	Air quality	Air quality + CO_2	Air quality
HPWH	1,518	365	2,000	500
Minimum efficiency ASHP	3,123	179	4,100	200
Very high efficiency ASHP	6,981	1,380	9,200	1,800

The majority of these benefits accrues after the first year of operation, and while both HPWHs and very high efficiency ASHPs see benefits in the first year, minimum efficiency heat pumps have a net first year cost (Appendix B). Our usage of SRMERs in the first three years of operation is conservative, and so it is notable that very high efficiency heat pumps and HPWHs are found to provide both climate and air quality benefits even in this first year.

Figure 6 shows the present value of the annual components of the damages across the lifetime of the appliances. The gray area represents the benefits from avoided on-site fossil combustion. The avoided emissions remain constant each year, but the present value of the benefits (gray area) declines over time because of the 2% discount rate. The blue area represents the damages caused by increased electricity consumption. The present value of the power sector damages declines over time for three reasons: the 2% discount rate, the change in the generation mix over time, and importantly, the shift from SRMERs to AERs.

The steep slope between 2026 and 2029 is caused by this shift from SRMERs to AERs. As described earlier, for the first three years of the equipment's operation, we calculate the emissions using SRMERs from AVERT, which represent the changes in emissions due to the extra, unplanned for load on the existing grid. Starting in the sixth year of operation, we use average emission factors and we account for the changing composition of the generation mix (i.e., decarbonization) over time. In the fourth and fifth years, we interpolate between the two types for factors, which is visible as the steep slope in the figure.

For the heat pump water heater and very high efficiency heat pump, the damages from increased power sector emissions (blue) are less than the avoided damages from local emissions (gray) in every year. For the minimum efficiency heat pump, the annual benefit is positive starting in its fourth year of operation.

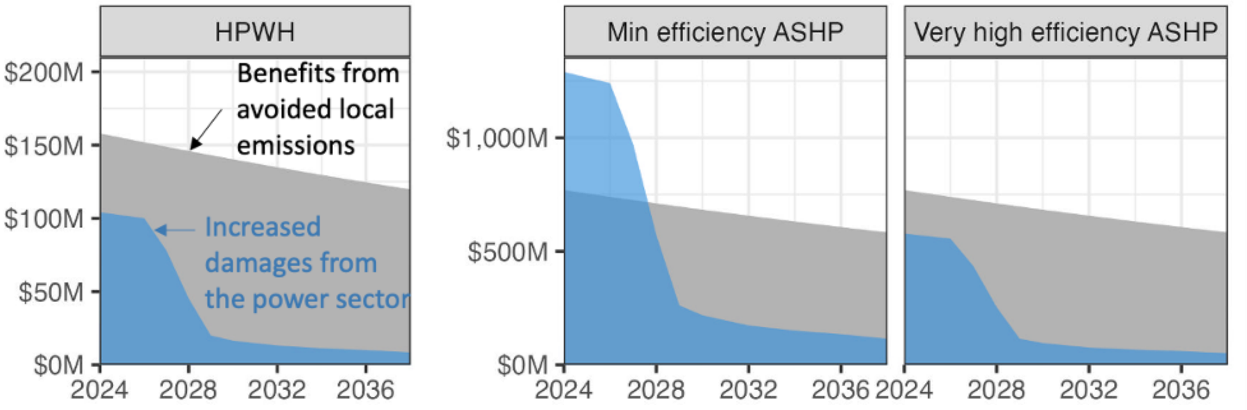

Figure 6. Present value of annual public benefits and costs of displacing 1% of fossil fueled water or space heating consumption with heat pumps. Future damages are discounted at 2%. Power sector emissions are calculated using SRMERs for the first two years, AERs starting in the fifth year, and a linear interpolation during the two intermediary years. Where the avoided damages from local emissions (gray) are higher than the increased damages from the power sector (blue), there is an overall benefit to society.

3.2.1 Avoided methane leakage

Methane is a potent greenhouse gas and is leaked from appliances and distribution infrastructure. Electrification of space and water heating will therefore reduce leakages of methane and contribute to climate benefits. However, the increased use of natural gas in the power system will counteract some of that benefit. We develop a first-order estimate of methane benefits from space and water heating electrification and find that, given our set of assumptions, lifetime methane benefits are less than 10% of the total lifetime climate and air quality benefits (Appendix D).

The relatively small value of avoiding methane leakage may seem surprising. For example, one might expect methane impacts to be a similar order of magnitude to CO_2 benefits given that the 20 year global warming potential of methane is cited as >80 times that of CO_2 (Forster et al. 2021) and that leakage rates of methane across the system can be well above 1% (Table D-1). However, two key concepts limit methane impacts to less than 10% of climate and air quality impacts. First, the social cost of methane emissions is estimated to be roughly 10 times that of the SCC, a much smaller difference than is found when considering global warming potentials (Rennert et al. 2022; Rennert and Prest 2022). Second, methane leakage is estimated to be higher through the production phase than the distribution phase including behind-the-meter leakage. Therefore, while the distribution phase leakage is uniquely avoided through electrification, the benefits are relatively low. Additionally, while the avoided production leakage from reduced residential demand may be relatively high, it is partially offset by production leakage from increased electricity demand.

Given the relatively low impacts found from our first-order estimate of methane emissions, we do not pursue the topic further. However, our methods and sources are fully described in Appendix D and can be easily adapted by readers to test the effect of different assumptions.

3.2.2 Refrigerant leakage

Similar to our analysis of methane leakage, we develop a first-order estimate of cost of refrigerant leakage from electrification of space and water heating (Appendix D). We find that the costs of increased refrigerant leakage are less than 10% of the total lifetime benefits (similar to methane, but as a cost rather than a benefit). A key concept which drives the relatively low impact of refrigerant leakage is that most heat pumps will replace the need for an air conditioning unit. In the case of replacement, the additional leakage from heat pumps is marginal compared to that which would have occurred from an air conditioner. In the case where a heat pump does not replace the need for an air conditioner, a very high efficiency heat pump contains 0.053 metric-tons of refrigerant on average, of which 70% can be expected to leak over its lifetime. In contrast, on average, each unit is expected to reduce 42 metric-tons of CO_2. As with the topic of methane leakage, we do not pursue further investigation of this topic, but do provide our detailed assumptions in Appendix D.

3.3 Regional

In all 14 regions, there is a lifetime benefit from electrification of residential water and space heating when considering the sum of climate and air quality impacts (Figure 7, Figure 8, Figure 10, Table 4). Lifetime benefits are found in all regions even for the minimum efficiency ASHP, though the magnitude of the benefits is, of course, lower when compared with very high efficiency ASHPs.

When isolating the air quality health impacts, there is a net lifetime benefit in all regions for HPWHs, 13 regions for the very high efficiency ASHPs, and 9 regions for the minimum efficiency ASHPs (Figure 7, Figure 9, Figure 11, Table 4). With very high efficiency heat pumps, no regions have a net negative air quality impact. The five regions that have a net negative lifetime air quality impact from minimum efficiency heat pumps are the Central, Midwest, Rocky Mountains, Southwest, and Tennessee regions.

The regions with the largest benefits tend to be those where the cooling load dominates the heating one, such as Florida and Texas, where the increased cooling efficiency of the heat pump produces net electricity savings.

The results are more mixed when only considering the first year of operation. See Appendix B for more information.

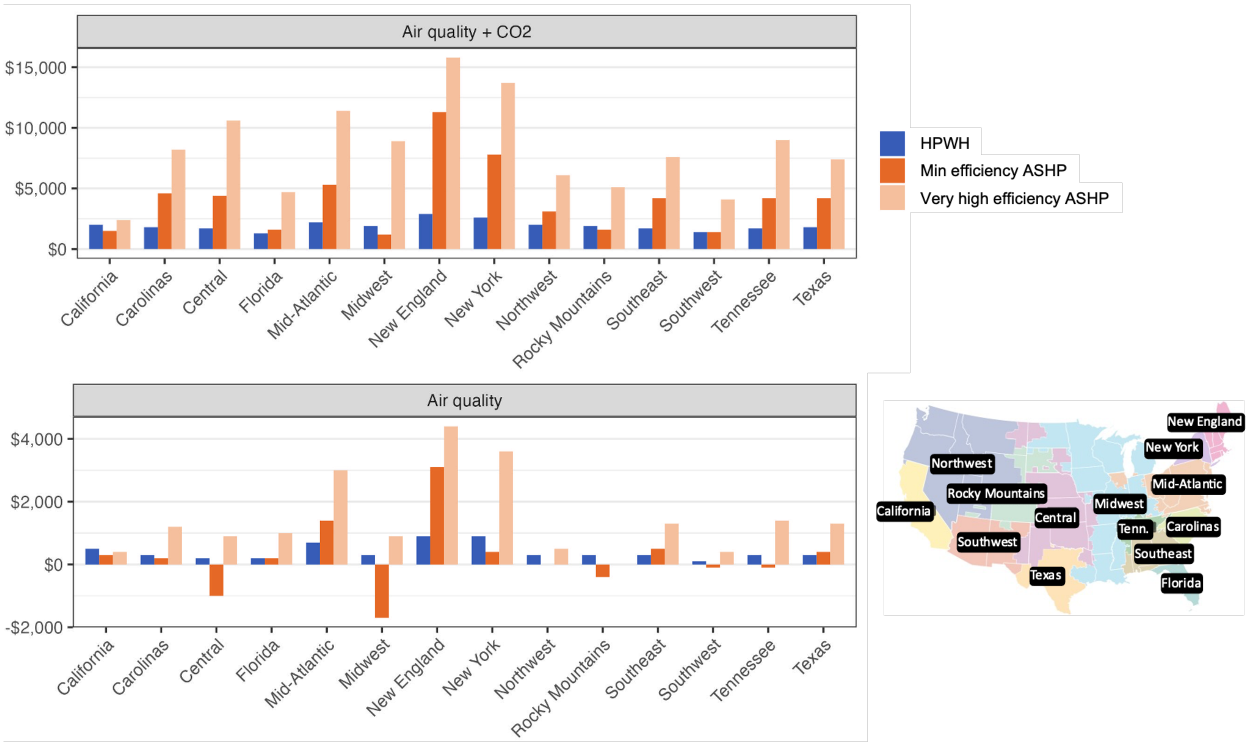

Figure 7. Present value of net lifetime public benefits and costs per household electrifying fossil fueled water heating and space heating consumption with heat pumps by AVERT region.

