Quadracci Sustainable Engineering Laboratory (QSEL)

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Roles of Electrification and a Cleaner Electric Grid in Achieving Deep Emission Reductions from Space Heating in the U.S.

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In this report, we look at some of the pathways to reducing residential space heating greenhouse gas (GHG) emissions in the U.S. In a previous report, we outlined the current state of affairs across the country (continental U.S. for now): differences in heating energy requirements, current heating fuels and electricity generation mix, and how all these combine to affect emissions. Here, we begin to chart a path forward. Most discussions on the subject have three major elements: (1) Efficiency (reduce the energy requirement through increased insulation, reduced air leakage and upgraded equipment), (2) Electrification (use efficient electric heat pumps instead of fossil fuels), and (3) "cleaning" the electricity grid (eliminating coal and shifting away from fossil fuels towards renewable energy and other low-carbon resources). (Another emerging area is smart controls and grid-interactive building systems, which we will set aside for now.) This report addresses the nuances of the second two measures in detail, recognizing that improving efficiency has benefits for (and should be part of) any path to deep GHG emissions reductions. We also identify important considerations that are often missing from the conversation, including the significant benefits of converting existing electric resistance heating to electric heat pumps and of dual source systems that maintain existing fossil fuel heating with new electric heat pumps in a transition period.

Introduction

In our previous report, we estimated space heating to be responsible for 57% of all residential GHG emissions. We also went into great detail on the primary drivers of these emissions and how they vary across the U.S.: Climate (and its effects on heating loads), home heating fuel (often driven by fuel availability and socioeconomic factors), and electricity grid emissions rate (a result of the mix of fuels and low-carbon resources used to generate electricity). Here we examine technological and societal choices that play an important role in future emissions reductions: Widespread adoption of efficient heating technologies, continued research and development of advanced heat pumps, elimination of the highest emission fuels used in electricity generation (particularly coal), expansion of low-carbon electricity resources (most likely wind and solar power), and integrated planning approaches to transition away from the status quo.

Let us consider two general electric heating technologies: electric resistance and electric heat pumps. While electric resistance (which can be used in baseboards or furnaces) is nearly 100% efficient, the primary driver of its high emissions is our continuing dependence on fossil fuels for electricity generation: 63% of all U.S. electricity generation (with significant geographical variation) [1]. However, technologies are available that can greatly reduce the energy demands of electricity-based heating before even considering reducing grid emissions rates. An electric heat pump (EHP), for the unfamiliar reader, is the same technology as in most air conditioning systems; a reversing valve allows such systems to provide warm air to a living space directly or through a central fan-duct system[1]. Some EHPs are capable of operating with an "efficiency" that exceeds 500%; in technical jargon, this efficiency metric is called the "coefficient of performance" (COP), the amount of heating delivered per unit electricity consumed. While such high performance is possible at more moderate outside temperatures, both COP and capacity degrade as temperatures drop, and electric resistance or some other supplemental heating is eventually required.

While EHPs have gotten considerable attention, they remain a small part of home heating. In fact, according to U.S. Census Bureau data, the percentage of households using EHPs as their main heating equipment held steady between 2005 (11.5% [2]) and 2017 (11.6% [3]). Remarkably, considering the energy costs and emissions associated with electric resistance, its share of households has increased from 20% to 31% in the same time period. Further, EHPs are generally concentrated where heating loads are low due to heating capacity derating at low outside temperatures. According to a 2015 survey by the U.S. Energy Information Administration [4], only 11% of EHP households are in cold or very cold climates where 38% of all heated homes are located.

The data sources underlying our heating model [5] do not differentiate the type of electric heating equipment; however, we were able to compute an estimated overall average COP of 1.2 for all electric heating. This is consistent with electric resistance systems being the dominant technology in a mix with legacy EHPs. We estimate that if all current electric heating were to be replaced with current commercially available EHPs, an overall average COP of 4.1 could be achieved, suggesting a possible 70% reduction of electricity for heating in homes that currently use electric heating and commensurate reductions in emissions. This point calls for emphasis: It is often missed and such a switch would have no adverse impact on the electric grid other than lower electricity sales, potentially freeing up capacity for additional electrification of heating (and other current fossil fuel uses, such as vehicles).

