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Abstract

In order to meet climate goals, it will be necessary to significantly reduce the greenhouse gases emitted by homes. A key factor in the US is to reduce the on-site combustion of fossil fuels for heating end-uses and to replace this with use of electric heat pump technologies connected to a low-carbon grid. The replacement of natural gas furnaces with electric heat pumps is a key home decarbonization strategy. However, the potential for space heating electrification to reduce greenhouse gas emissions depends on the carbon dioxide equivalent (CO_2e) content of the electricity used by the heat pump. This varies considerably depending on the source of electricity, with large state to state variability. Furthermore, household energy costs are likely to be impacted by the electrification of space heating, because retail energy prices for both natural gas and electricity in each state vary by factors of seven and four, respectively. Contractors, energy programs, government and building code officials, as well as consumers need clear indications of the likely CO_2e and energy cost impacts of proposed electrification projects, because these will affect decarbonization choices and rationales around scaled heating electrification. Government and utility programs also need to be aware of the likely outcomes of any supported/incentivized measures. In this paper, we investigate these effects by looking at new metrics to analyze the change in CO_2e emitted and the cost to meet home heating loads when switching from a natural gas furnace to a heat pump for the contiguous 48 states of the mainland US.

Key Words

Electrification, Decarbonization; Energy Retrofit; Heat Pumps; Carbon Savings; Energy Costs; Residential Buildings, HVAC, Heating, Furnace, AFUE, COP, Map, CO_2e.

1. Introduction

The largest site energy end-uses in US homes are space and water heating, accounting for 43% and 19% of total household usage, respectively [1]. 64% of US households are heated using natural gas or other combustible fuels [2], totaling approximately 59 million heating appliances. Replacing these heating appliances with electric heat pumps using low-carbon electricity has the potential to reduce household carbon emissions and energy costs [3] [4]. Others have explored how replacement of existing compressor-based cooling systems in the US with heat pumps could accelerate decarbonization of heating in the US [5].

While this paper focuses on the carbon and financial impacts in the US of replacing natural gas furnaces with heat pumps for space heating, there is also broad international interest in heat pump technologies for home heating that are summarized in [8]. Several related studies have been published focusing on the European Union (EU). For example, examining CO_2 savings for ground source heat pumps in in southwest Germany [22], or decarbonizing the EU heating sector through electrification [23]. These studies looked at issues such as the need for additional electric system capacity and regional variation in CO_2 emissions, but they did not use the decision making metrics for heat pump performance requirements studies in this paper. Broader policy issues are beyond the scope of this paper, however, there are studies available specifically focused on policy, e.g., in the EU [24].

Related analyses have been documented for electrification of water heating in the US that compared heat pump water heaters to natural gas and electric resistance options. An analysis allowing for the variable carbon content of electricity in the US estimated that heat pump water heaters with a Coefficient of Performance (COP) of 2 or better would reduce emissions in 80% of US households [6]. Another study [7] estimated the regional variation in installed costs and electricity rates needed for a heat pump water heater to break even compared to electric resistance water heaters – showing high variability from about \$250 to more than \$2250 (based on cost from 2010 and rates from 2012).

While electrification is increasing in new construction [9], new homes represent only 1% of homes in any given year in the US. Therefore, we need to include analyses for replacement of older heating systems in existing homes in our analysis. The energy system in the US is very diverse, with wide ranging retail prices for both natural gas and electricity, and similarly large variability in the carbon content of delivered electricity. The high variability in energy costs and carbon content of electricity between US states means that localized guidance is required for decarbonization strategies to be most effective and scalable in the market. If this variability is ignored, some locations have the potential to increase both carbon emissions and energy costs relative to current conditions when electrifying space heating.

The potential carbon savings from electrification of space heating will only be realized if replacement appliances are affordable in terms of both installation and operational costs. High first costs have been shown to be the most important factor currently deterring energy upgrades in US homes [10], [11]. Heat pump appliances must also be easily procured and maintained. The potential for electrification of space heating to negatively impact household energy budgets is of particular concern for low-income households. According to the US Energy Information Administration (EIA), in 2015 about 30% of households in the US were close to not paying their energy bills [12]. Several recent studies have investigated the topic of energy poverty in the context of electrification and a summary of how electrification can minimize energy poverty impacts can be found in [13]. While beyond the scope of this paper, there is also work connecting health to energy insecurity [14] and connecting these topics to energy efficiency programs [15].

This paper focuses on space heating rather than hot water and aims to use new metrics to investigate comparisons between natural gas furnaces and heat pumps. This is done in a manner directed towards decision making when selecting heat pumps, or for creating policy, R&D plans or carbon reduction/energy efficiency programs. To help provide guidance on CO_2e emissions and energy costs, we investigated the changes in CO_2e emissions and household energy costs associated with home heating loads, when switching from a natural gas furnace to an electric heat pump for the contiguous 48 states of the mainland US.

2. Methodology

We estimated the minimum seasonal average COP required of an electric heat pump technology to be CO_2e and energy cost neutral in each US state, relative to natural gas furnaces. In addition, we estimated percent CO_2e and energy cost savings in each US state that would be achieved by electric heat pumps with seasonal average COPs of 3. This COP represents high performance heat pumps that meet or exceed the Consortium for Energy Efficiency Tier 3 requirements for these technologies [16].

Annual average values from the year 2019 were used for both energy costs and carbon emissions, because that was the most recent year with both published energy prices and carbon emissions data available for the US. Projections based on anticipated changes in the US electric grid carbon intensity and retail energy prices are discussed later in this paper. Energy costs are based on state average residential retail natural gas and electricity prices as reported by the EIA in 2019 (see Table 1). These do not include time-of-use energy rates or seasonal changes in natural gas prices. Note that the EIA uses the term “Therm” for energy content of natural gas, common to the US but not the rest of the world. A therm is approximately 29.3 kWh. The CO_2e intensity of grid electricity in each state is estimated using the US EPA eGRID [17] total output emission factors (i.e., average emissions) for year 2019 (see Table 1). These factors do not reflect the time-varying carbon intensity of electricity, nor do they reflect the short- or long-run marginal emission rates for loads added to (or removed) from the grid at any given moment in time. The short-run marginal emissions (also included in the eGRID dataset) are roughly double these average values, and they are particularly useful if assessing changes in electricity consumption during peak periods [18]. Substantial uncertainties and modeling assumptions exist in the derivation and prediction of long- and short-run marginal emission rates, including prediction of what generation sources would be dispatched (or removed from the grid) at any given moment based on changes in demand. In contrast, average emissions for the grid are a more straightforward accounting exercise. Accounting for marginal and time-varying emissions is beyond the scope of this study, but remains a topic for future work, e.g., combining time-resolved heating loads and marginal emission factors from the NREL Cambium tool [19]. State-level results were extended to nationally representative values using data from the US Census Bureau’s American Community Survey [20], reporting the estimated count of natural gas space heating appliances in each US state (see Table 1).

Table 1. 2019 state mean retail prices for natural gas and electricity, and total output emission rates for CO_2e.

State	Count of Natural Gas Heating Appliances [Millions]	Natural Gas Price - Residential [$/Therm] (2019)	Natural Gas Price - Residential [$/kWh] (2019)	Electricity Price – Residential [$/kWh] (2019)	Average Total Output Emission Rate of CO2e for Delivered Electricity [kg/kWh] (2019)
Alaska	0.122	1.111	0.0379	0.2022	0.4422
Alabama	0.503	1.563	0.0533	0.0983	0.3563
Arkansas	0.450	1.105	0.0377	0.0822	0.5116
Arizona	0.878	1.349	0.0460	0.1052	0.3961
California	8.470	1.295	0.0442	0.1689	0.1756
Colorado	1.530	0.777	0.0265	0.1017	0.6038
Connecticut	0.500	1.461	0.0498	0.1866	0.2166
District Of Columbia	0.149	1.281	0.0437	0.1227	0.3618
Delaware	0.160	1.210	0.0413	0.1052	0.3227
Florida	0.368	2.173	0.0741	0.1044	0.3979
Georgia	1.488	1.487	0.0507	0.0986	0.3996
Hawaii	0.010	4.414	0.1506	0.2872	0.7088
Iowa	0.780	0.819	0.0279	0.0908	0.3908
Idaho	0.334	0.650	0.0222	0.0789	0.0959
Illinois	3.751	0.804	0.0274	0.0956	0.3292
Indiana	1.552	0.868	0.0296	0.0991	0.7413
Kansas	0.732	0.924	0.0315	0.1026	0.4053
Kentucky	0.645	1.085	0.0370	0.0861	0.8077
Louisiana	0.580	1.151	0.0393	0.0771	0.3748
Massachusetts	1.386	1.472	0.0502	0.1840	0.3541
Maryland	0.977	1.255	0.0428	0.1124	0.3351
Maine	0.045	1.605	0.0548	0.1404	0.0969
Michigan	3.031	0.808	0.0276	0.1156	0.4597
Minnesota	1.471	0.806	0.0275	0.1033	0.3996
Missouri	1.226	1.041	0.0355	0.0968	0.7252
Mississippi	0.317	1.077	0.0367	0.0928	0.3798
Montana	0.226	0.709	0.0242	0.0902	0.5728
North Carolina	0.989	1.288	0.0439	0.0945	0.3536
North Dakota	0.130	0.700	0.0239	0.0885	0.6566
Nebraska	0.457	0.790	0.0270	0.0908	0.5741
New Hampshire	0.115	1.575	0.0537	0.1715	0.1162
New Jersey	2.474	0.973	0.0332	0.1342	0.2473
New Mexico	0.490	0.640	0.0218	0.0899	0.6019
Nevada	0.664	0.950	0.0324	0.0878	0.3354
New York	4.520	1.261	0.0430	0.1434	0.1716
Ohio	3.076	0.958	0.0327	0.0958	0.5636
Oklahoma	0.763	0.940	0.0321	0.0786	0.3330
Oregon	0.608	0.997	0.0340	0.0881	0.1806
Pennsylvania	2.635	1.170	0.0399	0.0981	0.3442
Rhode Island	0.225	1.536	0.0524	0.1849	0.3866
South Carolina	0.465	1.314	0.0448	0.1002	0.2442
South Dakota	0.164	0.729	0.0249	0.0996	0.2232
Tennessee	0.831	0.945	0.0322	0.0969	0.3195
Texas	3.499	1.061	0.0362	0.0860	0.4143
Utah	0.828	0.782	0.0267	0.0824	0.7266
Virginia	1.042	1.262	0.0431	0.0952	0.2884
Vermont	0.049	1.314	0.0448	0.1536	0.0233
Washington	1.002	0.982	0.0335	0.0804	0.1357
Wisconsin	1.570	0.768	0.0262	0.1066	0.5593
West Virginia	0.291	0.990	0.0338	0.0849	0.8823
Wyoming	0.138	0.806	0.0275	0.0810	0.9385
U.S.	58.703	1.051	0.0359	0.1054	0.4033

Our approach, using 2019 price and emissions data, represents a real-time snapshot approach to assessing the impacts of heat pump adoption in the US. In contrast, a recent study [21] of heat pump adoption in the US accounted for future decarbonization of the electricity grid and looked at time-integrated savings. Our study is based on current rather than projected CO_2 emissions and costs, because these results are more useful and easier to understand for decision makers. The metrics we developed for this study can be used to update the performance comparisons of natural gas and electric heating as new information becomes available. The metrics and calculation methods used in this study do not need detailed knowledge of individual buildings or of the variability in the building stock – we assume the same building load (i.e., heat demand) is satisfied by the electric heat pump or the gas furnace, so the results are a relative measure of performance.