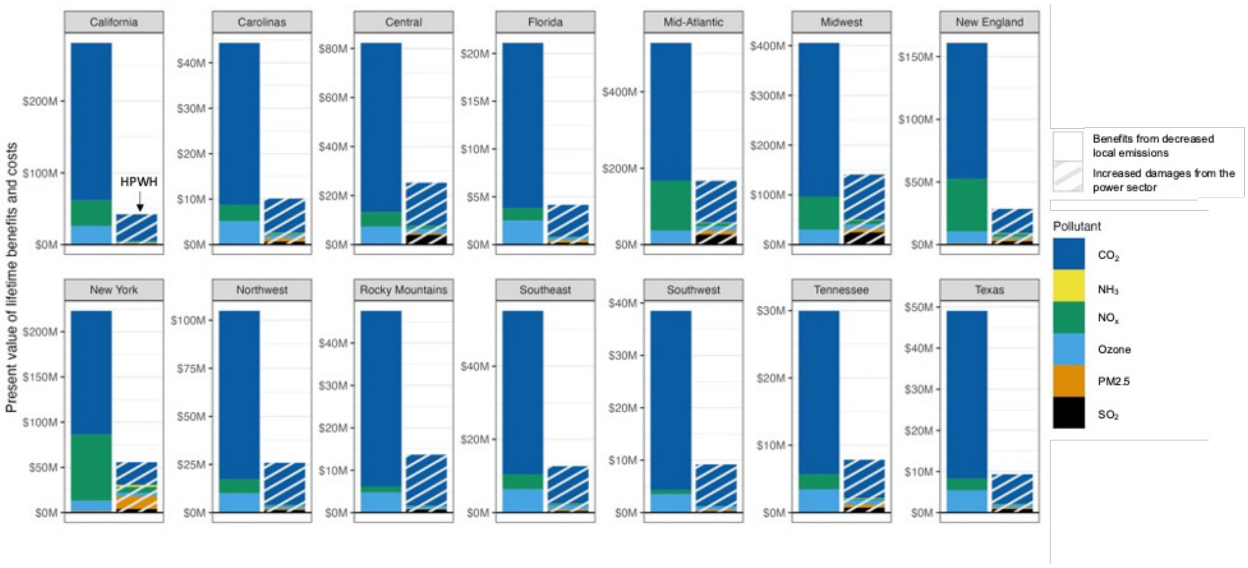

Figure 8. Present value of lifetime public benefits and costs of displacing 1% of fossil fueled water heating consumption with heat pumps by AVERT region. Solid bars indicate avoided damages from local emissions; hashed bars indicate increased damages from the power sector.

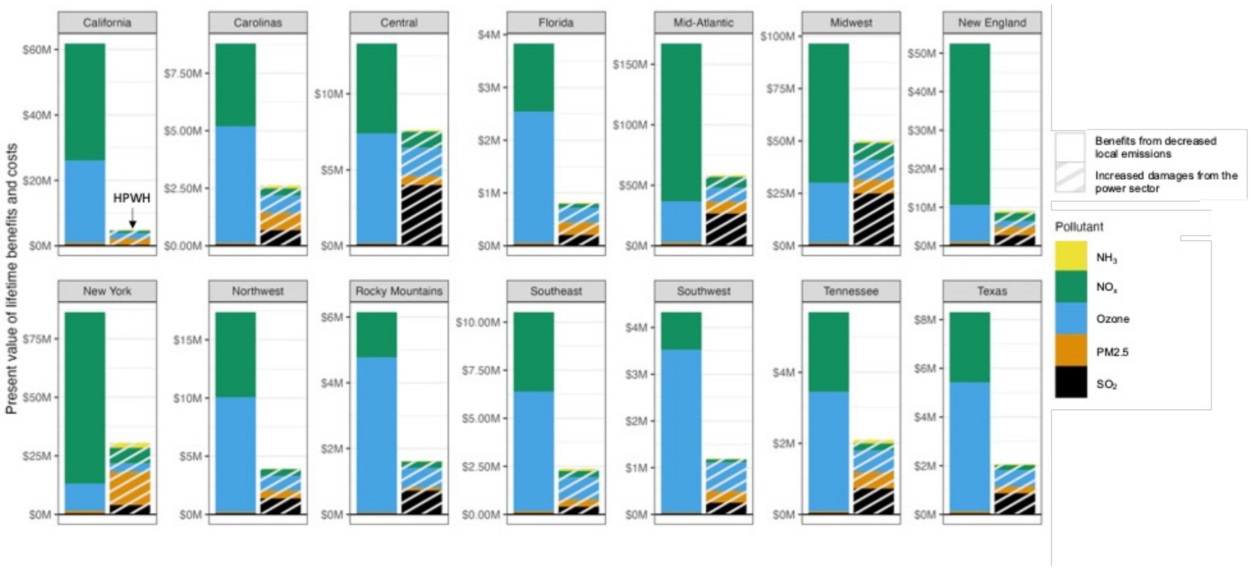

Figure 9. Present value of lifetime public benefits and costs from air quality pollutants of displacing 1% of fossil fueled water heating consumption with heat pumps by AVERT region. Solid bars indicate avoided damages from local emissions; hashed bars indicate increased damages from the power sector.

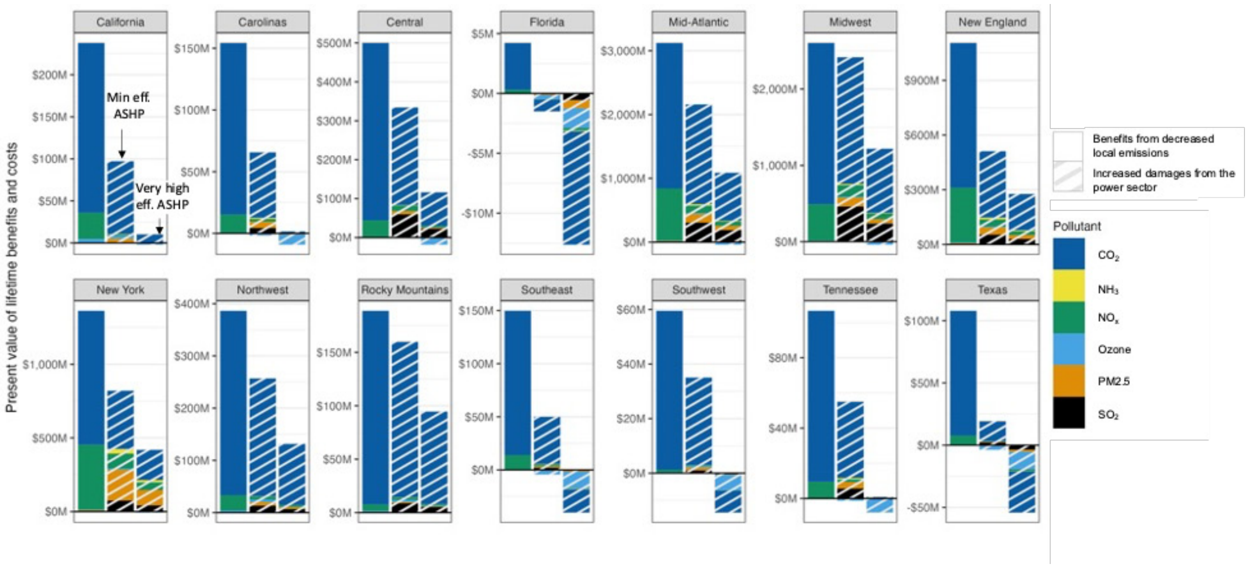

Figure 10. Present value of lifetime benefits and costs from of displacing 1% of fossil fueled space heating consumption with heat pumps by AVERT region. Solid bars indicate avoided damages from local emissions; hashed bars indicate increased damages from the power sector. The negative hashed bar for the very high efficiency ASHP is due to electricity savings from replacing less efficient air conditioners with higher efficiency cooling.

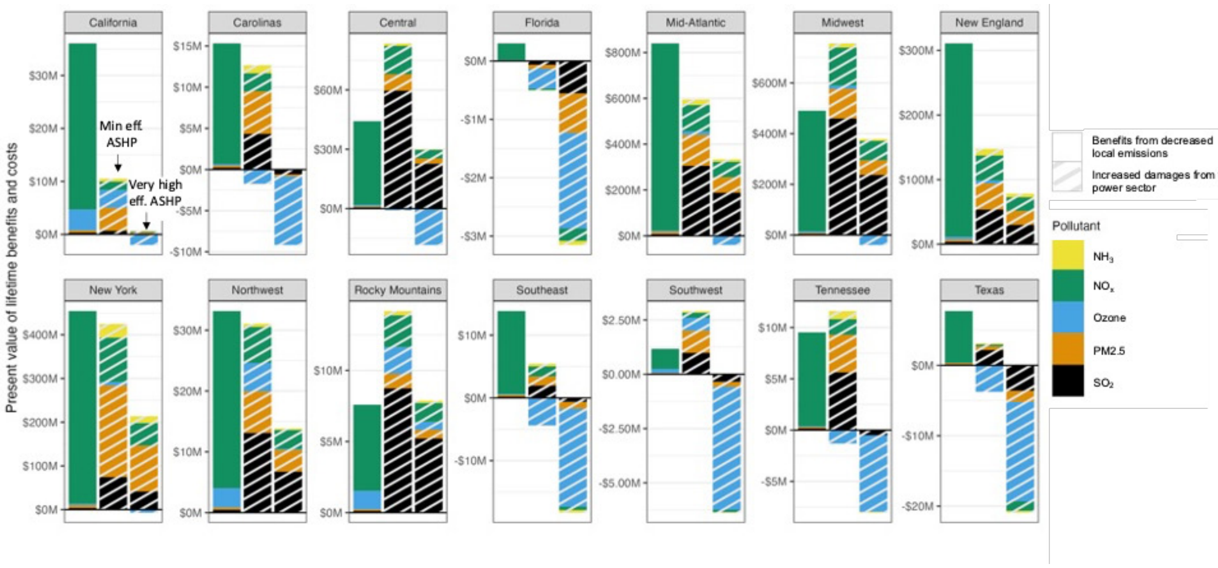

Figure 11. Present value of lifetime public benefits and costs from air quality pollutants of displacing 1% of fossil fueled space heating consumption with heat pumps by region. Solid bars indicate avoided damages from local emissions; hashed bars indicate increased damages from the power sector. The negative hashed bar for the very high efficiency ASHP is due to electricity savings from replacing less efficient air conditioners with higher efficiency cooling.