One could replace fuel oil with natural gas to reduce a home's GHG emissions. This would not be a simple or inexpensive task, requiring natural gas infrastructure extension to more rural areas for such a shift to occur at scale. Further, because fewer than 7% of

[1] Heat pumps that heat water are also available; these are currently more common in Europe. In this report, we focus on air-to-air or air-source heat pumps (ASHPs). Another alternative is a ground-source heat pump, which has improved performance at low temperatures, but with significantly higher cost, complexity and site-specific feasibility; a GSHP could certainly be the best choice for some homes.

homes currently use fuel oil, we estimate switching all fuel oil homes to natural gas would reduce overall residential space heating emissions by only 2%. Because of methane leakage during the production, processing, transmission and distribution of natural gas, we compute no GHG impact of a shift from propane to natural gas. We compute EHPs can be the lowest emission heating option vis-à-vis natural gas in most of the U.S. An exception is cold climate locations where the current electricity grid has high emissions rates (e.g. areas with significant amounts of coal-fired power), which collectively represent 13% of residential heating energy; however, this motivates investigating the impact of “cleaning” the grid supplying these locations. We therefore focus here on *environmentally beneficial electrification* – which broadly means converting fossil fuel-based heating systems to electricity-based systems where such a change would result in GHG emissions reductions – and the effects of efforts to integrate lower-emission resources into the electricity generation mix.

Electrification in the Current Grid

We first want to identify where and with what existing heating fuels electrification with EHPs would be environmentally beneficial. We computed the ratio of residential EHP emissions to those of other heating sources given the emissions rates of the existing grid (Figure 1). A value less than 1 represents emissions reductions with EHPs. We assumed a currently available high performance EHP, the 90th percentile performance “cold climate” EHP in a regularly updated database [6]. For fossil fuel-based heating, we assume efficiencies consistent with the U.S. Environmental Protection Agency’s EnergyStar ratings [7]: 95% for natural gas and propane, and 85% for fuel oil.

Two clear topline conclusions can be drawn from Figure 1: (1) Major GHG reductions in electrically heated homes are possibly across the U.S. if electric resistance heating is replaced by EHPs; and (2) except for parts of the northernmost Midwest (where it is very cold and grid emissions are high), significant reductions in GHG reductions are possible today from replacing any fossil fuel-based space heating with EHPs. There are challenges with the latter approach since such a shift may stress the existing distribution grid, more severely in some places than others. First, we look at the scale of the opportunity from an emission reductions perspective assuming unchanged electricity emissions rates from the current grid. Table 1 shows the impact of environmentally beneficial electrification with EHPs, including a breakdown of the effects within subsets of homes based on their current heating fuel. We also include the computed current size of the subsets as percentages of floor area, heating energy and heating emissions.