The method used to identify the minimum seasonal average heat pump COPs for carbon neutrality is illustrated in Figure 1. Each colored line represents a different CO_2e intensity of electricity in kilograms (kg) of CO_2e per kWh, with values spanning the range found in the US. As COP increases, the kg of CO_2e per unit of heating load are reduced until they are equivalent to the fixed value for natural gas at 95% efficiency (0.19 kg/kWh, illustrated by the black horizontal line). Where each colored line intersects the black line is the minimum COP value reported below. The COPs are only shown over the range from one to five, one representing electric resistance heat, and five representing the current upper bound for commercially available geothermal heat pump efficiency in the US [25]. The equation for deriving the minimum heat pump seasonal COP for carbon neutrality is shown in Equation 1.

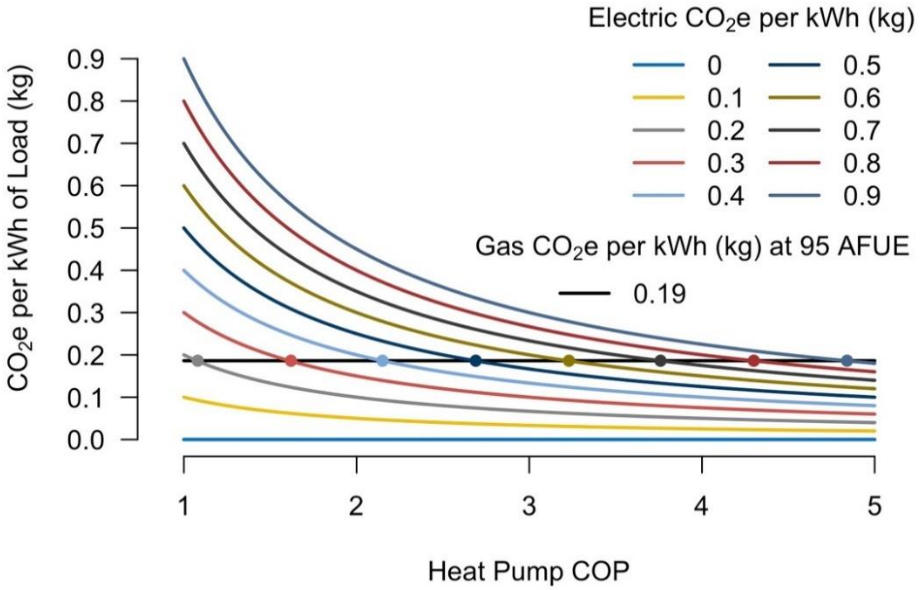

Figure 1. Illustration of minimum heat pump COP requirements for different CO_2e intensities of electricity compared with a 95 AFUE gas furnace.

$$COP_{elec} = \frac{(CO_2\text{e } per\ kWh_{elec})}{\left(\frac{CO_2\text{e } per\ kWh_{gas}}{COP_{gas}}\right)}$$ **Equation 1**

The method used to identify the minimum heat pump seasonal average COPs for energy cost neutrality is illustrated in Figure 2. The electricity cost per kWh of load decreases as the heat pump COP increases, until it is equivalent to the fixed value for natural gas at 95% efficiency (solid black line, assumed here to be the US average retail price of $0.038 per kWh). Where the two lines intersect is the minimum COP required for energy cost neutrality between gas and electricity. These values can be calculated for any arbitrary set of utility rates using Equation 2. Delivered fuels, such as propane ($0.0813 per kWh) and fuel oil ($0.0533 per kWh) [26], have higher costs, making the economics behind electrification with heat pumps much more beneficial in dwellings currently using delivered fuels.

$$COP_{elec} = \frac{(\$\ per\ kWh_{elec})}{\left(\frac{\$\ per\ kWh_{gas}}{COP_{gas}}\right)}$$ **Equation 2**

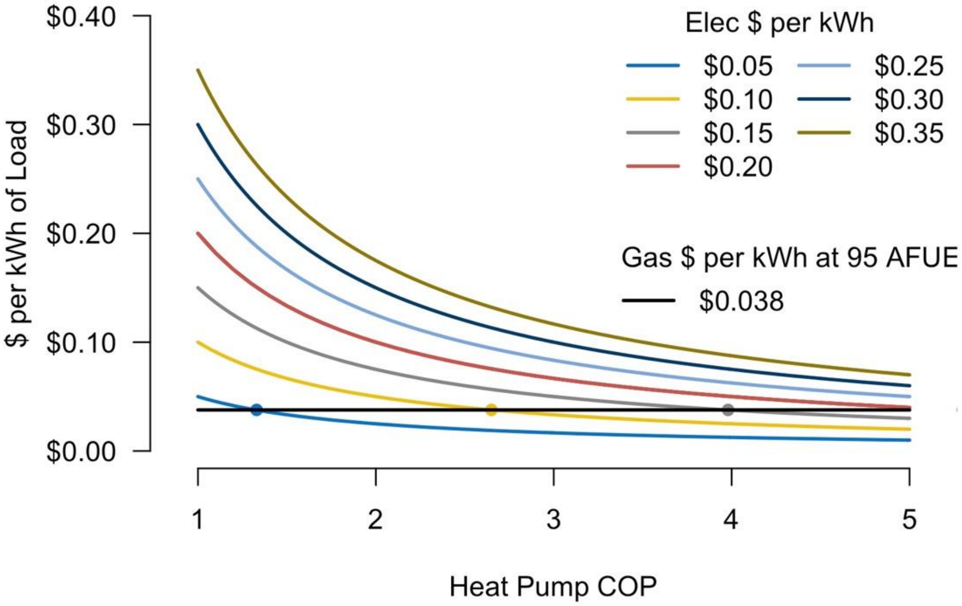

Figure 2. Illustration of energy cost analysis for heat pumps compared with a 95 AFUE gas furnace.

Electric heat pumps are compared to gas furnaces of three efficiencies: 65%, 80% and 95% AFUE (Annual Fuel Utilization Efficiency – the North American rating metric for furnace efficiency) [27]. In this analysis, we treat the AFUE efficiency ratings as seasonal average COPs for natural gas equipment (e.g., 65 AFUE equals a seasonal average COP of 0.65). The 65 AFUE comparison represents the change in CO_2e or energy costs relative to current equipment in a home with old, inefficient heating equipment. This represents the immediate, post-upgrade impact on a homeowner's utility bill and the change in emissions from an environmental perspective. The 80 and 95 AFUE options are a comparison of replacement options (or new construction comparisons), where existing gas equipment could be replaced by an electric heat pump or by gas equipment that is either just above the US federal minimum of 78 (80 AFUE) or high performance (95 AFUE). Notably, the electric heat pump COP values that we produce and use represent seasonal average COPs, which do not translate directly to rated efficiency values for residential heat pumps (i.e., Seasonal Energy Efficiency Ratio (SEER) and Heating Season Performance Factor (HSPF)). Two heat pumps with the same rated efficiency will result in different seasonal average COPs when installed in different climates. This is due to the dependence of heat pump efficiency on ambient temperatures and other factors, including the house heating load. Others have described methods to adjust heat pump ratings at standard conditions for energy analysis in specific climate regions [28]–[30].

To ensure the results are useful for a general audience and would be suitable for policy and program guidance, we made several simplifying assumptions including: (1) fixed efficiency equipment and no cooling, (2) ignoring refrigerant and methane (CH_4) leakage, and (3) not including installation costs. Each of these assumptions is discussed in more detail below.

The analysis used fixed equipment efficiency and assumes identical building loads for both the furnace and the electric heat pump in each state. Using the same building load and looking at relative performance means that we do not need to know the heating loads for each state or account for regional differences in construction. There is no accounting for changes in heat pump efficiency based on outdoor temperature, longer heat pump runtimes due to lower supply air temperatures, or the use of on-site photovoltaic systems to displace grid electricity. Impacts of space cooling are not included in this analysis.

Leakage of refrigerants from heat pumps and of methane gas (CH_4) from the natural gas supply chain are also not included in this analysis, yet both have important global warming impacts. Effectively, all heat pumps in the US market use refrigerants with high Global Warming Potential (GWP), and, if released, these can have climate impacts. A UK study estimated that 10% of household heat pump installations leaked, with median leakage of 35% of the initial refrigerant mass (annualized losses of 3.5%) [31]. Over 90% of leaks were "catastrophic" in which more than 50% of all refrigerant mass was released. Ongoing R&D is exploring the use of lower GWP refrigerants, along with strategies to reduce the amount of refrigerant required for an installation, as well as to reduce leakage and increase end-of-life recovery. Harrod & Shapiro discuss preventing leakage during install, commissioning and removal of equipment [32]. The leakage of CH_4 from the natural gas distribution system is currently estimated to be 2-3% of gross production [33], but due to the much higher GWP of CH_4 [34], these leaks could represent a large fraction of the global warming impacts associated with natural gas use in homes. In fact, due to increased radiative forcing of CH_4 gas, Alvarez et al. [33] estimate that emissions across the supply chain, per unit of gas consumed, results in roughly the same radiative forcing as does the combustion of delivered natural gas over a 20-year time horizon (+31% over 100 years). In addition, these CH_4 leakage estimates do not include leaks in the local distribution systems or at end-uses (e.g., in buildings), which others have estimated to exceed the 2-3% figure for the larger distribution system [35]–[38]. If the impacts of CH_4 and refrigerant leaks were included, both types of heating appliances would have increased carbon emissions. The net-effects would require more detailed analyses beyond the scope of this paper.

Installation costs for these technologies are ignored in this analysis and could be factored into these types of analyses in the future. To give an idea of these costs in 2019 US dollars, a recently compiled database of US home energy upgrade measures [39], reports that the installation costs for heat pumps for space conditioning are typically \$8,000 per dwelling (\$58.56/m^2), while fossil fuel space heating appliances are typically \$5,100 per dwelling (\$29.06/m^2). This represents a typical first cost increase of roughly \$3,000 for heat pump equipment. The cost differential was much higher for higher performance mini-split heat pumps, whose typical installed cost was \$12,100 per dwelling (\$68.46/m^2), or roughly \$7,000 more than a fossil fuel appliance. However, these cost differences disappear for the substantial number of homes that have both fossil fuel heating and central air conditioning (72% of single-family homes according to the US Energy Information Administration Residential Energy Consumption Survey database [40]). In these homes, a new heat pump replaces both the existing gas furnace and the existing heat pump used for cooling.