Table 4. Present value of net lifetime benefits and costs by region of water or space heating electrification using heat pumps. The air quality pollutants included are NH_3, NO_x, ozone, $PM_{2.5}$, and SO_2 in outdoor air. Per household benefits represent the public benefit per household that electrifies.

	Displacing 1% of fossil fueled stock ($M)						Per household ($)					
	Air quality + CO_2			Air quality			Air quality + CO_2			Air quality		
	HPWH	Min. eff. ASHP	V. high eff. ASHP	HPWH	Min. eff. ASHP	V. high eff. ASHP	HPWH	Min. eff. ASHP	V. high eff. ASHP	HPWH	Min. eff. ASHP	V. high eff. ASHP
California	239	141	230	57	26	37	2,000	1,500	2,400	500	300	400
Carolinas	34	90	162	6	4	24	1,800	4,600	8,200	300	200	1,200
Central	57	167	402	6	-39	33	1,700	4,400	10,600	200	-1,000	900
Florida	17	6	17	3	1	3	1,300	1,600	4,700	200	200	1,000
Mid-Atlantic	361	964	2,075	109	246	546	2,200	5,300	11,400	700	1,400	3,000
Midwest	264	187	1,426	46	-266	151	1,900	1,200	8,900	300	-1,700	900
New England	132	594	830	43	163	234	2,900	11,300	15,800	900	3,100	4,400
New York	167	542	951	56	30	247	2,600	7,800	13,700	900	400	3,600
Northwest	79	129	255	13	2	19	2,000	3,100	6,100	300	0	500
Rocky Mountains	34	29	94	5	-7	0	1,900	1,600	5,100	300	-400	0
Southeast	42	104	190	8	13	32	1,700	4,200	7,600	300	500	1,300
Southwest	29	24	74	3	-2	8	1,400	1,400	4,100	100	-100	400
Tennessee	22	53	114	4	-1	18	1,700	4,200	9,000	300	-100	1,400
Texas	40	92	162	6	8	29	1,800	4,200	7,400	300	400	1,300
National	1,518	3,123	6,981	365	179	1,380	2,000	4,100	9,200	500	200	1,800

3.4 Sensitivity to methodological choices

3.4.1 Long-run marginal vs. average electricity emission rates

As described in the introduction and methodology, long-run marginal emission rates (LRMERs) offer an alternative approach to average emission factors for assessing the long term emission impacts of new demand (or new supply) on a system. To test the sensitivity of our results to the choice of rates, we apply LRMERs instead of average emission factors for electricity use three or more years in the future. We run this sensitivity test only for CO_2 emissions, as LRMERs for the air pollutants of interest are not available. The long-run marginal emissions are approximately 100% higher than those calculated with the AERs. However, this 100% increase is to a relatively small portion of damages (represented by the thin blue area for later years in Figure 6) – damages from the first three years of emissions dominate the lifetime damages from increased power sector emissions (50-60% of the total). Thus, our overall results are not sensitive to the choice between average and LRMERs. Specifically, we find that total lifetime benefits are decreased by only 5% and 10% for HPWHs and very high efficiency ASHPs, respectively, when LRMERs are used instead of AERs (Table 5). An important exception however is that minimum efficiency ASHP results are sensitive to the choice of emission factors, showing a 47% decline in lifetime benefits. (Minimum efficiency ASHPs are more sensitive to choice of electric sector emission factor because they, by definition, use more electricity).

Table 5. Present value of net lifetime public benefit of displacing 1% of fossil fueled water or space heating consumption with heat pumps using average or long-run marginal emission factors. Includes both CO_2 and air quality pollutants in outdoor air.

	Lifetime benefit ($M)		
	Short-run and average	Short-run and long-run	% Decrease
HPWH	1,518	1,436	5%
Minimum efficiency ASHP	3,123	1,670	47%
Very high efficiency ASHP	6,981	6,289	10%

We use AERs for the main analysis because the overall results are not sensitive to the choice of factors and because LMRERs are not available for the air quality pollutants.

3.4.2 Timing of the transition from short-run marginal to average emission rates

One key methodological choice is when to transition from SRMERs to AERs, as shown in the steep decline in annual damages from the power sector during the transition period (Figure 6). EPA recommends that the SRMERs from AVERT only be used for electricity consumption up to 5 years in the future (EPA 2023a). In our main analysis, we use SRMERs for heat pump operation in 2024-2026, AERs from 2029, with a linear interpolation between the two in 2027-2028.

To test the sensitivity of our results to the timing of the transition between types of rates, we begin the transition to AERs two years earlier, in 2025. This can also be thought of as utilities starting to plan for electrification sooner. As shown in Figure 12, the impact varies widely by region and technology. For example, net air quality and CO_2 benefits increase by 70% in the Midwest for the minimum efficiency ASHP and decrease by 10% in Florida for the very high efficiency ASHP. The small decrease in benefits occur in regions with net electricity savings from cooling because the SRMERs weight savings in the summer hours more strongly than the AERs do.

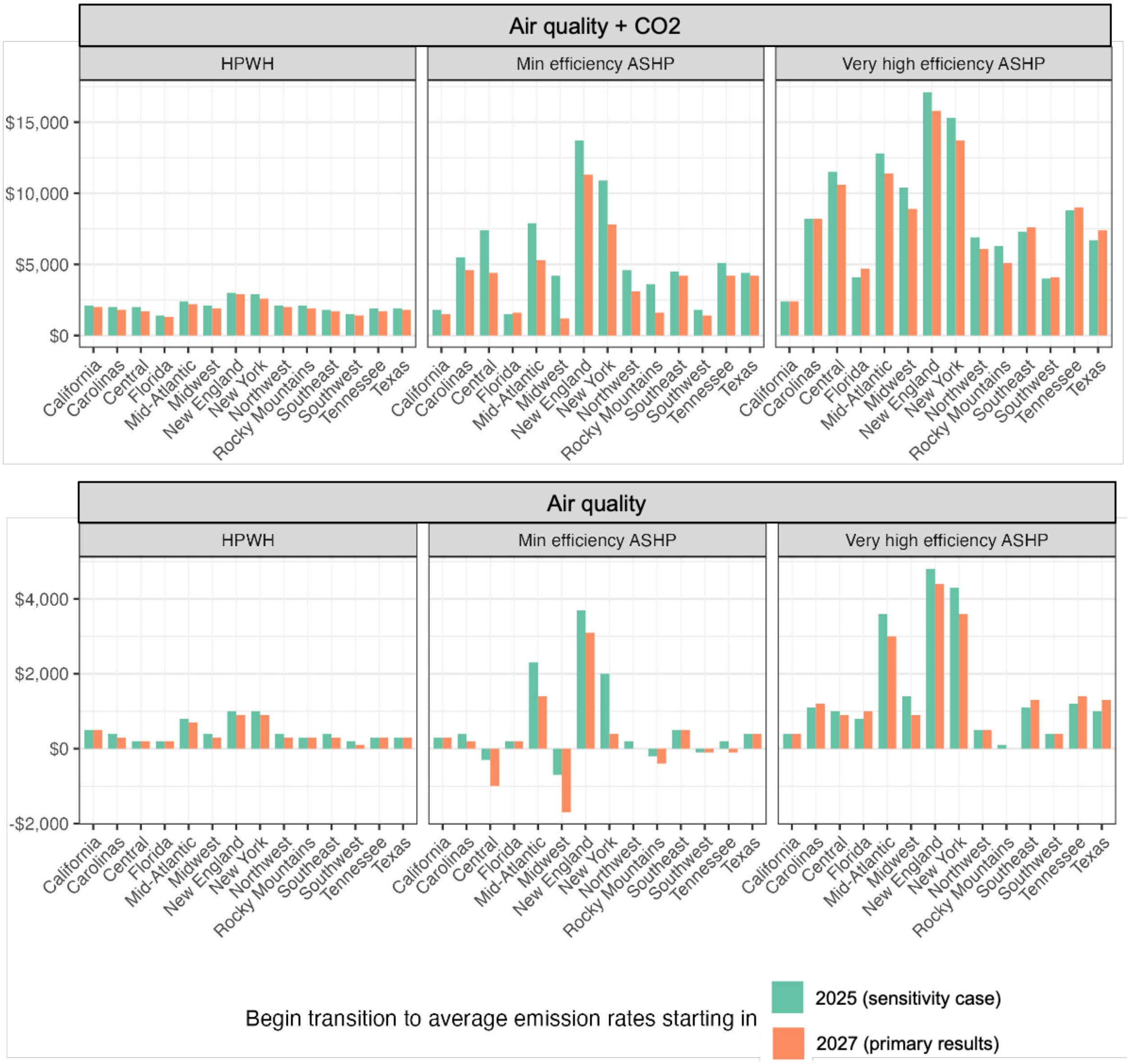

Figure 12. Comparison of benefits by year transitioning to AERs: present value of net lifetime public benefit per household electrifying fossil fueled water heating and space heating with heat pumps by AVERT region.

4. Discussion and conclusion

Here we examine the emissions trade-offs associated with electrifying residential space heating and water heating. For the contiguous United States we find that replacing 1% of fossil fueled water heating with HPWHs and replacing 1% of fossil fueled space heating with very efficient ASHPs reduces climate damages and provides outdoor air quality health benefits. Specifically, more CO_2 emissions are avoided from eliminating combustion in residential homes associated with existing appliances than are caused by generating the electricity to power the heat pumps. Likewise, more health damages are avoided from eliminating NO_x, $PM_{2.5}$, SO_2, and NH_3 emissions associated with existing appliances than are caused by the electricity generation used to power the heat pumps. Although both types of pollutants contribute to the benefit of residential electrification, the climate benefits from CO_2 reductions account for approximately 80% of the net benefits. Further, and as described below, these positive results are robust to the most important methodological decisions incorporated in our analysis.