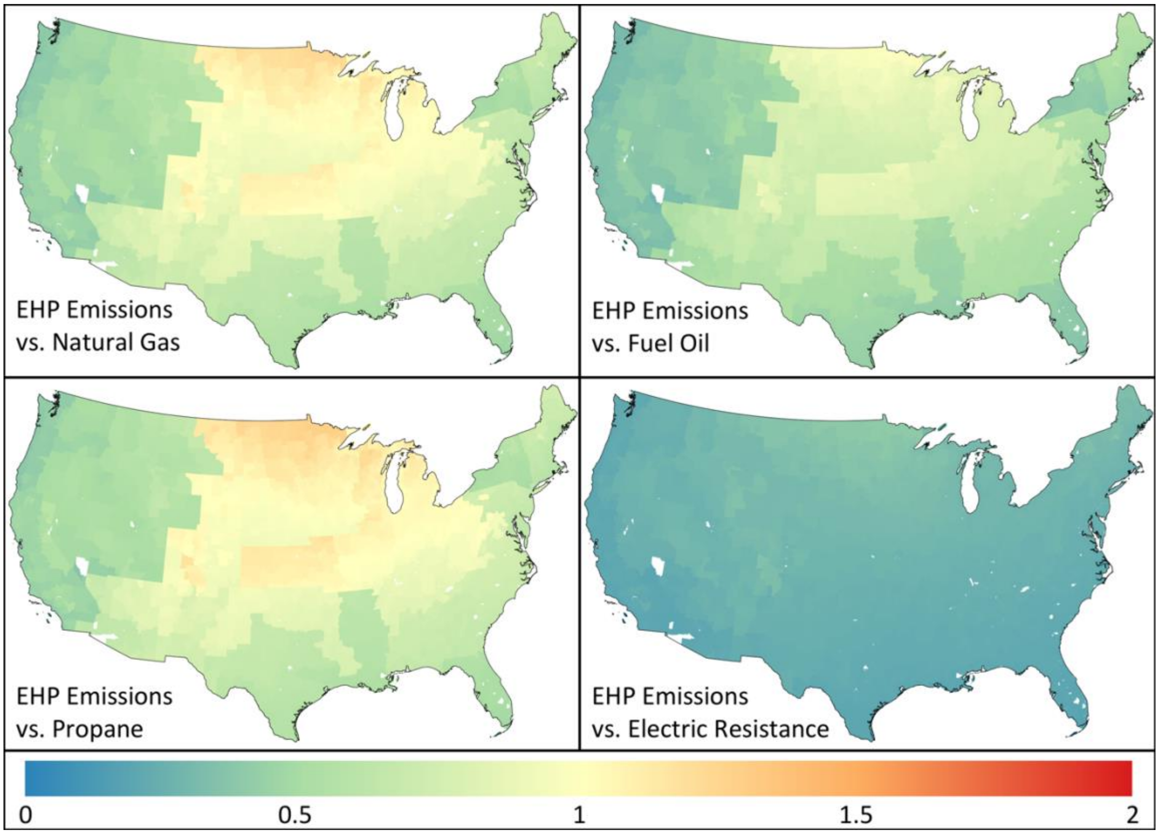


Figure 1 | Comparing heat pump GHG emissions to other heating sources. Computed ratio of residential space heating emissions with heat pumps to emissions with other heating fuels. All computations are at the census tract level.

Table 1 – Computed Greenhouse Gas Emissions Reductions from Environmentally Beneficial Electrification with Electric Heat Pumps and the Current Electricity Grid

Current Heat Source	Subset as Percentage of Corresponding Total			GHG Emissions Reduction	
	Floor Area	Heating Energy	Heating Emissions	Within Subset	All Heating Emissions
Natural Gas	49%	53%	44%	37%	16%
Electricity	35%	27%	42%	70%	30%
Fuel Oil	6.7%	9.3%	8.6%	53%	4.6%
Propane	5.9%	6.6%	5.2%	33%	1.7%
Total Reduction from Environmental Beneficial Electrification:					**52%**

The biggest benefit in the current electricity system comes from replacing existing electric heating (largely electric resistance) with EHPs. This is not widely understood and is largely a result of our emission estimates electric heating being based on the electricity being provided primarily by non-baseload electricity generation. We compute that, if all homes with electric resistance heating were to shift to currently available EHP technologies, space heating emissions could be reduced by 70% across those homes. In targeted areas, emission reductions would be even more significant. This, in itself, would have a major impact on space heating emissions, reducing *total* U.S. space heating emissions by 30%. By comparison, we compute that electrification of current fossil fuel-based heating wherever it is environmentally beneficial with the current grid could reduce total space heating emissions by about 23%.