3. Results

US national average percent savings for CO_2e and energy cost are shown in Table 2, when comparing an electric heat pump with a seasonal average COP of 3 against gas furnaces of varying efficiency. Table 2 also shows the minimum electric heat pump seasonal COP values required for CO_2e and energy cost neutrality with gas furnaces. These averages are weighted according to the count of natural gas heating appliances present in each state (see Table 1).

Overall, savings are higher and minimum COPs are lower for the carbon assessment, while energy costs have lower savings and require higher performance heat pumps to break-even with gas furnaces. As the gas furnace AFUE increases from 65 to 95, savings are reduced, and minimum COPs increase for both the energy cost and CO_2e metrics. When compared with high-efficiency, 95 AFUE gas furnaces (as in new construction), weighted average energy cost savings for heat pumps are slightly negative (i.e., increased energy costs), and seasonal average heat pump COPs must be greater than 3, representing very high-performance appliances. The economics and carbon reductions are most beneficial when replacing older, low efficiency natural gas heating appliances. Homes with these low efficiency appliances should see weighted average heating energy bill savings of roughly one third and carbon reductions of one half. In summary, only the best available air source heat pumps on the market in the US, with COPs greater than 3, can compete in terms of energy costs with a high-performance natural gas heater at 95 AFUE. Moderate performance heat pumps can achieve carbon neutrality quite readily.

Table 2. US national average percent savings with a COP 3 heat pump and break even COPs for CO_2e and energy cost. Weighted according to the count of gas furnace heating appliances in each state. Aggregated by gas furnace efficiency.

	CO_2e Savings (%)	Energy Cost Savings (%)	CO_2e COP	Energy Cost COP
65 AFUE	56%	31%	1.5	2.1
80 AFUE	45%	15%	1.7	2.6
95 AFUE	35%	-1%	2.0	3.1

While US national weighted averages provide an important high-level summary, state-by-state analysis is critical, as energy programs, utility companies, building codes and consumers operate at the state and local levels. The minimum seasonal COPs required for CO_2e or energy cost neutrality are mapped for each state in the following figures, with green colors corresponding to lower minimum COPs and orange/red colors with higher COPs. Lower values (green color states) are better from a CO_2e or energy cost perspective for electric heat pumps, and higher values (red color states) are better for gas heating.

Figure 3 is a map of minimum heat pump seasonal COP required for CO_2e neutrality compared to an existing 65 AFUE furnace. In all but two states (Wyoming and West Virginia), only moderate heat pump performance is required to have lower CO_2e emissions than a 65 AFUE gas furnace. Figure 4 is a map of minimum heat pump COP required to be energy cost neutral with the same 65 AFUE gas furnace. This shows that when replacing older, less efficient equipment, an electric heat pump provides energy cost neutrality (or savings) in all the contiguous US states.

Figure 5 and Figure 6 show the same analysis, but for replacement of an 80 AFUE furnace. The number of states that require heat pumps with a seasonal COP greater than 3 to achieve CO_2e neutrality is expanded from two to six (adding Utah, Indiana, Kentucky, and Missouri). When looking at energy cost neutrality, the states requiring higher COPs increases to eight, with a markedly different geographic distribution around the country than those from the CO_2e equivalence map. This occurs because state-level patterns in the carbon intensity of grid electricity are different from state-level trends in the relative costs of natural gas and electricity. The higher performance heat pumps with COPs greater than three are required in states with the highest ratios of electricity to natural gas costs, which includes parts of the West coast, upper Midwest and New England.

Figure 7 and Figure 8 compare an electric heat pump to a 95 AFUE furnace. In several states, the high CO_2e content of electricity makes it extremely challenging for a heat pump to break even with a high-performance gas furnace from a CO_2e perspective. The geographic trends remain the same from previous plots, but higher seasonal COPs are required in larger portions of the mountain west for carbon neutrality, including Montana, North Dakota, Colorado, New Mexico and Nebraska. From an energy cost perspective, the low price of natural gas compared to electricity in many states means that just less than half (45%) of states need a seasonal average COP greater than 3, and a few (2%) require a COP of 4 when comparing to a high efficiency gas furnace. These states comprise nearly the entire Northern section of the US (excluding, Washington, Oregon and Maine), along with a few states in the desert southwest (New Mexico and Colorado) and California. The potential to increase energy costs for households relative to a high efficiency gas appliance represents a significant decarbonization challenge, particularly for low-income households.

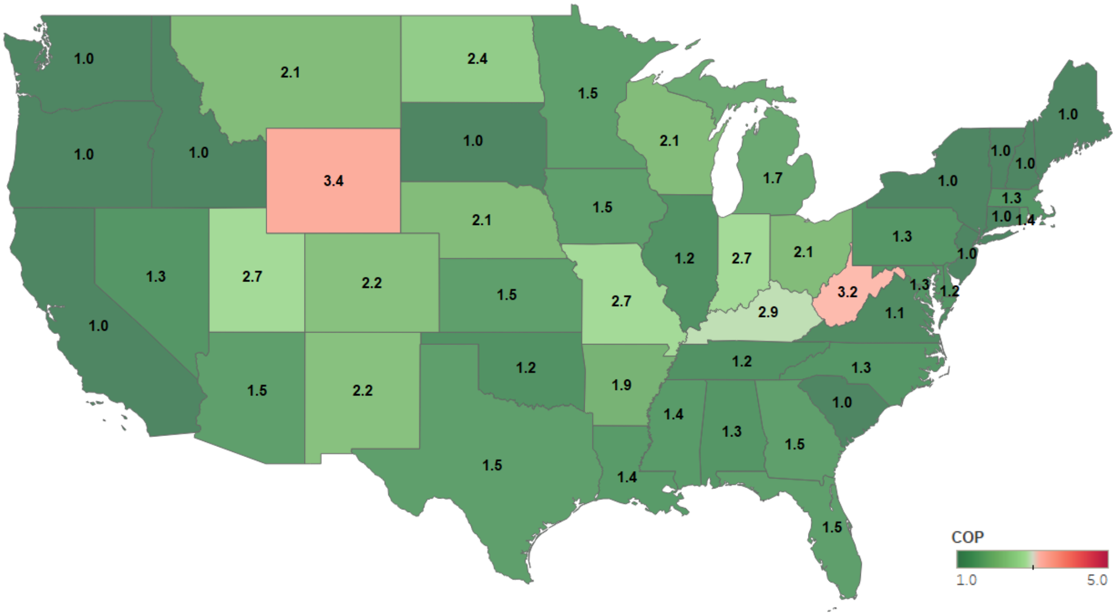

Figure 3. Minimum heat pump COP required for CO_2e neutrality in each US state, compared with a 65 AFUE natural gas furnace.

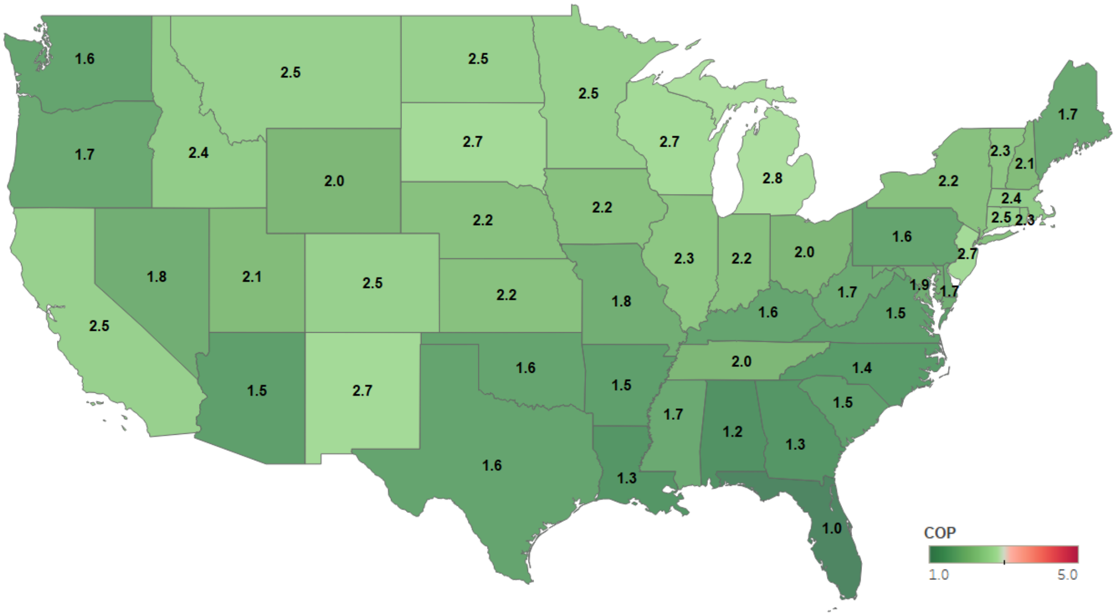

Figure 4. Minimum heat pump COP required for energy cost neutrality in each US state, compared with a 65 AFUE natural gas furnace.

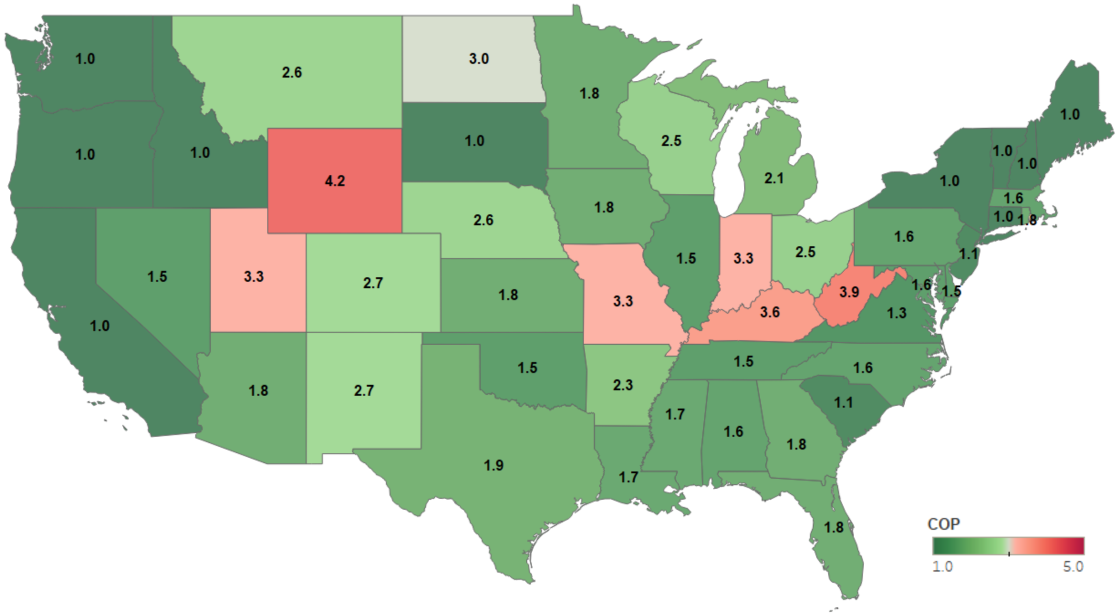

Figure 5. Minimum heat pump COP required for CO2e neutrality in each US state, compared with an 80 AFUE natural gas furnace.