The benefits of the minimum efficiency ASHPs are more mixed: Across the contiguous United States, replacing 1% of fossil fuel space heating needs with low efficiency ASHPs reduces CO_2 emissions but only marginally improves air quality. Impacts vary by region, with 5 of 14 regions showing that minimum efficiency ASHPs causing air quality penalties, though in all regions, they help to reduce climate damages. Because the net health impact is small in many regions, the conclusion of whether it is a cost or benefit overall is sensitive to methodological choices. In contrast, high efficiency ASHPs provide air quality benefits in 13 of 14 regions, and because the impacts are larger, the overall conclusion is not as sensitive to methodological choices.

One important implication of these findings is that the efficiency of the ASHP is important to consider if designing policy to promote *both* climate and regional air quality improvements with electrification.

That benefits of the minimum efficiency ASHPs are smaller and less robust than those of the very high efficiency ASHPs is an important finding because the specifications of the minimum efficiency ASHPs are less efficient than, but close to, the cutoff for qualification for ENERGY STAR ® designation, which is used in many incentive programs including IRA Rebates.

If a policy goal is to ensure that fossil-to-ASHP incentives provide both air pollution and climate benefits in all regions, robust efficiency requirements or other policies such as emissions controls on existing power plants are necessary to achieve that goal.

There are challenges to accelerating adoption of very efficient ASHPs, including that they have significantly higher upfront costs (Wilson et al. 2024). Though not covered in this paper, future research could assess detailed trade-offs between increased efficiency, upfront costs, operational savings, and air quality and climate benefits.

An important aspect of this work is the consideration of the impacts on climate and air quality over the lifetime of the appliance. A key methodological choice we make is to assume that during the first few years of a heat pump's lifetime its electricity is supplied by generators on the margin. The use of SRMERs leads to a conservative estimate of both air quality and climate benefits because they are typically higher than AERs (Holland et al. 2022, Figure 2). We justify the use of SRMERs for the early years of a heat pump's lifetime based on the idea that heat pump adoption rates are higher than previously planned due to the relatively new incentives included in the IRA (i.e., we assume grid planners have not included IRA-related electrification in their load forecasts). If instead one assumed average emission (or long-run marginal emission) rates from the start of a heat pump's life, our lifetime benefit estimates would increase (Figure 12). We also stress that future research on this topic should not apply short run marginal emission rates across the life of the appliance, but only at the beginning of an appliance's lifetime.

We also make choices about future emission rates from the electricity system, taking a mid-case future scenario to determine average emission rates in later years of each heat pump's lifetime. Our results are relatively insensitive to more aggressive decarbonization pathways because average emission rates are expected to be relatively low even in the mid-case decarbonization scenario, thus further reductions of average emission rates provide only small additional benefits to heat pumps. Similarly, the choice of AERs or LRMERs has little effect on our results, with the exception of the minimum efficiency ASHPs where use of LRMERs notably dampens the benefit calculation. The implication of the results described in this paragraph is that benefits can be achieved from deploying heat pumps now, and benefits are not dependent on the realization of a more aggressive decarbonization effort. Also, heat pumps installed in the future will have higher lifetime benefits, both because utilities will have been planning for them and because average emissions rates are expected to decline.

An additional assumption to consider is our choice of appliance replacement. We have assumed that all ages and efficiencies of equipment are equally likely to be replaced. However, it is common to replace equipment when it fails, so the fossil fueled equipment that is replaced first may be older and less efficient than the stock average. Thus, our assumption of equally likely replacement is a conservative assumption with respect to benefit estimates.

Finally, it is important to consider that though we present point values in this paper, there is substantial uncertainty in the air quality benefits and the climate benefits. Uncertainty in the epidemiological functions, air quality modeling, and estimates of the social cost of carbon was not a focus of this work. Instead we focused on capturing the balance between increased power sector emissions and decreased residential emissions. The social cost of carbon estimates have relatively wide uncertainty ranges, and updates to the SCC could substantially change the relative importance of the air quality versus climate impacts. For example, Rennert et al. 2022 report a \$44–\$413 per tCO_2: 5%–95% range for the Social Cost of Carbon, with the mean value being \$185/tCO_2. The total CO_2 benefits calculated in this work would directly scale with a shift in the social cost of carbon estimate. Similarly, while air quality health impact estimates have a relatively narrower range of uncertainty than the SCC, key epidemiological studies show a range of roughly 2X in the mortality risks of exposure to a given level of PM2.5. In this analysis we use the H6C study (Lepeule et al. 2012) from EASIUR for the air quality damages. If we used the results from the American Cancer Society (Krewski et al. 2009), or an average between the two studies, instead, the air quality damage rates and therefore benefits would be larger. That said, while the choice of epidemiological study might shift the magnitude of the air quality benefits, it would not change which scenario (i.e., regions or equipment choice) leads to air quality benefits or penalties, as both the local benefits and power sector penalties would be scaled equally.

In summary, to provide lifetime climate benefits, policymakers can promote residential electrification with HPWHs and even minimum efficiency ASHPs in the contiguous United States. While HPWHs and very high efficiency ASHPs in all regions provide air quality benefits, ASHPs must be more efficient than the minimum standard in five of the fourteen grid regions to achieve air quality benefits with current emission rates from existing power plants. However, these benefits can be achieved even in a mid-case grid decarbonization scenario.

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Appendix A. Appliance emission factors

A.1 EPA's AP-42 Emission Factors

The EPA's Compilation of Air Pollutant Emission Factors (AP-42) compiled air pollutants by source for nitrogen oxide (NO_x), sulfur oxide (SO_x), and particulate matter ($PM_{2.5}$) (EPA 1995). Table A-1 shows the values from AP-42, where SO_x and $PM_{2.5}$ are intended to be applicable for all combustor types (commercial and residential, all appliances and equipment), but the values for NO_x from natural gas combustion differ for different combustor types. The value provided in Table A-1, 94 lb/10^6 scf, is intended for residential space heating and water heating.

Table A-1. EPA's AP-42 emission factors for NO_x, SO_x, and $PM_{2.5}$ from natural gas and distillate fuel oil combustion (EPA 1995).

	Natural Gas Combustion (lb/10^6 scf)	Distillate Fuel Oil Combustion (lb/10^3 gal)
NO_x	94	20
SO_x	0.6	36
$PM_{2.5}$	7.6	2

A.2 Updated $PM_{2.5}$ Emission Factors from a Recent Study

A 2009 report from the Brookhaven National Laboratory (BNL) measured emissions from a wide range of residential heating equipment burning different fuels: natural gas, fuel oil, and wood pellets (McDonald 2009). The study measured O_2, CO_2, CO, NO_x, and SO_2, and found that emission factors were as expected and they fell within the range provided in AP-42. For that reason, BNL's report focused on emissions of fine particulate matter, $PM_{2.5}$.

BNL found a very strong linear relationship between $PM_{2.5}$ emissions and the sulfur content of the liquid fuels being studied (Figure A-1). The tests were performed using a conventional cast iron boiler equipped with a flame retention head burner. The fuels tested included:

- ASTM No.2 fuel oil with very high sulfur content (5780 ppm)
- Typical ASTM No.2 fuel oil with sulfur below 0.5 percent (1520 ppm, average value)
- Low sulfur heating oil (322 ppm)
- Ultra-low sulfur (ULS) diesel fuel (11 ppm)

Additional tests were conducted using the typical, low, and ULS fuel oil on different types of residential heating equipment, including: a conventional oil-fired warm air furnace, a high efficiency condensing warm air furnace, and a condensing hydronic boiler.

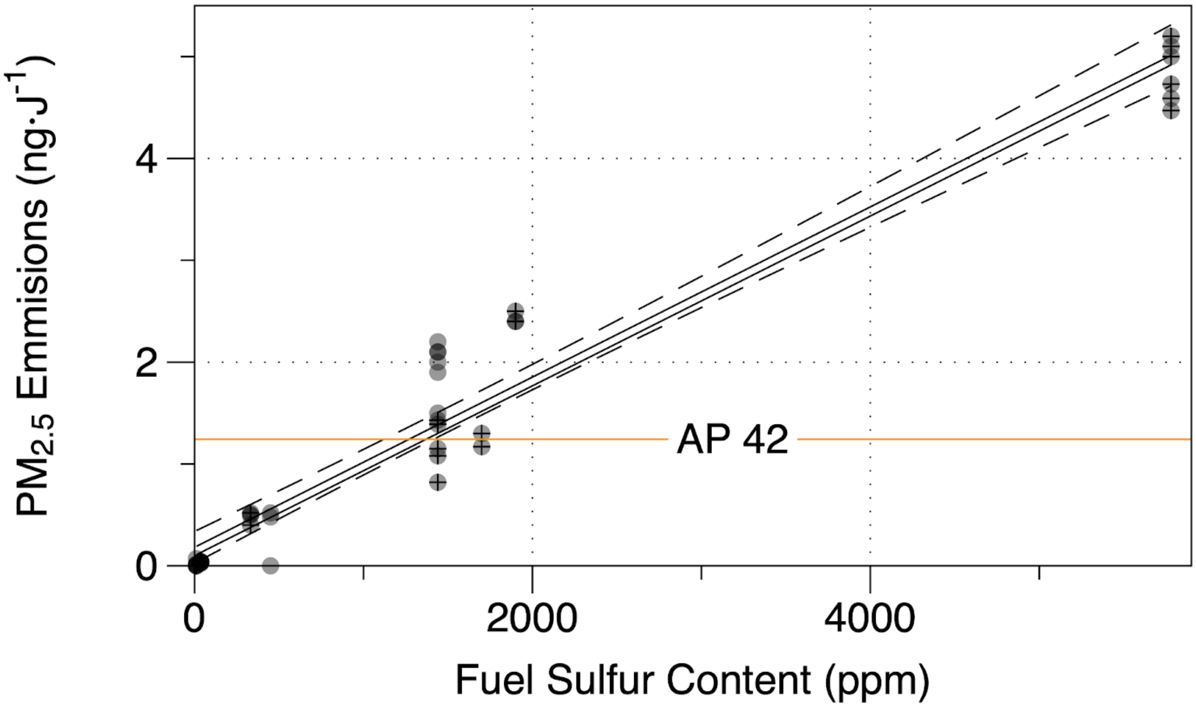

Figure A-1. BNL results of measured PM2.5 emission factors from residential heating equipment using fuel oil with different sulfur content (McDonald 2009).