We note that carrying out these measures alone would result in computed space heating-related emissions reduction of more than half, representing very significant potential within the current electricity system. However, it also belies the limits of reducing emissions from fossil fuels in the current electricity system given that the computations shown in Table 1 would require replacing more than 84% of current fossil fuel-based heating (the portion for which it is environmentally beneficial to do so) and 100% of all current electric heating with new EHPs.

Electrification of homes currently using fuel oil is environmentally beneficial in all areas analyzed; however, the overall emissions benefit is small (4.6% of all heating emissions) because of the fairly limited existing usage of fuel oil. The situation for natural gas and propane is more nuanced since environmentally beneficial electrification with EHPs is highly dependent on the grid emissions rate, which in turn depends on the extent to which coal and gas fuel the grid. We determine EHPs can reduce most homes' heating-related GHG emissions, but not in the cold, coal-dependent northern Midwest. If all natural gas-heated homes for which a shift to EHPs would be environmentally beneficial were to make such a shift, we compute space heating GHG emissions within the subset could be reduced by 37%, a 16% reduction in total space heating emissions. Because of the limited current use of propane, environmentally beneficial electrification of those homes would only reduce total space heating emissions by 1.7%.

At this point, we have established that, with the current grid (1) large reductions of GHG emissions from current electric resistance heating are possible with a shift to EHPs; (2) shifting fuel oil heating to EHPs significantly reduces emissions in all areas analyzed, but the effect is small given limited current fuel oil usage; and (3) natural gas and propane present a more complex situation, but in most locations, significant GHG emissions reductions are possible (though the relative impact of propane electrification is small because of its limited current usage). In following sections, we go into detail on the combined effects of building heating system and electricity system changes. Given the conclusions we have drawn thus far, and the current dominance of natural gas as a heating fuel and its emissions vis-à-vis fuel oil and propane, we simplify the presentation of our computations and figures below by using natural gas heating as a reference point for heating electrification. Wherever electrification of natural gas heating is environmentally beneficial, we can assume the same for fuel oil and propane.

Paths Forward to Drive Further Emissions Reductions

There are currently several trends that, if accelerated, can drive deeper potential reductions in energy-related GHG emissions generally and space heating emissions, specifically: Advances in EHP energy efficiency, increased use of low-carbon resources for electricity generation (primarily renewable energy, such as wind and solar power), and lower-emission natural gas replacing higher-emission coal in electricity generation.

In the subsections below, we investigate the effects of these broader changes, as well as a transitional approach, on residential space heating emissions.

Electrification with Improved Electric Heat Pump Technology

Building thermal efficiency (e.g. increased insulation and reduced air leakage) is not the primary focus of this report but has historically been thought of as the primary path to building energy usage reductions. Certainly, any building emissions reduction strategy should include efficiency measures, which will be beneficial regardless of the heating source. Assessments to date have been mixed and rigorous studies are few; for one reference point, the American Council for an Energy-Efficient Economy has estimated that widespread energy efficiency upgrades of existing homes could reduce their GHG emissions by 18% [8]. While this is promising, we do know that retrofits of all homes in the U.S. would require a very different approach than has successfully improved equipment performance standards to date. Here, we focus on the latter.

The U.S. Department of Energy has set EHP performance targets for higher COP and lesser capacity derating at low outside temperatures [9]. The capacity derating issue is important as it has consequences for equipment cost and system sizing; we discuss it qualitatively later in this report, but focus for now on COP effects on GHG emissions. There are also other significant implications of low COPs at low outside temperatures; in particular, the resulting high peak electricity loads could increase energy costs nonlinearly and costly new underutilized electricity distribution infrastructure could be required. We investigated the peak load issue in detail in a recent paper [5] that also describes the model used for the computations in this report.

Figure 2 shows a map of the computed ratio of EHP emissions to the emissions of natural gas heating across the U.S. The figure compares the same currently available EHP described above to an EHP meeting the DOE performance targets. The weighted average ratios presented weigh each census tract by its total computed space heating demand and include only those census tracts where electrification is environmentally beneficial; that is, only where computed GHG emissions of EHPs are lower than those associated with natural gas heating.