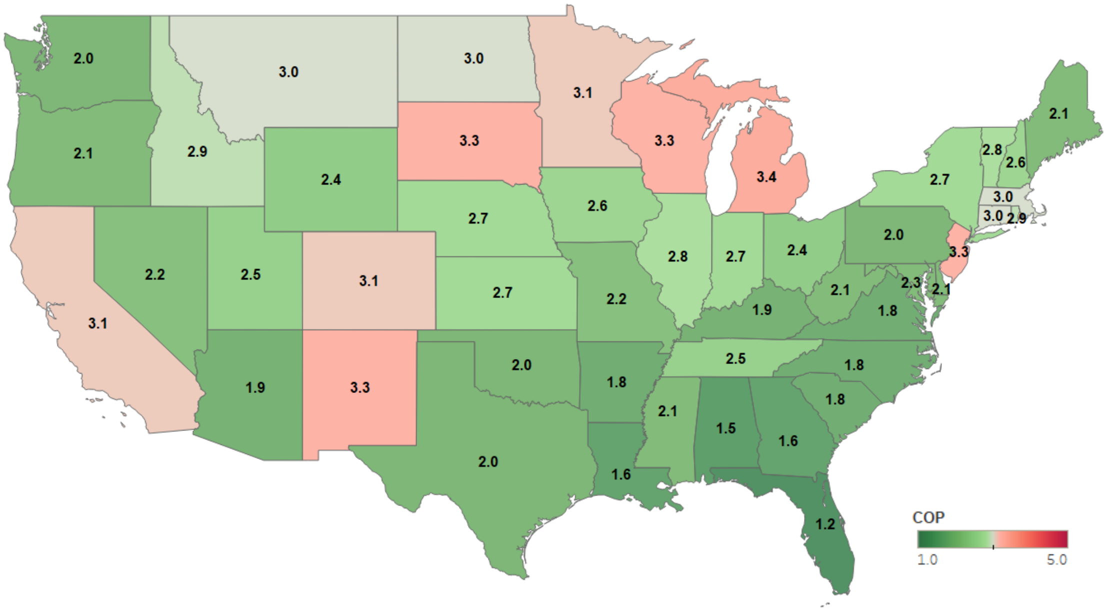

Figure 6. Minimum heat pump COP required for energy cost neutrality in each US state, compared with an 80 AFUE natural gas furnace.

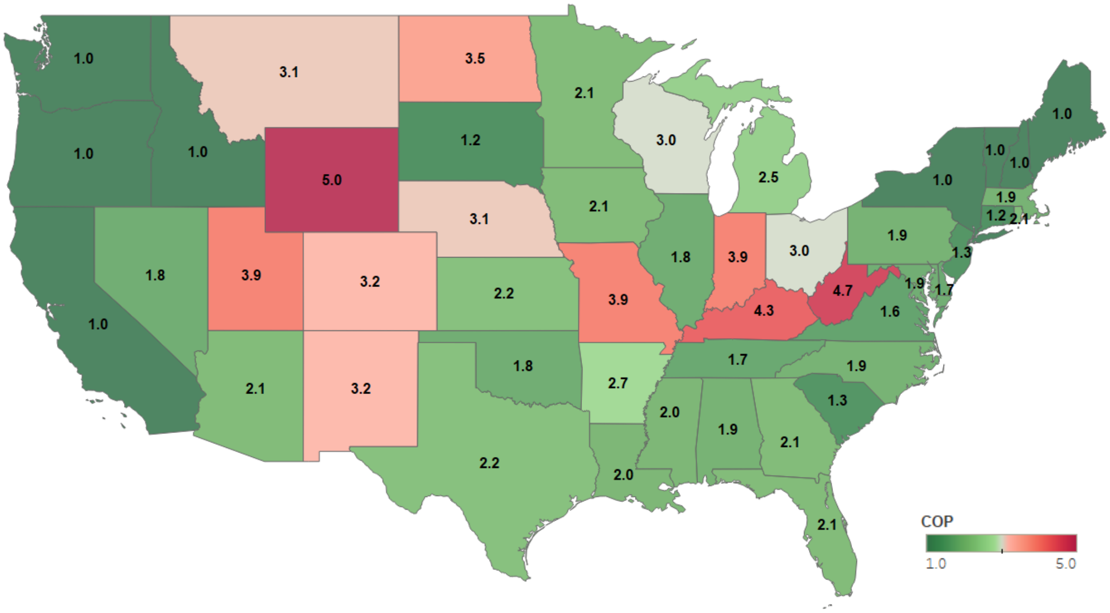

Figure 7. Minimum heat pump COP required for CO_2e neutrality in each US state, compared with a 95 AFUE natural gas furnace.

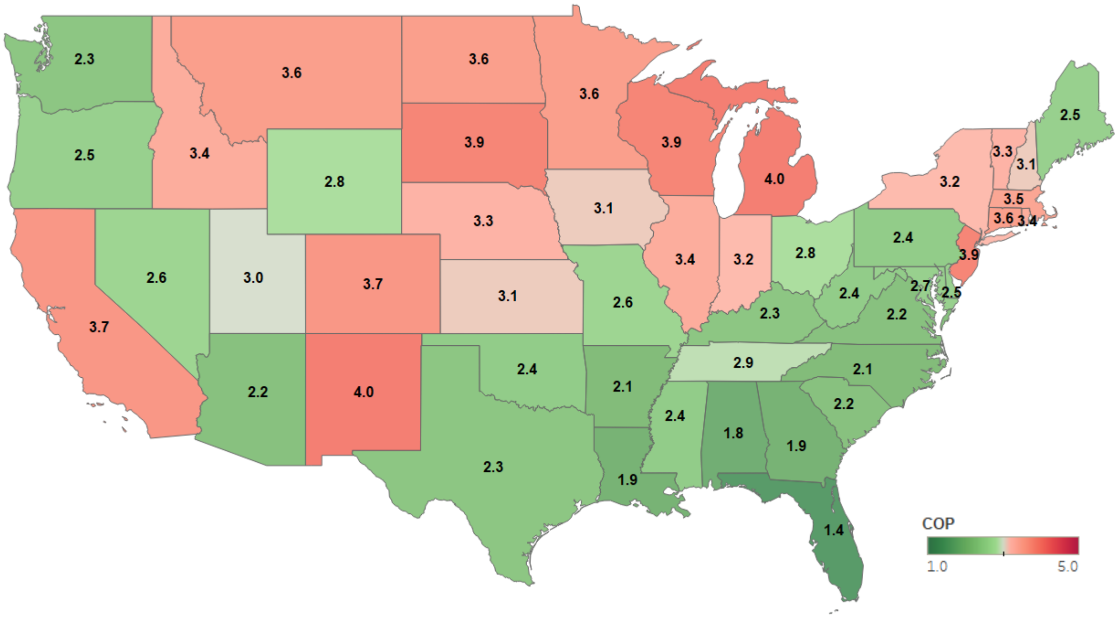

Figure 8. Minimum heat pump COP required for energy cost neutrality in each US state, compared with a 95 AFUE natural gas furnace.

The geographic trends in the CO_2e and cost neutrality results are quite distinct. To observe related trends in both parameters, we combined the two metrics in Figure 9, Figure 10, and Figure 11. To aid in interpretation, we have included horizontal and vertical lines at a seasonal average COP of 3, which represents the achievable performance of a high efficiency heat pump technology in most climate zones. The figures are subdivided into four plot regions: both CO_2e and energy cost benefit (lower left), two plot regions where there is either a CO_2e benefit (lower right) or an energy cost benefit (upper left), and a plot region where there is neither a CO_2e or cost benefit (upper right). The points representing each state are scaled according to the count of natural gas heating appliances in each state, so larger points represent states with more gas appliances (see Table 1). Another recent study used different calculation approaches and metrics to investigate the impact of carbon taxes [41]. Rather than determining the relative performance in terms of carbon and energy cost neutrality of natural gas and heat pump heating approaches, it focused on potential financial savings based on assumptions about house size. Their results and geographical mapping show similar trends and broad agreement with the results shown here.

For a 65 AFUE furnace replacement (Figure 9), nearly all states can achieve energy cost and carbon neutrality (or savings) using current heat pump technologies. The three states requiring heat pumps with a COP above 3 represent only 1% of gas heating appliances nationally. For an 80 AFUE gas furnace comparison (Figure 10), numerous states require COPs greater than three to be cost or carbon neutral. Several states with carbon benefits but increased energy costs represent high numbers of gas appliances, including California, New Jersey and Michigan. When compared to a 95 AFUE gas furnace

(Figure 11), 22 states remain in the lower-left plot region, where good heat pumps are currently a likely win-win for both carbon emissions and energy costs. Another 17 states have evident CO_2e benefits, but will likely increase energy costs. This category includes a majority of the states in the US with the highest number of gas heating appliances. For these states with CO_2e benefits, but where energy costs are likely to increase, other upgrade strategies may be needed to limit the potential increases, particularly for low income households or energy programs that support low income bill payments. Energy upgrade projects would need to include load reduction strategies (e.g., insulation, air sealing) or on-site generation in these cases to avoid cost increases. The six states with low-cost, high-CO_2e electricity can realize immediate energy bill reductions, but at the expense of increased CO_2e emissions. Reduced grid CO_2e intensity in the future will mitigate this. The remaining six states are likely to both increase energy costs and carbon emission when comparing an electric heat pump with a 95 AFUE gas furnace. These are states that are not good candidates for switching from an efficient gas furnace without additional energy upgrades and increased renewables in their electricity generation.