AP-42 emission factor of 2 lb/10^3 gal, or about 1.3 ng/J, corresponding to fuel oil with a higher sulfur content more typical of the 1990s. We applied the linear relationship shown in Figure A-1 and calculated a 99.4% reduction in $PM_{2.5}$ emission factor when the sulfur content is decreased from 2,500 ppm to 15 ppm (ULS fuel oil).

Many states in the northeast have begun their transition to ULS fuel oil since the early 2010s. In 2012, New York became the first state to require ULS fuel oil that has a sulfur content of 15 ppm or less. Delaware and New Jersey transitioned to ULS fuel oil in 2016, and all six New England states transitioned in 2018. This transition is also reflected in the stock data for distillate fuel oil available from the U.S. Energy Information Administration (Figure A-2), where over 90% of the inventoried stock was ULS.

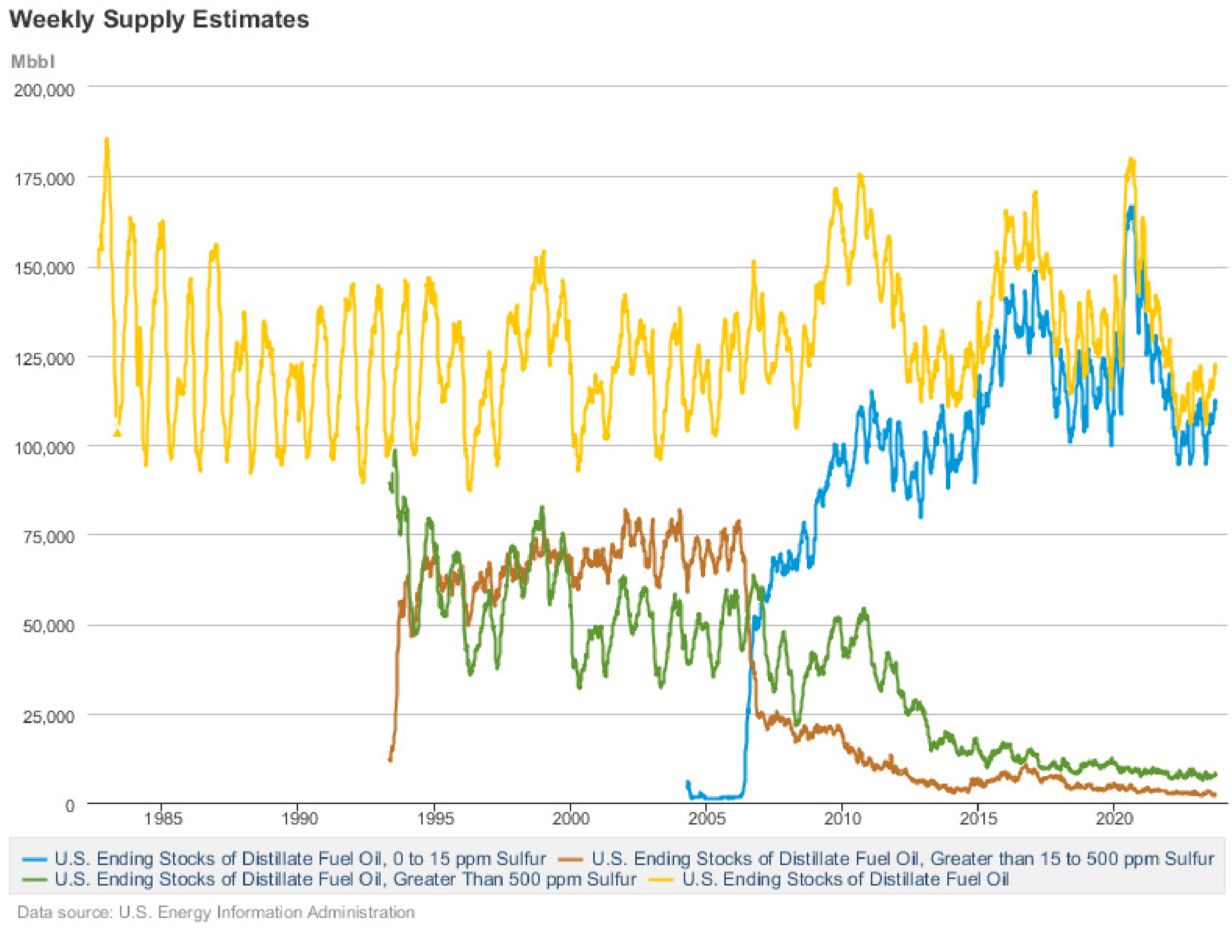

Figure A-2. Time trend of U.S. stocks of distillate fuel oil with different sulfur content, showing that ultra-low sulfur (ULS, in blue) fuel oil dominates the overall inventory.
https://www.eia.gov/dnav/pet/pet_sum_sndw_dcus_nus_w.htm

Figure A-3 shows the $PM_{2.5}$ emissions from the different fuels that BNL had tested, where the results were plotted separately for all fuel oil tested by BNL and ULS only (in green). The median value of 0.027 ng/J from BNL results for ULS corresponds to about 98% decrease in PM2.5 emissions from EPA's AP-42 earlier estimate.

BNL results also suggested a much reduced $PM_{2.5}$ emission factor for natural gas. The median measured value was 0.015 ng/J, which corresponds to 0.04 lb/10^6 scf, or about 99% reduction in emissions from EPA's AP-42 earlier estimate. For modeling of the health impacts from $PM_{2.5}$, these substantially reduced emission rates with respect to EPA's AP-42 values were used.

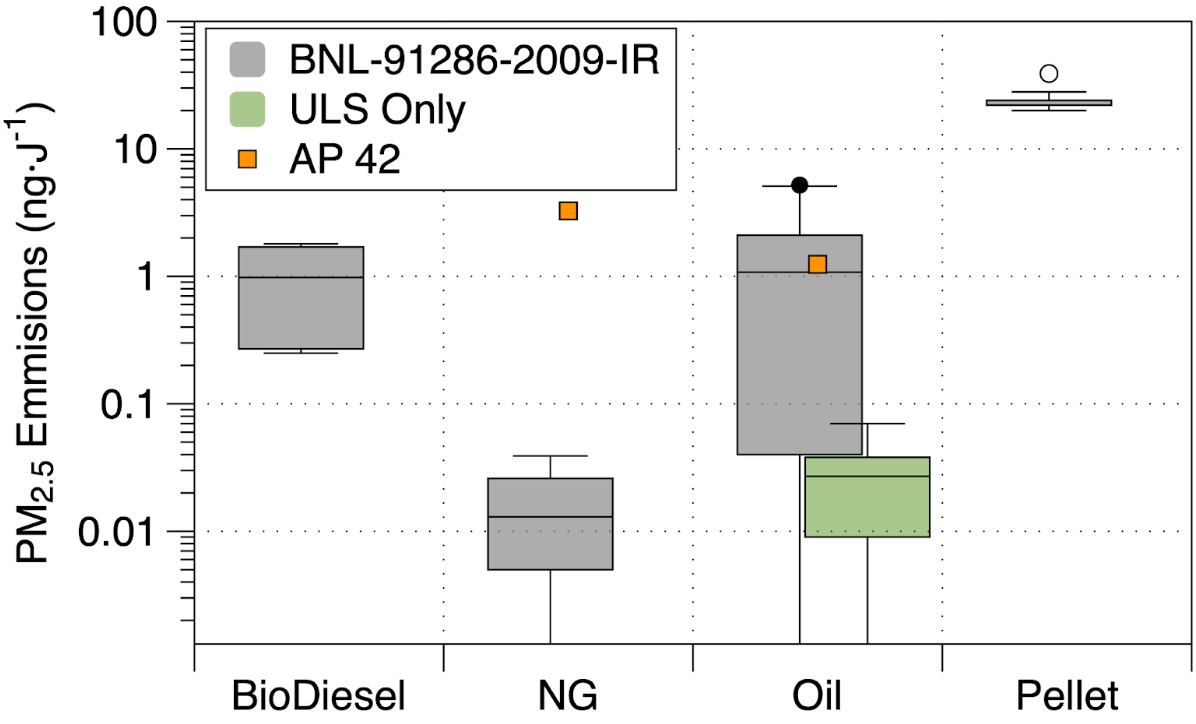

Figure A-3. $PM_{2.5}$ emission factors measured by BNL from residential heating equipment using different fuel types. Results for ultra-low sulfur (ULS, in green) fuel oil were plotted separately. EPA's AP-42 estimates were plotted in orange square for comparison. Data from McDonald (2009).

A.3 Implications from Ultra-Low NO_x Natural Gas

The adoption of low and ultra-low NO_x rules in certain local jurisdictions may have resulted in reduction in NO_x emission factors from gas appliances in some areas. A recent report by the Regulatory Assistance Program summarized existing state and local rules on water heaters (Shenot et al. 2023). There are multiple jurisdictions that have adopted NO_x emission limits for gas-fired water heaters, including several local air agencies in California, and the states of Utah and Texas. However, due to their limited applicability, and the replacement rate of residential appliances, the overall impact of these ruling on emission factors on a national scale is limited. The report found no emission limits in any jurisdiction in the U.S. for water heaters that use fuel oil or propane.

- California: South Coast Air Quality Management District (SCAQMD) was the first agency regulating water heaters in 1998. Currently, nine California air districts regulate NO_x emissions from gas-fueled space heaters and water heaters: Bay Area, San Joaquin Valley, South Coast, Yolo-Solano, San Diego County, and Sacramento Metro. Those districts enforce the emission limit of 10 ng/J NO_x for water heaters (or 24 lb/10^6 scf, assuming a heating value of 1035 Btu/scf for natural gas).
- Texas established a statewide limit in 2000. It adopts the same 10 ng/J NO_x limit as used in California.

- Utah established regulation of gas water heaters in 2015. It sets the limit of 10 ng/J for small water heaters for residential use, and 14 ng/J for large water heaters for commercial use.

In summary, no adjustment was made to the AP-42 NO_x emission rates, due to low representation of low ultra-low NO_x appliances expected at the national level.

Appendix B. First year results

The main text presents the lifetime benefits and costs of electrifying residential space and water heating. This appendix presents the analogous figures and table for operating the heat pump in 2024.