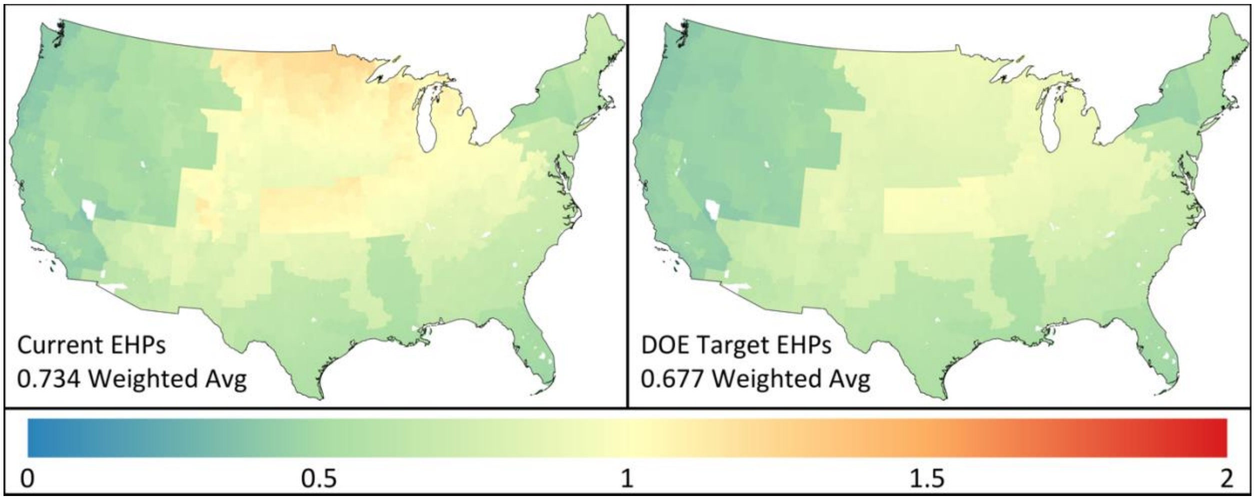


Figure 2 | Comparing currently available heat pumps and U.S. Department of Energy target performance heat pumps. Computed ratio of residential space heating emissions with heat pumps to emissions with natural gas heating. Note: The weighted averages include heat pumps only where environmentally beneficial.

Our computations indicate that widespread use of future advanced EHPs would reduce emissions by only 8% relative to currently available EHPs. We should note two primary advantages of these anticipated EHP advances not captured by this analysis: (1) Improved COP at low temperatures would reduce peak electricity demands, likely resulting in less need for new infrastructure capacity. The biggest impact is likely to be avoiding expensive new distribution system capacity, but also generation capacity and, perhaps, new transmission lines. (2) Improved heating capacity at low temperatures would mitigate the need for oversizing equipment, which increases installed costs and can lead to adverse cycling effects, such as thermal comfort issues and decreased equipment life. Later in this report, we look at one transitional approach that could mitigate these effects. While these considerations are important and will affect the system designs for individual buildings, it is clear that to achieve very deep emissions reductions, lower GHG emissions rates of the electricity supply will be required. The aggregate emissions reduction with DOE target EHPs relative to the reduction with currently available EHPs does not vary significantly with the underlying electricity grid emissions rate, so the following two subsections focus on currently available EHPs before revisiting the DOE target EHPs later in the report.

Heating Electrification with a Cleaner Grid

There are two major trends in electricity supply that affect grid emissions: (1) The growth in renewable energy supply, such as from wind and solar power, and (2) the shift from higher emission fossil fuels (primarily coal) to lower emission natural gas. How these shifts occur in specific areas of the country is a complex issue; here, we investigate the effects of broad shifts in electricity supply, leaving complex analyses of wind and solar integration in particular for other research and future reports.