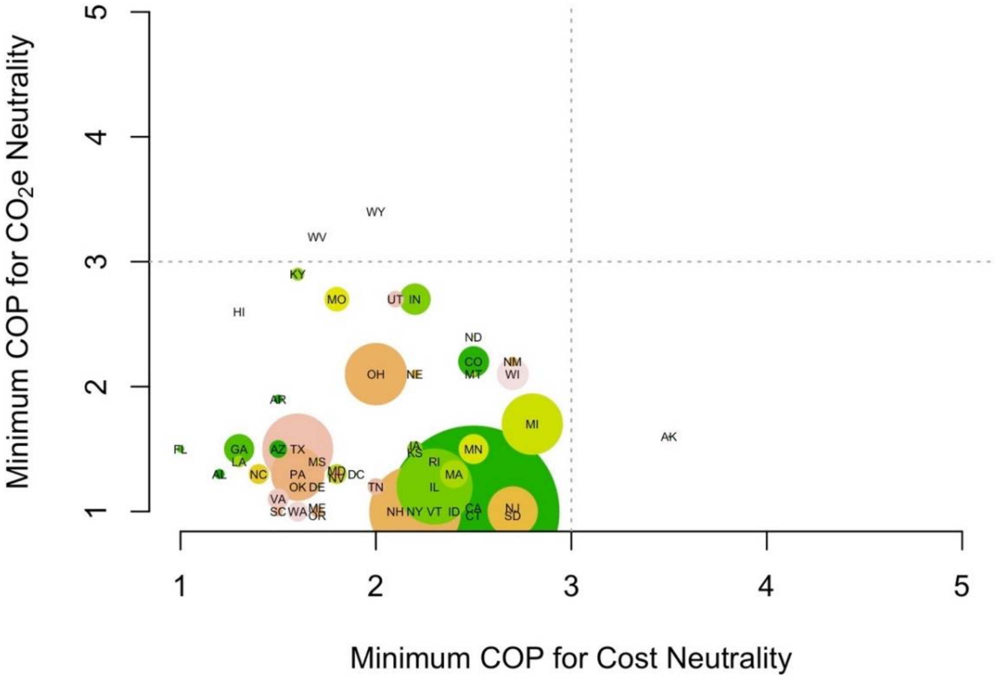

Figure 9. Minimum heat pump COPs required for CO_2e and energy cost neutrality in each US state, compared with a 65 AFUE natural gas furnace. Points are scaled according to the count of natural gas space heating appliances in each state.

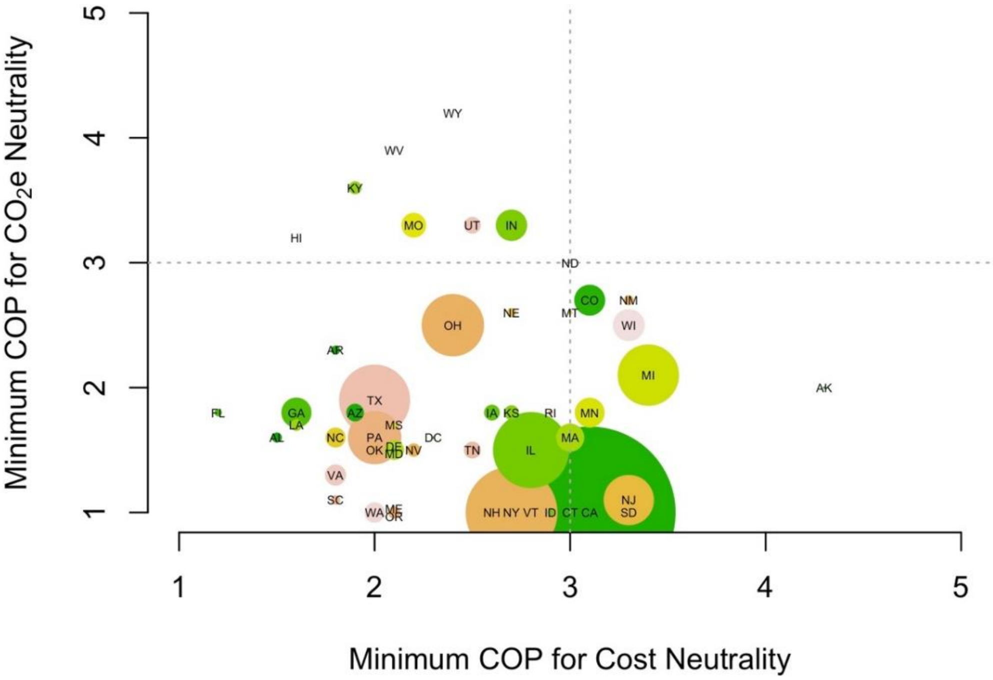

Figure 10. Minimum heat pump COPs required for CO$_2$e and energy cost neutrality in each US state, compared with an 80 AFUE natural gas furnace. Points are scaled according to the count of natural gas space heating appliances in each state.

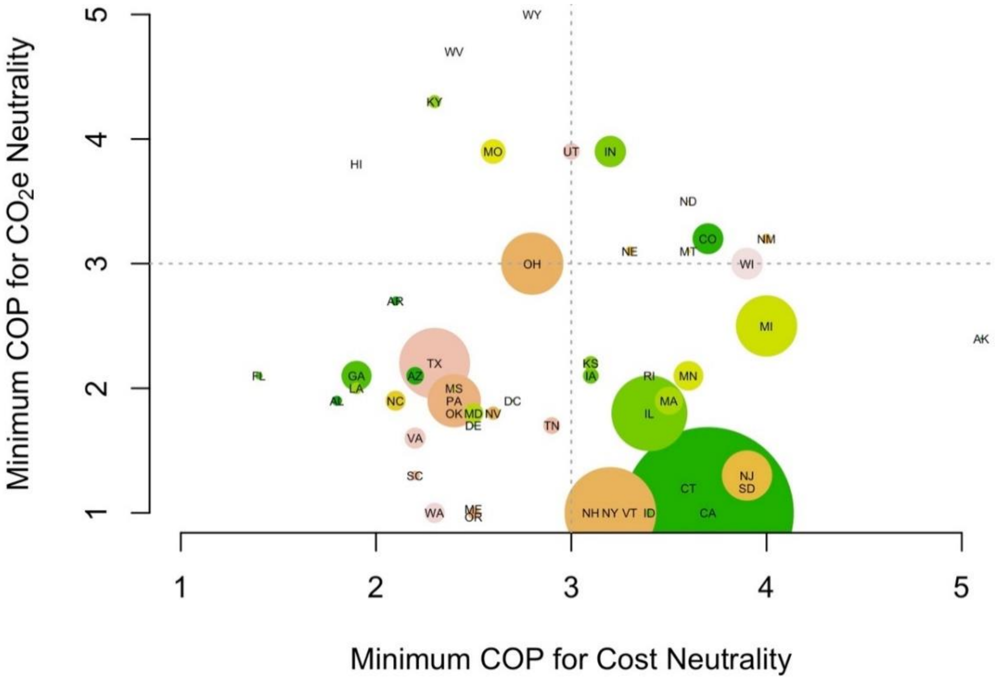

Figure 11. Minimum heat pump COPs required for CO$_2$e and energy cost neutrality in each US state, compared with a 95 AFUE natural gas furnace. Points are scaled according to the count of natural gas space heating appliances in each state.

Finally, we examine this topic from a different perspective, rather than calculating break-even heat pump COPs, we assume a seasonal average heat pump COP of 3 and assess anticipated CO$_2$e and energy costs savings in each state relative to gas heating appliances. Figure 12, Figure 13 and Figure 14, show the CO_2e savings for the three furnace efficiency levels mapped onto each state (i.e., 65 AFUE, 80 AFUE and 95 AFUE). Similar to the results above, in all but two states, a COP 3 heat pump provides CO_2e savings when retrofitting an older home with a, low-efficiency furnace (65 AFUE). Even in those two states the CO_2e increase is small (6% and 12%) relative to the CO_2e reductions in the other states. Many states show CO_2e savings in the 70-80% range, with some approaching 90%, showing that using heat pumps would have a significant effect on emissions. When comparing to a 95 AFUE furnace, nine states show no CO_2e savings, with the 80 AFUE furnace being between these two extremes. For five states the increase is more than 25% and without increases in renewable electricity these states are not good candidates for this replacement strategy. The greatest savings compared to a 95 AFUE furnace are mostly in the Western and Northeastern states with low CO_2e content electricity, and these states are seeing CO_2e reductions in the 50-80% range.

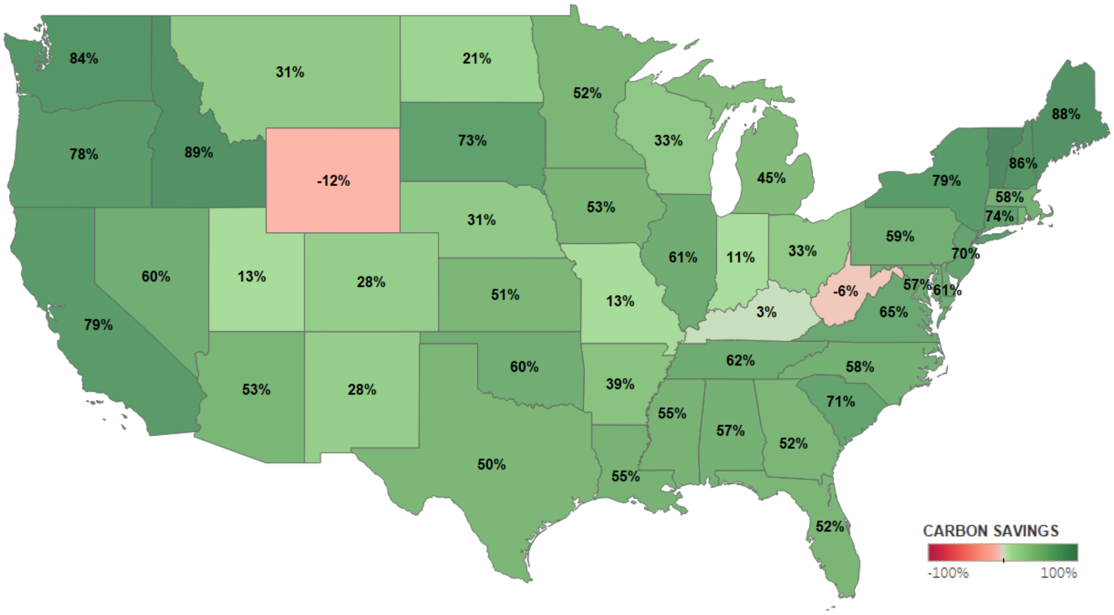

Figure 12. CO_2e savings replacing a 65 AFUE furnace with a COP 3 heat pump.