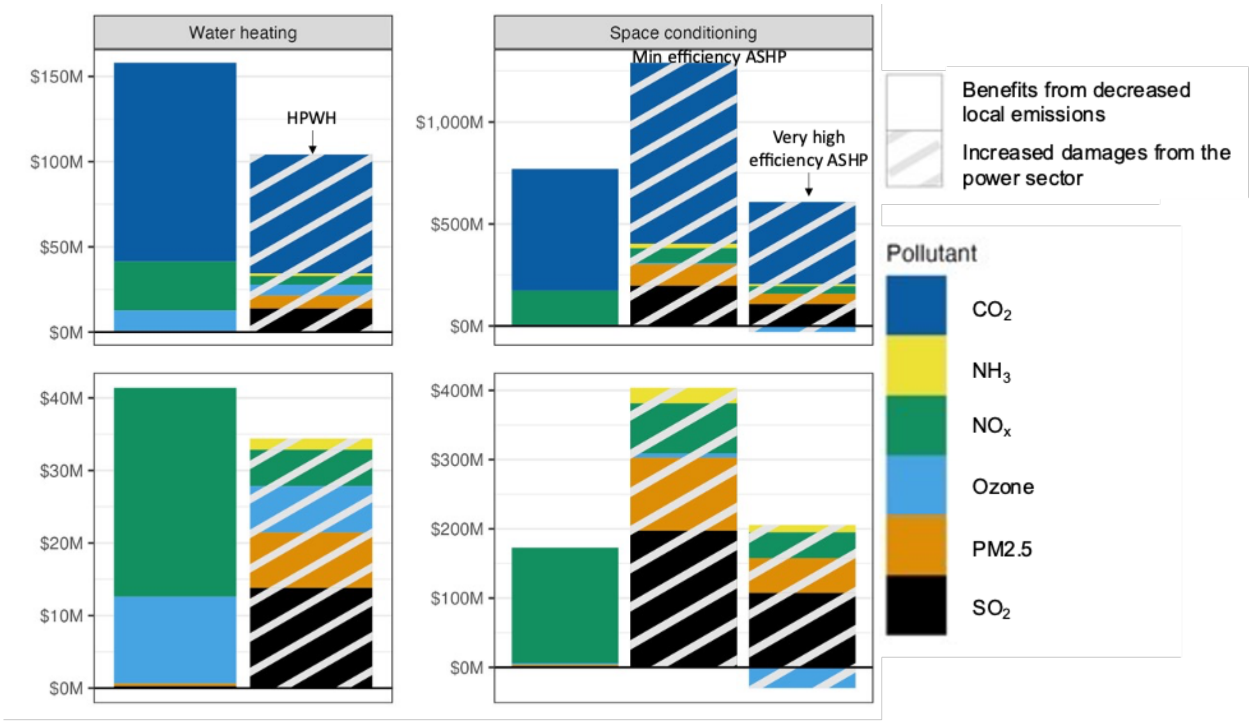

Figure B-1. Present value of the first year public benefits and costs of displacing 1% of fossil fueled water heating (left) and space heating (right) consumption with heat pumps. Solid bars indicate benefits from decreased local emissions; hashed bars indicate increased damages from the power sector. The top panel includes CO_2; the bottom one only include air quality pollutants. The negative hashed bar for the very high efficiency ASHP is due to electricity savings from replacing less efficient air conditioners with higher efficiency cooling.

Table B-1. Present value of first year public benefits and costs of water or space heating electrification using heat pumps. The air quality pollutants included are NH_3, NO_x, ozone, $PM_{2.5}$, and SO_2 in outdoor air. Per household benefits represent the public benefit per household that electrifies.

	Displacing 1% of fossil fueled stock ($M)		Per household ($)	
	Air quality + CO_2	Air quality	Air quality + CO_2	Air quality
HPWH	54	7	0	0
Minimum efficiency ASHP	-521	-231	-700	-300
Very high efficiency ASHP	192	-3	300	0

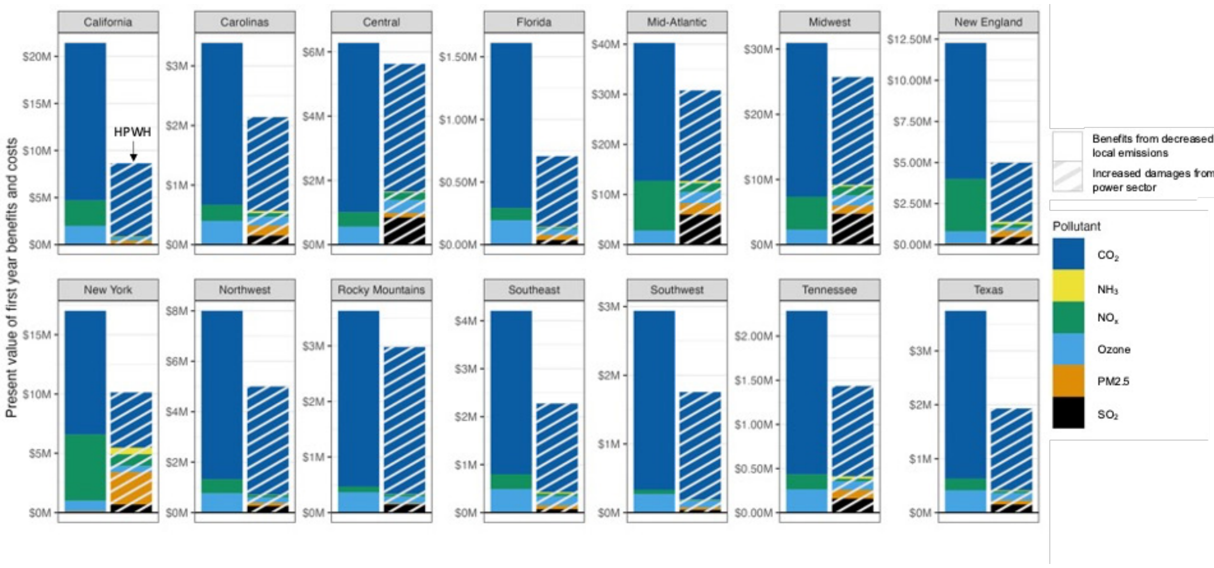

Figure B-2. Present value of first year public benefits and costs of displacing 1% of fossil fueled water heating consumption with heat pumps by AVERT region. Solid bars indicate avoided damages from local emissions; hashed bars indicate increased damages from the power sector.

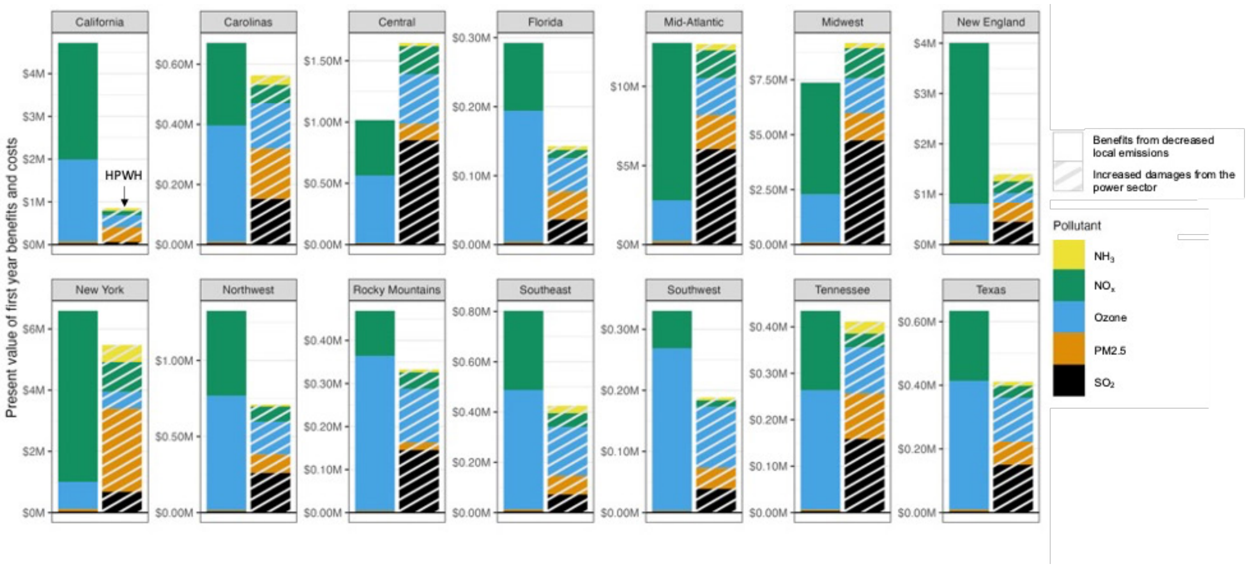

Figure B-3. Present value of first year public benefits and costs from air quality pollutants of displacing 1% of fossil fueled water heating consumption with heat pumps by AVERT region. Solid bars indicate avoided damages from local emissions; hashed bars indicate increased damages from the power sector.

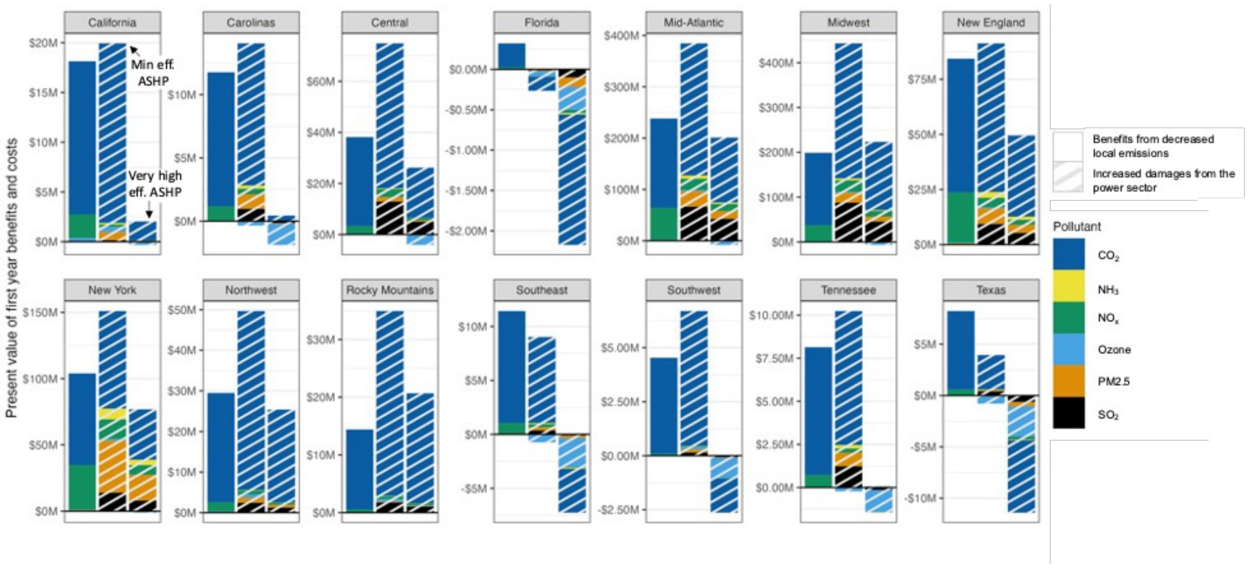

Figure B-4. Present value of first year public benefits and costs from of displacing 1% of fossil fueled space heating consumption with heat pumps by AVERT region. Solid bars indicate avoided damages from local emissions; hashed bars indicate increased damages from the power sector. The negative hashed bar for the very high efficiency ASHP is due to electricity savings from replacing less efficient air conditioners with higher efficiency cooling.