In less than 20 years, renewable energy has grown from less than 8% of electricity generation to more than 17%. This shift has been supported by both policy and economics. Different states and regions have significant renewable energy and GHG goals. At the same time, the cost of renewable energy has dramatically decreased faster than most anyone anticipated. There has also already been a significant shift away from coal and towards natural gas in U.S. electricity generation. According to the U.S. Department of Energy's Energy Information Administration, as recently as 2003, coal generated more than half of all electricity and natural gas contributed less than 17%. In 2019, coal generated 23% of electricity and natural gas 38%.

As we have established the clear benefits of converting existing electric heating to currently available high-performance EHPs, we can first summarize those effects in an evolving grid before probing the situation with current fossil fuel-based heating. Table 2 summarizes the computed effects of a cleaner grid on GHG emissions from current electric heating systems and the conversion of those systems to EHPs. We can first see the effect of the shift to new EHPs described above: 70% reduction in electricity-related space heating emissions and its 30% reduction in overall heating emissions. Converting all existing electric heating could reduce total residential energy-related emissions by 17% (last column in Table 2). This is similar to the scale of overall emissions reduction (20% in last column of Table 2) that would accompany replacing current non-natural gas fossil fuel electricity generation (primarily coal) to natural gas without any change in heating systems. The combination of the two becomes particularly powerful primarily due to the effect on existing electricity usage: 33% reduction in space heating emissions and 32% in total residential emissions.

If future EHPs meet DOE performance targets, the effect on space heating emissions would be relatively small, particularly in comparison to the impacts of (1) a shift of electric resistance heating to EHPs and (2) a cleaner electricity supply. We therefore see a much bigger impact of a significant increase in the share of electricity generated from renewables in the values in Table 2. If half of the current share of fossil fuel-based electricity generation (supplying both heating alone and overall electricity usage) shifts to low-carbon sources, computed emissions reductions from space heating could approach 40% and from all residential energy-related emissions could approach 50%.

Table 2 – Exploring Emissions Reductions from Current Electric Heating[1]

Description		Fraction of All Residential Space Heating Energy			Residential Greenhouse Gas Emissions (MMtCO2e)					
					Space Heating Only			All Energy-Related Residential Emissions		
Electric Heating[2]	Electricity Grid	Electric Res.	Electric HPs[3]	Fossil Fuels	Electricity	Fossil Fuels[4]	All Sources	Electricity	Fossil Fuels[4]	All Sources
Current situation	Current situation / fuel mix	20%	7%	69%	250	339	589	636	402	1037
Current situation	Shift all coal elec. gen. to gas ("coal to gas")[5]	20%	7%	69%	182 [-27%]	339	521 [-12%]	430 [-32%]	402	832 [-20%]
Shift to all EHPs	Current situation / fuel mix	0%	27%	69%	74 [-70%]	339	413 [-30%]	460 [-28%]	402	862 [-17%]
Shift to all EHPs	Coal to gas	0%	27%	69%	54 [-78%]	339	393 [-33%]	303 [-52%]	402	705 [-32%]
Shift to all DOE Target EHPs	Coal to gas	0%	27%	69%	51 [-80%]	339	390 [-34%]	299 [-53%]	402	701 [-32%]
Shift to all EHPs	Coal to gas **+** 50% fossil fuel gen. replaced by low-carbon	0%	27%	69%	27 [-89%]	339	366 [-38%]	151 [-76%]	402	553 [-47%]
Shift to all DOE Target EHPs	Coal to gas **+** 50% fossil fuel gen. replaced by low-carbon	0%	27%	69%	25 [-90%]	339	364 [-38%]	149 [-76%]	402	551 [-47%]

1 All percentages shown in brackets are relative to first row values of corresponding column (current situation).
2 No change to on-site fossil fuel heating in this table.
3 Current heat pump heating energy estimated based on computed census tract-level average electric heating COPs.
4 Refers to on-site combustion of fossil fuels. "Electricity" columns account for fossil fuel use in electricity generation.
5 Also includes shifting other fossil fuel electricity generation to natural gas, though this is small compared to coal.