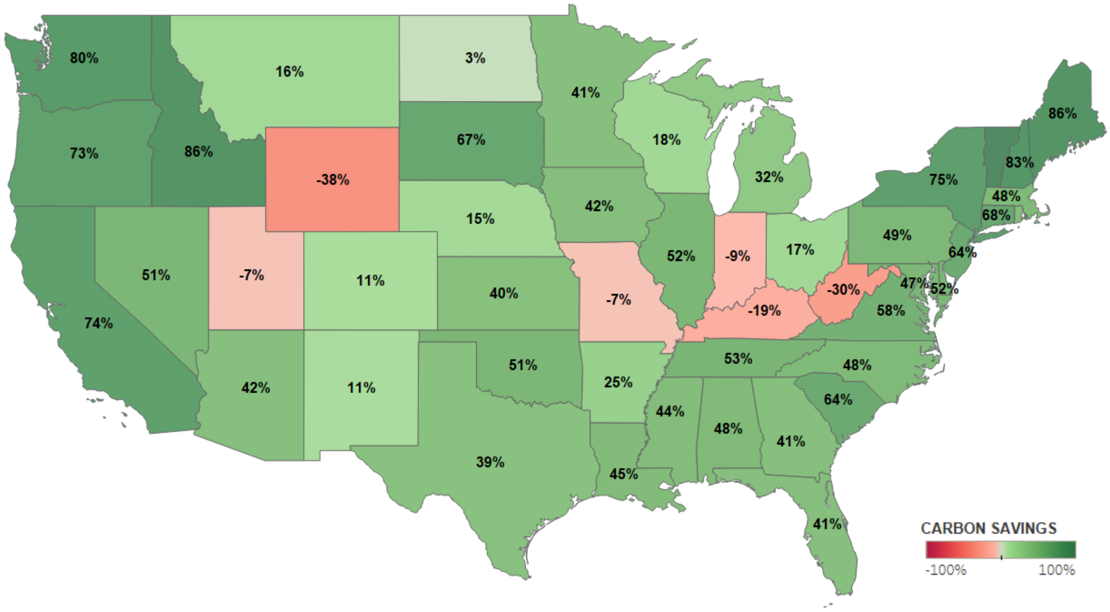

Figure 13. CO_2e savings replacing an 80 AFUE furnace with a COP 3 heat pump.

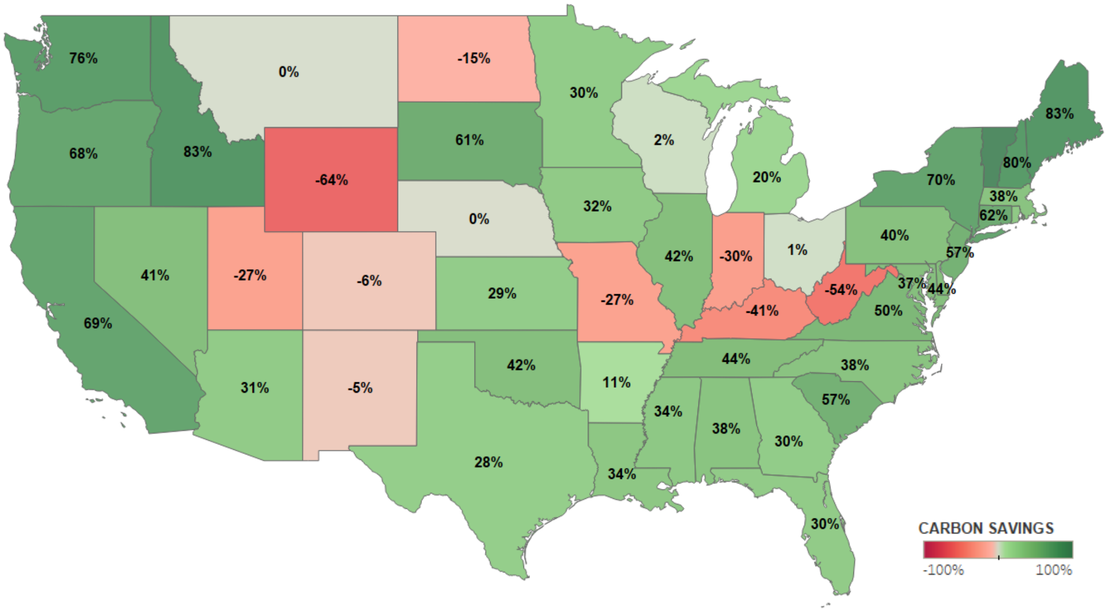

Figure 14. CO_2e savings replacing a 95 AFUE furnace with a COP 3 heat pump.

Figure 15, Figure 16 and Figure 17 combine the CO_2e and cost savings with the results scaled by the count of natural gas appliances in each state. As with the cost and carbon neutrality plots, we split the figures into four regions: the upper right represents both carbon and cost savings, the lower left is both carbon and cost increases with heat pump installation, the top left represents carbon savings with energy cost increases, and the lower right represents cost savings with carbon increases.

When heat pumps at a seasonal average COP of 3 are compared with a natural gas furnace with an AFUE of 65 (see Figure 15), nearly all states show both carbon and cost savings, including all states with large numbers of natural gas appliances. Many of the states with the most gas appliances are notable for having lower cost savings (<25%) and higher carbon savings (>50%), including California, New York, Illinois, Michigan and New Jersey. States with more moderate savings for both metrics include Texas, Georgia, Pennsylvania, Arizona and Virginia. When replacing old, existing gas furnaces with high performance heat pumps, carbon and cost benefits should be possible in nearly all states in the US. The only state with increased costs using a heat pump would be the state of Alaska.

If comparing the heat pumps with a natural gas furnace with an AFUE of 80 (Figure 16), the results are much more varied. This comparison represents a minimum efficiency furnace installed in new construction, or a more recently installed gas furnace in an existing home. While carbon reductions remain large for many of the states with the most gas heating appliances, the energy cost savings are sharply reduced, with many of the largest states showing neutral energy costs relative to natural gas, with savings +/- 10%, including California, New Jersey, Michigan, Illinois and New York. In many of these locations, energy costs are likely to remain comparable with an 80 AFUE gas furnace, while reducing carbon emissions by 25-75%. Some states with large numbers of gas appliances are notable for having either increased carbon emission or low carbon savings (<20%), including Kentucky, Missouri, Indiana, Utah, Colorado, Ohio and Wisconsin. In these states, use of heat pumps in new construction or in replacement of newer gas appliances in existing homes will only provide CO_2e benefits if the renewable content of local grid electricity is increased, or on-site renewables are used.

High performance, 95 AFUE natural gas heating appliances are compared with COP 3 heat pumps in Figure 17. Only a handful of states with many natural gas appliances remain in the upper right quadrant of the plot, where both carbon and energy cost savings are likely. For states that remain in the upper right plot region, high performance heat pumps should provide cost and carbon benefits in both new construction and when assessing heating replacement in existing homes with high efficiency gas furnaces. Large states with low or negative carbon savings, including Indiana, Missouri, Colorado, Ohio and Wisconsin, need to consider the use of rooftop PV to generate clean electricity on-site, or require a longer-term view of decarbonization in which the future electric grid has more renewables. When compared with a high efficiency gas furnace, nearly all of the states in the US with the most gas appliances have energy cost increases.

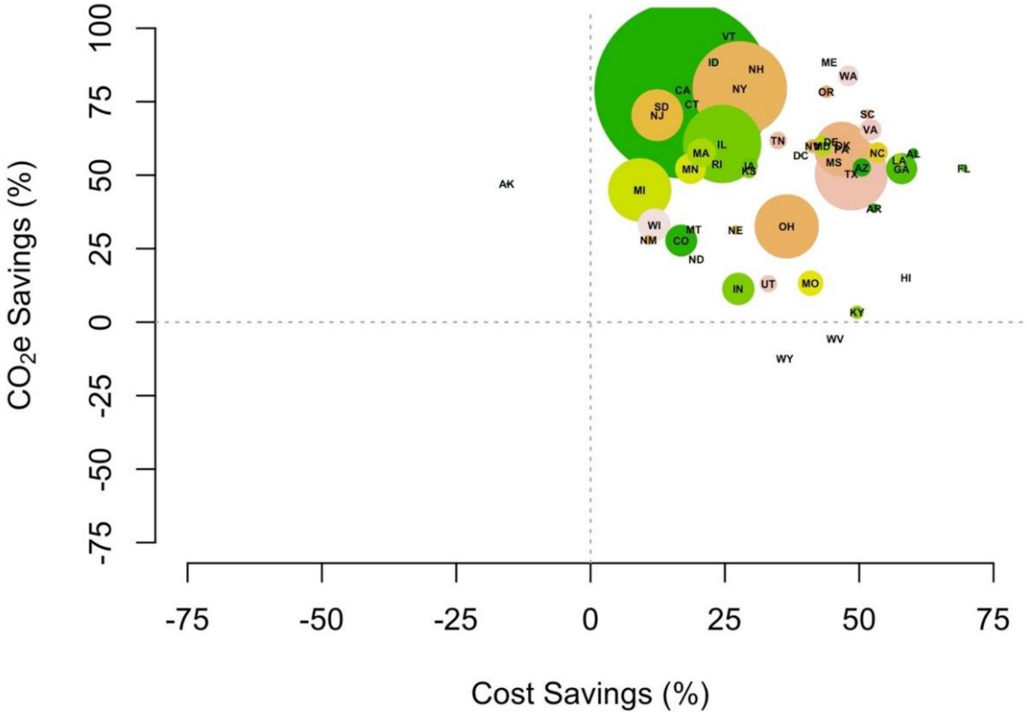

Figure 15. Percent savings for CO₂e and energy cost in each US state, when replacing a 65 AFUE furnace with a COP 3 heat pump.

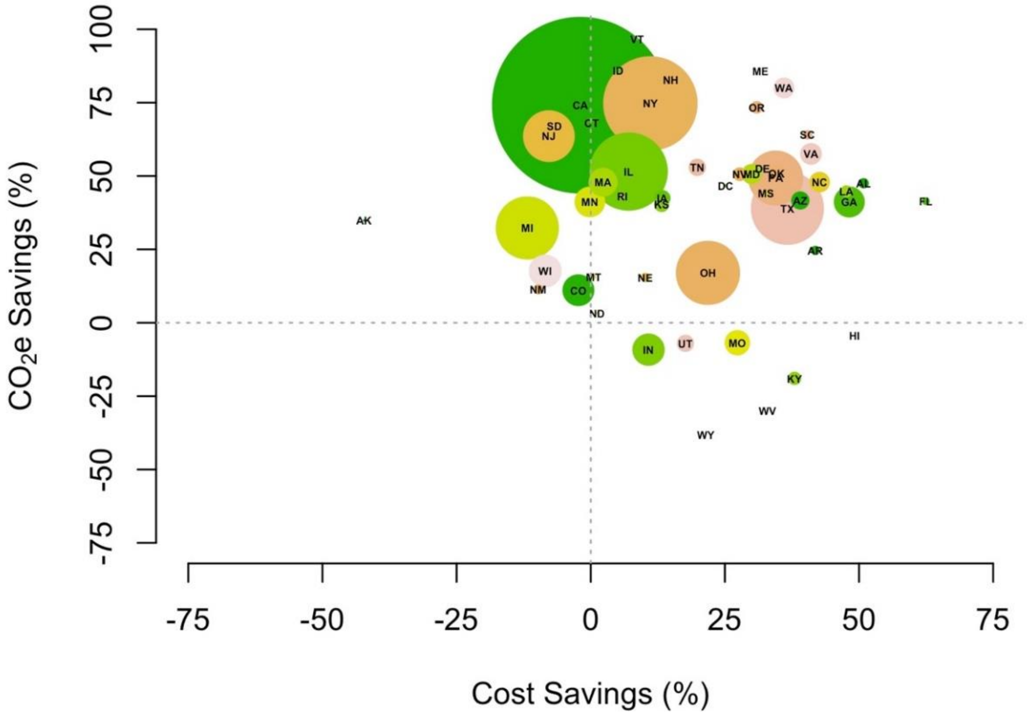

Figure 16. Percent savings for CO2e and energy cost in each US state, when replacing a 80 AFUE furnace with a COP 3 heat pump.