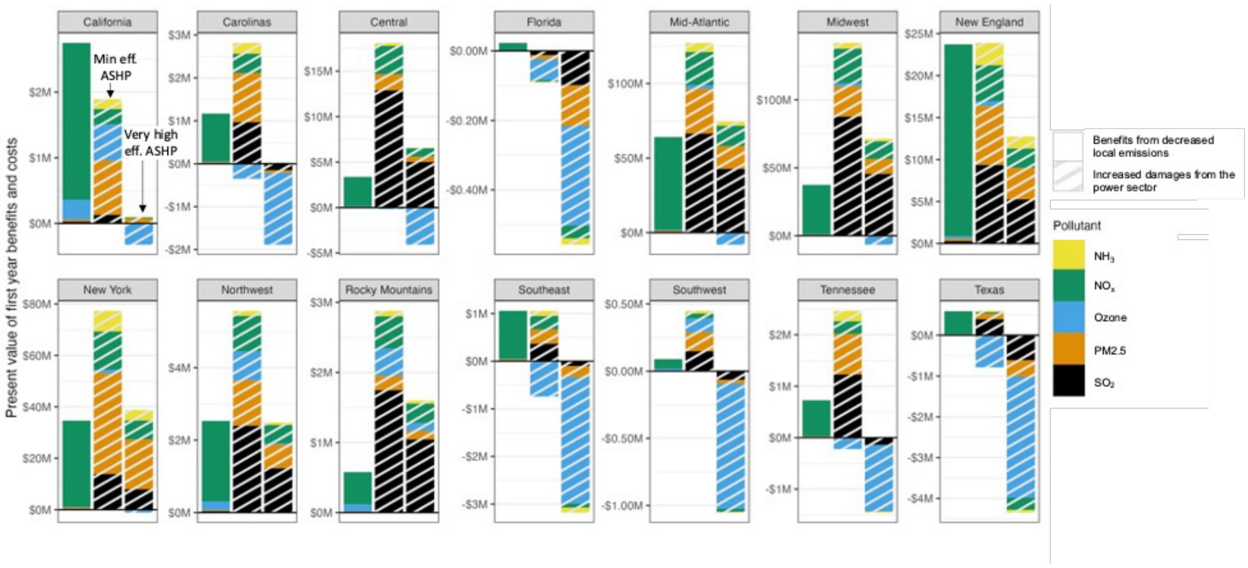

Figure B-5. Present value of first year public benefits and costs from air quality pollutants of displacing 1% of fossil fueled space heating consumption with heat pumps by AVERT region. Solid bars indicate avoided damages from local emissions; hashed bars indicate increased damages from the power sector. The negative hashed bar for the very high efficiency ASHP is due to electricity savings from replacing less efficient air conditioners with higher efficiency cooling.

Table B-2. Present value of first year public benefits and costs of water or space heating electrification using heat pumps by AVERT region. The air quality pollutants included are NH_3, NO_x, ozone, $PM_{2.5}$, and SO_2 in outdoor air. Per household benefits represent the public benefit per household that electrifies.

	Displacing 1% of fossil fueled stock ($M)						Per household ($)					
	Air quality + CO_2			Air quality			Air quality + CO_2			Air quality		
	HPWH	Min. eff. ASHP	V. high eff. ASHP	HPWH	Min. eff. ASHP	V. high eff. ASHP	HPWH	Min. eff. ASHP	V. high eff. ASHP	HPWH	Min. eff. ASHP	V. high eff. ASHP
California	13	-2	16	4	1	3	100	0	200	0	0	0
Carolinas	1	-2	13	0	-1	3	100	-100	700	0	-100	200
Central	1	-37	16	-1	-15	1	0	-1,000	400	0	-400	0
Florida	1	1	2	0	0	1	100	200	700	0	0	200
Mid-Atlantic	9	-146	45	0	-63	-2	100	-800	200	0	-300	0
Midwest	5	-244	-18	-2	-104	-27	0	-1,500	-100	0	-700	-200
New England	7	-7	35	3	0	11	200	-100	700	100	0	200
New York	7	-47	28	1	-43	-3	100	-700	400	0	-600	0
Northwest	3	-20	4	1	-3	0	100	-500	100	0	-100	0
Rocky Mountains	1	-21	-6	0	-2	-1	0	-1,100	-300	0	-100	-100
Southeast	2	3	19	0	1	4	100	100	700	0	0	200
Southwest	1	-2	7	0	0	1	100	-100	400	0	0	100
Tennessee	1	-2	10	0	-2	2	100	-100	800	0	-100	200
Texas	2	5	20	0	1	5	100	200	900	0	0	200
National	54	-521	192	7	-231	-3	100	-700	300	0	-300	0

Appendix C. Heat pump efficiencies

Table C-1. Heat pump efficiencies: federal appliance standards, Energy Star, IRA rebate levels, and ResStock. Bold indicates the original metric used to define the performance standard; plain text indicates a calculated value. SEER (seasonal energy efficiency ratio) and HSPF (heating seasonal performance factor) were replaced with SEER2 and HSPF2 in January 2023.

	SEER	HSPF	SEER2	HSPF2
Ducted				
Standard (2015)	**14.0**	**8.2**	13.3	7.0
Standard (2023)	15.0	8.8	**14.3**	**7.5**
Energy Star	15.9	9.2	**15.2**	**7.8**
Energy Star cold climate	15.9	9.5	**15.2**	**8.1**
IRA incentive - south	15.9	9.2	**15.2**	**7.8**
IRA incentive - north	15.9	9.5	**15.2**	**8.1**
ResStock “minimum efficiency”	**15.0**	**9.0**	14.3	7.7
ResStock “high efficiency”	**24.0**	**13.0**	22.9	11.1
Energy Star most efficient	17.7	9.5	**16.9**	**8.1**
Highest heating efficiency in Energy Star certified product list	22.6	12.9	**21.5**	**11.0**
Non-ducted				
Standard (2015)	**14.0**	**8.2**	13.3	7.0
Standard (2023)	15.0	8.8	**14.3**	**7.5**
Energy Star	15.9	9.2	**15.2**	**7.8**
Energy Star cold climate	15.9	10.0	**15.2**	**8.5**
IRA rebate - south	16.8	10.6	**16.0**	**9.0**
IRA rebate - north	16.8	11.1	**16.0**	**9.5**
ResStock “minimum efficiency”	**15.0**	**9.0**	14.3	7.7
ResStock “high efficiency”	**29.3**	**14.0**	27.9	11.9
Energy Star most efficient	16.8	10.6	**16.0**	**9.0**
Energy Star most efficient cold climate	16.8	11.1	**16.0**	**9.5**
Highest heating efficiency in Energy Star certified product list	30.4	25.8	**29.0**	**22.0**

Appendix D. Methane and refrigerants

D.1 Methane

To understand the order of magnitude effect of leakage, we use estimates of methane emissions during natural gas production, at the power plant, and behind the meter (BTM) in residences. We do not consider leaks in the natural gas transmission or distribution systems because the pipelines would continue to be pressurized. The assumptions and sources for this method are shown in Table D-1.

Table D-1. Key assumptions for fugitive methane emissions.

	Symbol	Value	Data source
Natural gas leakage – production	R_p	1.4%	Burns and Grubert 2021
Natural gas leakage – power plant	R_{pp}	0.4%	Lavoie et al. 2017
Natural gas leakage – BTM	R_{btm}	0.5%	Fischer et al. 2018
Share of marginal electricity from natural gas	M_{ng}	75% (2024) – 37% (2038)	
Natural gas power plant efficiency	E_{pp}	50%	Pistochini et al. 2022
Social cost of methane	SCM	$2,126/metric ton	Rennert and Prest 2022

We calculate the savings attributable to reduced fugitive emissions as

$$savings = (local\ NG\ savings * (R_p + R_{btm}) - electricity\ increase * \frac{M_{ng}}{E_{pp}} * (R_p + R_{pp})) * SCM$$

We reduce the share of marginal electricity consumption coming from natural gas over the heat pump's lifetime and apply a 2% discount rate to calculate the lifetime savings from fugitive methane.

Table D-2 compares the first year and lifetime benefits of electrification from reduced fugitive emissions to the air quality and CO_2 benefits. We find that lifetime methane benefits are about 6% of the air quality and CO_2 benefits under these assumptions.

Table D-2. Comparison of "Air quality + CO_2" net benefit estimates (as in the main text) to a first-order estimate of the net benefit estimates of avoided methane emissions. The comparison shows that methane impacts are small compared to "Air quality + CO_2" benefits. Net benefits were calculated based on displacement of 1% of fossil fueled water or space heating consumption with heat pumps. Methane is not included in the "Air quality + CO_2" column.

	Lifetime benefit ($M)		First year benefit ($M)	
	Air quality + CO_2	Methane	Air quality + CO_2	Methane
HPWH	1,518	91	54	6
Minimum efficiency ASHP	3,123	200	-521	9
Very high efficiency ASHP	6,981	397	192	28

One caveat is that the impact of methane on the atmospheric system is an area of active study. For example, McDuffie et al. (2023) argue that the standard social cost of methane is too low because it does not include the health impacts from increased ozone due to methane emissions. Including those effects approximately doubles the social cost of methane, which would in turn double the benefits from reduced methane emissions.