We can now investigate the emissions impact of environmentally beneficial electrification of current fossil fuel heating in an evolving grid, continuing to use natural gas as our reference point. We computed the ratio of residential EHP emissions to the emissions of natural gas heating across the U.S. for increasing fractions of low-carbon resources replacing fossil fuel electricity generation both with the current fossil fuel generation mix for each region and with natural gas replacing other fossil fuels in electricity generation. The results are shown in Figure 3.

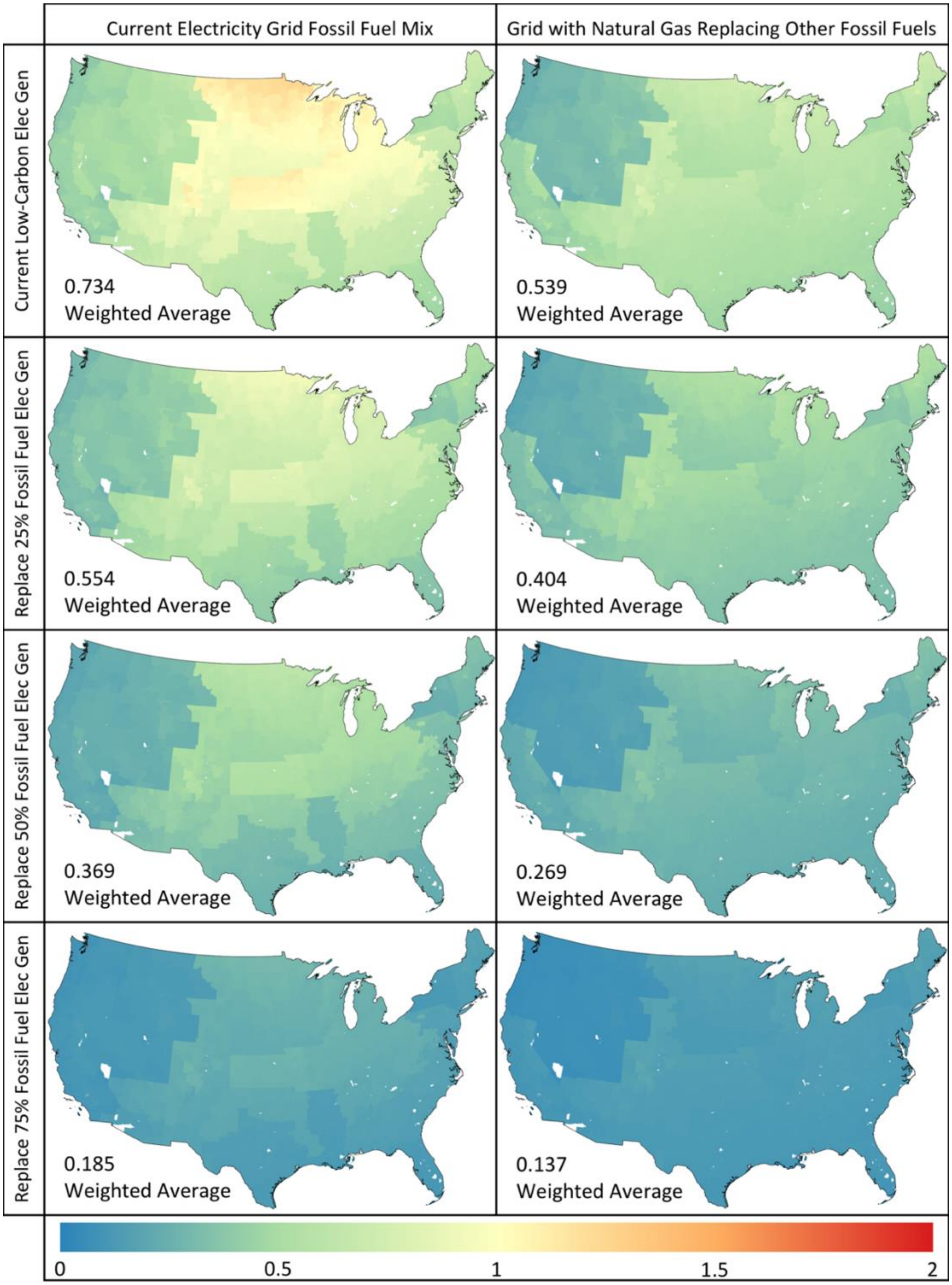


Figure 3 | Comparing GHG emissions reductions from heat pumps with shifts in electricity supply mix. Computed ratio of residential space heating emissions with currently available heat pumps to emissions with natural gas. Figures in the left column show a progressively greater contribution of low-carbon electricity with the relative share of different fuels in the remaining fossil fuel mix unchanged; figures in the right column show a progressively greater contribution of low-carbon electricity where natural gas has already replaced all other fossil fuels, primarily coal. Note: The weighted average fractions of space heating-related emissions include heat pumps only where environmentally beneficial.

The topline result from Figure 3 is that with a parallel shift in all fossil fuel-based electricity generation to natural gas (in effect from coal to gas), electrification of heating with EHPs reduces heating-related GHG emissions throughout the U.S., and by a considerable amount. However, the impact of this shift is limited without greatly scaling up the low-carbon electricity supply. If a goal were to achieve emissions reductions of 80% relative to natural gas heating, we compute that 50-75% of the current fraction of electricity generation from fossil fuels would need to shift to low-carbon sources, though eliminating coal in electricity generation would continue to have a major impact.

These results imply that some combination of growth in renewable energy, a shift away from coal to natural gas for remaining fossil fuel-based generation, and advances in EHP technology can combine to achieve the emission reduction potential of EHP for homes across the U.S. The primary barrier at present is the continuing reliance on coal in the Midwest exacerbated by the very