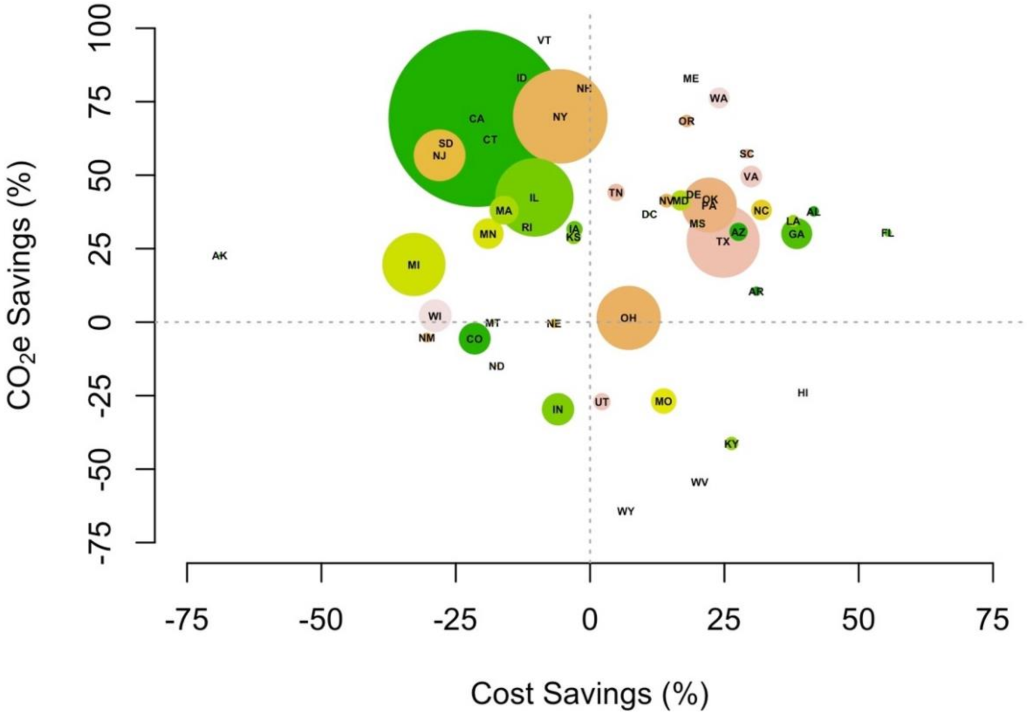

Figure 17. Percent savings for CO$_2$e and energy cost in each US state, when replacing a 95 AFUE furnace with a COP 3 heat pump.

Based on this analysis, in Table 3, the 17 states in the US with more than one million natural gas heating appliances each were categorized based on their carbon and energy cost savings at each level of natural gas furnace efficiency. These states represent 74% (43.7 million) of all-natural gas heating appliances in the US. This table identifies high priority locations where many gas appliances are located in existing homes, and it gives clear guidance on where and when heat pumps with a seasonal average COP of 3 are a viable economic and carbon replacement for gas furnaces. The states in each field of the table are sorted according to their gas appliance counts, so, for example, in the 95 AFUE category with both carbon and cost savings, Texas (TX) has the most gas appliances, followed by Ohio (OH), etc.

We offer the following general guidance depending on which category each state falls into:

- **States with both carbon and cost savings** currently should pursue policies that support electrification of space heating using high performance heat pumps. Lower performance heat pumps may or may not achieve the same goals, and state-by-state analysis is required.
- **States with carbon savings and cost increases**, the increased cost for operating a heat pump can be addressed through building load reductions (e.g., insulation and air sealing), higher heat pump COPs, higher natural gas prices, or lower electricity prices.

- **States with cost savings and carbon increases** currently are likely to benefit from future reductions in the carbon intensity of the grid. Alternatively, homes in these locations must use low-carbon electricity generated on-site or procured remotely, in order to avoid increased carbon emissions when electrifying space heating with heat pumps. On-site generation will also improve the energy cost economics in these locations.
- **States with increased carbon and energy costs** must rely on future decarbonization of the local electrical supply, as well as changes in energy prices, namely increased natural gas prices and reduced electricity prices. Enhanced heat pump performance is an additional option in these locations, which currently would mean use of ground-source heat pumps, which have higher average COPs than air source technologies.

Table 3. List of US states with more than one million natural gas heating appliances, categorized based on carbon and energy cost savings, when replacing natural gas furnaces with heat pumps with at COP of 3. States are sorted in each field according to the total count of gas appliances in those states. States with fewer than one million gas appliances are excluded.

	Carbon and Cost Savings	Carbon and Cost Increases	Carbon Savings and Cost Increase	Carbon Increase and Cost Savings
65 AFUE	CA, NY, IL, TX, OH, MI, PA, NJ, WI, IN, CO, GA, MN, MA, MO, VA, WA			
80 AFUE	NY, IL, TX, OH, PA, GA, MA, VA, WA		CA, MI, NJ, WI, CO, MN	IN, MO
95 AFUE	TX, OH, PA, GA, VA, WA	IN, CO	CA, NY, IL, MI, NJ, WI, MN, MA	MO

As noted in the methods section, this study is focused on current decision making and used the latest available US carbon and energy price data from 2019. Longer term planning for policy and programs may want to include estimates for changes over time in the carbon intensity of the grid and in retail energy prices.

Our carbon emission estimates are conservative, in that they do not take credit for a cleaner grid that does not yet exist. Nevertheless, over-time estimates can be made using the Cambium data sets published by the National Renewable Energy Laboratory (NREL), which model both US state- and national-level grid dynamics over the period from 2018 to 2050 [19]. This is done for three scenarios, including business-as-usual, along with relatively low and high renewable energy prices. The business-as-usual scenario predicts that US national average CO_2e associated with delivered grid electricity will go down by 4.8% year-on-year, from 442.9 kg per megawatt hour in 2018 to 196.0 kg per MWh in 2050. Using the same methods we apply to state-level data in our analysis, this suggests that break-even electric heat pump seasonal COPs nationally will also be reduced by 4.8% year-on-year, from 2.3 in 2018 to 1.0 in 2050. If comparing a 95 AFUE gas furnace against an electric heat pump with a seasonal average COP of 3, US national year 2018 carbon savings would be 23%, while this would increase to 44% by 2030, to 51% by 2040 and to 66% carbon savings by 2050. If these projections prove correct, then our results based on 2019 data underestimate the carbon emission reductions that will accrue over the next three decades, resulting from a switch from natural gas to electric heat pump space conditioning technologies.

The future of electricity and gas retail prices is highly uncertain, making future cost comparisons challenging and potentially highly misleading. Accordingly, we did not attempt such an analysis in this study. However, the EIA publishes projected retail residential energy prices for the US out to 2050 in their Annual Energy Outlook [42], [43], represented as 2020 US dollars per million Btu for electricity and natural gas. These projections show very little change in retail residential energy prices over the next three decades. Natural gas prices are predicted to increase marginally, from $10.14 per million Btu in 2020 to $11.76 in 2050. Electricity rates are predicted to decrease marginally, from $35.77 per million Btu in 2020 to $34.96 in 2050. If accurate, these shifts would result in an energy cost neutral heat pump seasonal COP going from 3.35 in 2020 to 2.82 in 2050. If implementing an electric heat pump with a COP of 3, US average cost savings would shift from -11% (increased energy costs) in 2020 to energy cost savings of 6% in the year 2050. If the projections are valid, this would lead to small increases over coming decades in energy cost savings for electric heat pumps.

4. Conclusions

While this is a simplified analysis, the results show that it is important to include the variability in CO_2e content of electricity and the differences between electricity and natural gas prices when making decisions about home heating decarbonization efforts. The high state-to-state variability of the CO_2e content and price of electricity results in a range of heat pump seasonal average COPs from one to five required for CO_2e equivalency, and from one to four for energy cost equivalency. These analyses for the US suggest which states are currently the best and worst for pursuing electrification of heating strategies for CO_2e and energy cost reduction. In some locations, including the Pacific Northwest and the Northeast, low CO_2e intensity grid electricity makes heat pumps very favorable, with CO_2e reductions approaching 90% in some scenarios. The vast majority of states can be CO_2e neutral with typical modern heat pump equipment, compared with 95 and 65 AFUE gas appliances. Achieving energy cost equivalency generally requires higher COPs in states with the most natural gas appliances. This is due to the lower cost per kWh for natural gas compared with electricity in all states. In 98% of states, high performance heat pumps can be energy cost neutral with 65 AFUE gas appliances, but this drops to 55% of states for 95 AFUE gas furnaces. This difference in outcomes for CO_2e and energy cost equivalency cannot be ignored if we want to have equitable decarbonization of homes.

The results presented here are primarily for general guidance. Future work could include temperature-dependent heat pump efficiencies, refined savings estimates using climate zone adjustments for seasonal heat pump efficiency, assessing the impacts of marginal emission rates, time-varying CO_2e emissions and energy costs, projected future changes in CO_2e content of electricity, and potential impacts of methane and refrigerant leaks. Extended analysis could also include installation costs and inclusion of other decarbonization measures, such as insulating and air sealing of homes, or the use of on-site photovoltaic systems to displace grid electricity. Similar analyses could also be performed for other electric technologies, such as heat pump water heaters and clothes driers, and induction cooking.

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References

[1] US Energy Information Administration (EIA), “Energy use in homes,” 2015. https://www.eia.gov/energyexplained/use-of-energy/homes.php (accessed Oct. 28, 2021).

[2] US Energy Information Administration, “RECS 2015 Space Heating in US Homes,” *Table HC6.1 Space heating in U.S. homes by housing unit type, 2015*, Nov. 05, 2021. https://www.eia.gov/consumption/residential/data/2015/hc/php/hc6.1.php (accessed Nov. 05, 2021).