D.2 Refrigerants

Refrigerants are also potent greenhouse gases, so we develop a first-order estimate of the damages due to increased refrigerant usage from electrifying space heating. Table D-3 shows the key assumptions and sources used within our first-order estimate. In addition, we assume that houses with and without air conditioning in the baseline are equally likely to adopt a heat pump for space conditioning. In houses with air conditioning, we only count the incremental amount of refrigerant in the heat pump above the air conditioner, as we assume those houses would have replaced the air conditioning unit if not for the addition of a heat pump.

Table D-3. Key assumptions for fugitive refrigerant emissions from ASHPs.

	Symbol	Value	Data source
Refrigerant		R-410a	Pistochini et al. 2022
Refrigerant charge – AC	Ch_{AC}	0.98 kg/ton AC[13]	Pistochini et al. 2022
Refrigerant charge – heat pump	Ch_{HP}	1.2 kg/ton AC	Pistochini et al. 2022
AC capacity	C_{AC}	2.4 tons AC	ResStock – median peak cooling load oversized by 15%
Heat pump capacity – minimum efficiency	C_{HP}	3.9 tons AC	ResStock – median peak heating load oversized by 15%
Heat pump capacity – high efficiency	C_{HP}	4.4 tons AC	ResStock – median peak heating load oversized by 30%
Social cost of R-410a (50-50% R-32 and R-125 by mass; 2.5% discount rate)	SCR	$203,988/metric ton	EPA 2021
Refrigerant leakage	L	0.5% at installation, 5.8% annually, 25% at disposal	Pistochini et al. 2022
1% of dwelling units with fossil fueled heating, without AC in the baseline	DU_{heat}	5,894,152	ResStock
1% of dwelling units with fossil fueled heating, with AC in the baseline	DU_{AC}	47,414,818	ResStock

The equations below show how we calculate the lifetime cost of refrigerant leakage. We first calculate the incremental amount of refrigerant required for heat pumps to replace 1% of fossil fueled heating (R). We then calculate the cost over the 15 year lifetime of the heat pumps using the leakage rate specific to the year of operation and a discount rate of 2%.

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[13] Tons of air conditioning (12,000 Btu/hr) measure heating and cooling capacity.

$$R = incremental\ refrigerant\ required$$
$$= C_{HP} * Ch_{HP} * DU_{heat} + (C_{HP} * Ch_{HP} - C_{AC} * Ch_{AC}) * DU_{AC}$$

$$lifetime\ cost = \sum_{i=1}^{15} \frac{R * L_i}{1.02^i} * SCR$$

Table D-4 compares the lifetime cost of refrigerant leakage to the air quality and CO_2 benefits of electrification. We find that including the costs from refrigerants reduces the lifetime benefits of electrification by less than 10% under these assumptions. However, this estimate varies substantially depending on the assumptions. For example, if we assume that the heat pumps are replacing air conditioners of the same size, then the costs from refrigerant leakage reduces the lifetime benefits of electrification by less than 2%.

Table D-4. Comparison of "Air quality + CO_2" net benefit estimates (as in the main text) to a first-order estimate of the cost estimates of increased refrigerant leakage. The comparison shows that refrigerant penalties are small compared to "Air quality + CO_2" benefits. Impacts were calculated based on displacement of 1% of fossil fueled water or space heating consumption with heat pumps. Refrigerants are not included in the "Air quality + CO_2" column.

	Lifetime benefit ($M)	
	Air quality + CO_2	Refrigerants
Minimum efficiency ASHP	3,123	-360
Very high efficiency ASHP	6,981	-440

The costs from refrigerants in heat pumps are likely to decline in the future due to existing policies. For example, the 2020 American Innovation and Manufacturing (AIM) Act[14] authorizes EPA to manage and minimize the use of certain refrigerants. In addition, California has capped the global warming potential of refrigerants that are allowed to be sold starting in 2025.[15]

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[14] https://www.epa.gov/climate-hfcs-reduction

[15] https://ww2.arb.ca.gov/our-work/programs/sb-1206/about

Appendix E. Carbon dioxide emission rates

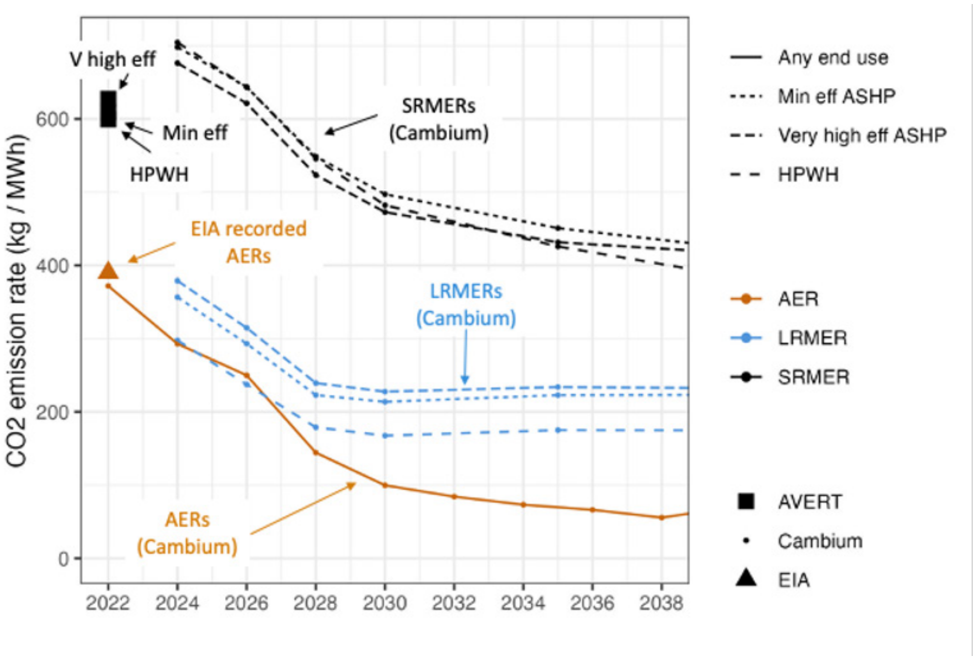

Figure E-1. Comparison of average, short-run marginal, and long-run marginal emission rates for CO_2 from EIA, AVERT, and Cambium. Because the factors themselves are hourly, the short- and long-run marginal emissions rates are calculated separately for the minimum efficiency ASHP, very high efficiency ASHP, and HPWH. The differences are due to the timing of electricity consumption.

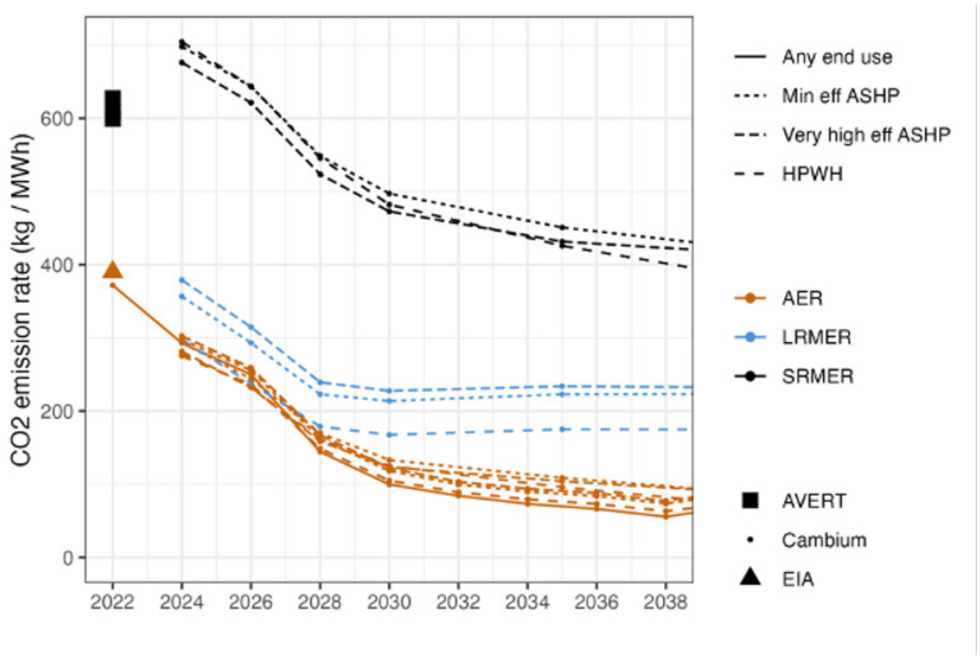

Figure E-2. Comparison of average, short-run marginal, and long-run marginal emission rates for CO_2 from EIA, AVERT, and Cambium. Because the factors themselves are hourly, the short- and long-run marginal emissions rates are calculated separately for the minimum efficiency ASHP, very high efficiency ASHP, and HPWH. The differences are due to the timing of electricity consumption. For average emission rates from Cambium (orange lines), the solid line shows the national average, and the dashed lines show averages calculated from annual and hourly regional emissions.

Appendix F. Conservative and optimistic assumptions

To conduct this analysis we make a variety of assumptions about emission rates, equipment replacement, and factors to include. Table F-1 summarizes some of them and indicates whether they are conservative or optimistic. We also note assumptions that have an important impact on the results that do not clearly fall into either category.

Table F-1. Analysis assumptions: conservative, optimistic, and impact with unknown direction

Conservative	Optimistic	Unknown direction
SRMERs for three years of operation before transitioning to AERs (Figure 12)	AERs rather than LRMERs after the first years of operation (Table 5)	Power sector emissions will maintain the same geographic distribution
Newer or efficient equipment is as likely to be replaced as older or inefficient equipment	Excluding impacts of refrigerant leakage (Appendix D)	Population will maintain the same geographic distribution
Excluding benefits from avoided methane leakage (Appendix D)		1% replacement of fossil consumption; larger changes to electricity demand could have different dynamics
Choice of epidemiological risk rates		Midpoint of the estimates of SCC and health damages
Heat pump begins operating in 2024		Mid case decarbonization scenario

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Consumer Benefits of Clean Energy:

Climate and health benefits from electrifying residential space and water heating

Margaret Pigman, Dev Millstein, Natalie Mims Frik, Wanyu R. Chan and William W. Delp

December 2024

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