[3] S. Billimoria, L. Guccione, M. Henchen, and L. Louis-Prescott, “The Economics of Electrifying Buildings: How Electric Space and Water Heating Supports Decarbonization of Residential Buildings,” Rocky Mountain Institute, Boulder, CO, 2018. Accessed: Dec. 05, 2019. [Online]. Available: http://www.rmi.org/insights/reports/economics-electrifying-buildings/

[4] Energy and Environmental Economics, “Residential Building Electrification in California: Consumer Economics, Greenhouse Gases and Grid Impacts,” Energy and Environmental Economics (E3), San Francisco, CA, Apr. 2019. Accessed: Dec. 05, 2019. [Online]. Available: https://www.ethree.com/wp-content/uploads/2019/04/E3_Residential_Building_Electrification_in_California_April_2019.pdf

[5] S. Pantano, M. Malinowski, A. Gard-Murray, and N. Adams, “3H ‘Hybrid Heat Homes’: An Incentive Program to Electrify Space Heating and Reduce Energy Bills in American Homes,” CLASP, Washington, D.C., May 2021. Accessed: Jul. 12, 2021. [Online]. Available: https://www.clasp.ngo/ research/all/3h-hybrid-heat-homes-an-incentive-program-to-electrify-space- heating-and-reduce-energy-bills-in-american-homes/

[6] P. Alstone, E. Mills, J. Carman, and A. Cervantes, “Toward Carbon-Free Hot Water and Industrial Heat with Efficient and Flexible Heat Pumps,” Schatz Energy Research Center, Arcata, CA, Aug. 2021. Accessed: Aug. 17, 2021. [Online]. Available: http://schatzcenter.org/publications

[7] J. Maguire, J. Burch, T. Merrigan, and S. Ong, “Regional Variation in Residential Heat Pump Water Heater Performance in the U.S.,” NREL/CP--5500-60295, 1220279, Jan. 2014. doi: 10.2172/1220279.

[8] A. S. Gaur, D. Z. Fitiwi, and J. Curtis, “Heat pumps and our low-carbon future: A comprehensive review,” *Energy Research & Social Science*, vol. 71, p. 101764, Jan. 2021, doi: 10.1016/j.erss.2020.101764.

[9] L. Davis, “What Matters for Electrification? Evidence from 70 Years of U.S. Home Heating Choices,” Haas School of Business at University of California, Berkeley;, WP 309, 2020.

[10] W. R. Chan, B. D. Less, and I. S. Walker, “DOE Deep Energy Retrofit Cost Survey,” Lawrence Berkeely National Laboratory, Berkeley, CA, Mar. 2021. Accessed: Apr. 28, 2021. [Online]. Available: https://doi.org/10.20357/B7MC70

[11] B. D. Less, I. S. Walker, and N. Casquero-Modrego, “Emerging Pathways to Upgrade the US Housing Stock: A Review of the Home Energy Upgrade Literature,” Lawrence Berkeley National Lab, Berkeley, CA, Mar. 2021. Accessed: Apr. 28, 2021. [Online]. Available: https://doi.org/10.20357/B7GP53

[12] US Energy Information Administration (EIA), “One in Three U.S. Households Faces a Challenge in Meeting Energy NeedsToday in Energy,” 2018. https://www.eia.gov/todayinenergy/detail.php?id=37072# (accessed Oct. 28, 2021).

[13] Y. A. Tan and B. Jung, “Decarbonizing Homes Improving Health in Low-Income Communities through Beneficial Electrification.” RMI, 2021. Accessed: Nov. 01, 2021. [Online]. Available: http://www.rmi.org/insight/decarbonizing-homes

[14] D. Hernández and E. Siegel, “Energy insecurity and its ill health effects: A community perspective on the energy-health nexus in New York City,” p. 15, 2020.

[15] B. Tonn, B. Hawkins, E. Rose, and M. Marincic, “Income, housing and health: Poverty in the United States through the prism of residential energy efficiency programs,” *Energy Research & Social Science*, vol. 73, p. 101945, Mar. 2021, doi: 10.1016/j.erss.2021.101945.

[16] CEE, “CEE Residential Heating and Cooling Systems Initiative.” Consortium for Energy Efficiency, Jan. 15, 2021. Accessed: Nov. 03, 2021. [Online]. Available: https://library.cee1.org/system/files/library/9570/CEE_ResHVAC_ElectricSpecs_15Jan2021.pdf

[17] US Environmental Protection Agency (EPA), “US EPA eGRID,” 2019. https://www.epa.gov/egrid/data-explorer (accessed Oct. 28, 2021).

[18] S. S. Rothschild and A. Diem, “Total, Non-baseload, eGRID Subregion, State? Guidance on the Use of eGRID Output Emission Rates,” presented at the 18th Annual International Emission Inventory Conference, Baltimore, MD, Apr. 2009. Accessed: Oct. 27, 2021. [Online]. Available: https://www3.epa.gov/ttnchie1/conference/ei18/session5/rothschild.pdf

[19] P. Gagnon, W. Frazier, E. Hale, and W. Cole, “Cambium data for 2020 Standard Scenarios,” 2020. https://cambium.nrel.gov/ (accessed Oct. 28, 2021).

[20] U.S. Census Bureau, “Selected Housing Characteristics. American Community Survey (TableID: DP04),” 2019. https://data.census.gov/cedsci/table?q=DP04&g=0100000US%240400000&tid=ACSDP1Y2019.DP04&hidePreview=true (accessed Oct. 28, 2021).

[21] T. A. Deetjen, L. Walsh, and P. Vaishnav, “US residential heat pumps: the private economic potential and its emissions, health, and grid impacts,” *Environ. Res. Lett.*, p. 18, 2021.

[22] P. Blum, G. Campillo, W. MUnch, and T. KOlbel, “CO2 savings of ground source heat pump systems - A regional analysis,” *Renewable Energy*, p. 6, 2010.

[23] G. Thomaßen, “The decarbonisation of the EU heating sector through electrification: A parametric analysis,” *Energy Policy*, p. 17, 2021.

[24] N. Kerr and M. Winskel, “A Review of Heat Decarbonisation Policies in Europe,” Feb. 2021, doi: 10.7488/ERA/794.

[25] US EPA, “ENERGY STAR Most Efficient 2021 — Geothermal Heat Pumps,” *energystar.gov*, 2021. https://www.energystar.gov/products/energy_star_most_efficient_2020/geothermal_heat_pumps (accessed Nov. 03, 2021).

[26] US Energy Information Administration (EIA), “Petroleum and Other Liquids. Weekly Heating Oil and Propane Prices.,” 2021. https://www.eia.gov/dnav/pet/pet_pri_wfr_a_EPD2F_PRS_dpgal_w.htm (accessed Oct. 28, 2021).

[27] ANSI/ASHRAE, “ANSI/ASHRAE 103-2017: Method of testing for annual fuel utilization efficiency of residential central furnaces and boilers.,” 2017, [Online]. Available: https://webstore.ansi.org/preview-pages/ASHRAE/preview_ANSI+ASHRAE+103-2017.pdf

[28] P. Fairey, D. Parker, B. Wilcox, and M. Lombardi, “Climate Impacts on Heating Seasonal Performance Factor (HSPF) and Seasonal Energy Efficiency Ratio (SEER) for Air Source Heat Pumps,” *ASHRAE Transactions*, vol. 110, no. 2, 2004, Accessed: Oct. 27, 2021. [Online]. Available: http://www.fsec.ucf.edu/en/publications/html/fsec-pf-413-04/

[29] P. Francisco, L. Palmiter, and D. Baylon, “Understanding Heating Seasonal Performance Factors for Heat Pumps,” Washington, D.C., 2004. Accessed: Oct. 27, 2021. [Online]. Available: https://www.aceee.org/files/proceedings/2004/data/papers/SS04_Panel1_Paper08.pdf

[30] C. K. Rice, B. Shen, and S. S. Shrestha, “An analysis of representative heating load lines for residential HSPF ratings,” ORNL/TM--2015/281, 1214506, Jul. 2015. doi: 10.2172/1214506.

[31] Eunomia Research & Consulting Ltd and Centre for Air Conditioning and Refrigeration Research, “Impacts of Leakage from Refrigerants in Heat Pumps,” UK Department of Energy and Climate Change, 2014. Accessed: Oct. 28, 2021. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/303689/Eunomia_-_DECC_Refrigerants_in_Heat_Pumps_Final_Report.pdf

[32] J. Harrod and I. Shapiro, “Preventing Refrigerant Leaks in Heat Pump Systems,” *ASHRAE Journal*, Jan. 2021, Accessed: Oct. 28, 2021. [Online]. Available: https://www.taitem.com/wp-content/uploads/036-043_Harrod_PRINT.pdf

[33] R. A. Alvarez *et al.*, “Assessment of methane emissions from the U.S. oil and gas supply chain,” *Science*, p. eaar7204, Jun. 2018, doi: 10.1126/science.aar7204.

[34] US Environmental Protection Agency (EPA), “Understanding Global Warming Potentials,” 2021. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials#Learn%20why (accessed Oct. 28, 2021).

[35] K. McKain *et al.*, “Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts,” *Proc Natl Acad Sci USA*, vol. 112, no. 7, pp. 1941–1946, Feb. 2015, doi: 10.1073/pnas.1416261112.

[36] B. K. Lamb *et al.*, “Direct and Indirect Measurements and Modeling of Methane Emissions in Indianapolis, Indiana,” *Environ. Sci. Technol.*, vol. 50, no. 16, pp. 8910–8917, Aug. 2016, doi: 10.1021/acs.est.6b01198.

[37] D. Wunch *et al.*, “Quantifying the loss of processed natural gas within California’s South Coast Air Basin using long-term measurements of ethane and methane,” *Atmos. Chem. Phys.*, vol. 16, no. 22, pp. 14091–14105, Nov. 2016, doi: 10.5194/acp-16-14091-2016.

[38] M. R. Sargent *et al.*, “Majority of US urban natural gas emissions unaccounted for in inventories,” *Proc Natl Acad Sci USA*, vol. 118, no. 44, p. e2105804118, Nov. 2021, doi: 10.1073/pnas.2105804118.

[39] B. D. Less, I. S. Walker, N. Casquero-Modrego, and L. Rainer, “The Cost of Decarbonization and Energy Upgrade Retrofits for US Homes,” Lawrence Berkeley National Laboratory (LBNL), 2021.

[40] US Energy Information Administration (EIA), “Residential Energy Consumption Survey (RECS). Table HC7.1 Air Conditioning in U.S. Homes by Housing Unit Type,” 2015. https://www.eia.gov/consumption/residential/data/2015/hc/php/hc7.1.php (accessed Oct. 28, 2021).

[41] P. Vaishnav and A. M. Fatimah, “The Environmental Consequences of Electrifying Space Heating,” *Environ. Sci. Technol.*, p. 10, 2020.

[42] US Energy Information Administration (EIA), “Analysis & Projections,” *Analysis & Projections*, 2021. https://www.eia.gov/analysis/projection-data.php (accessed Dec. 13, 2021).

[43] US Energy Information Administration (EIA), “Annual Energy Outlook 2021,” *Annual Energy Outlook 2021*, 2021. https://www.eia.gov/outlooks/aeo/ (accessed Dec. 13, 2021).