cold temperatures in that part of the country. It should be noted that Figure 3 is based on computed values for discrete scenarios that do not include the complex system dynamics of wide-scale shifts in supply and demand, nor considerations of how such shifts might occur in the existing electricity grid and in existing buildings with legacy heating systems.

Transitioning to Full Heating Electrification with Dual Source Systems

The greatest need for heating is in the coldest climates and yet EHPs' poorest performance is at low temperatures; until the recent emergence of EHPs specifically designed for cold climates, this effect generally precluded their use in cold climates. For example, an older EHP unit that might be rated to deliver 36,000 Btu/hr at an ambient temperature of 32°F, could essentially operate as an electric resistance heater at 10°F ambient and might only deliver 18,000 Btu/hr. There is both a significant capacity and COP drop exactly when the need for heat is highest. Hence, there persists considerable consumer skepticism because of the cold temperature performance of older EHPs. Homeowners had to use some other form of supplemental heat, or the homeowner paid dearly for the much higher electricity draw if indeed the heat pump was sized for the coldest temperature. It is worth noting that if one provides say 36,000 Btu/hr of heating at a COP of 1 (assuming that the room needs to be warmed from 10°F to 70°F, a difference of 60°F) the electric draw would be 6 times that in cooling mode when ambient air is 100°F. Two effects drive this difference: the indoor-outdoor cooling temperature difference is half that of heating (so one needs only half the cooling energy, 18,000 Btu/hr) and (2) the COP in cooling mode is also much higher, say 3. If the electricity distribution grid was sized for air-conditioning and everyone starts to use electric heat pumps as their exclusive source of heating, the distribution grid would be severely strained under the older EHP models and if EHP were exclusively used for heating.

Cold-climate heat humps have addressed some of these issues to a significant extent. In colder climates where land area is less of a concern, ground source heat pumps (GSHP) have also been used but at a significantly higher capital cost. One approach in buildings with existing fossil fuel heating systems would be to install EHPs without removing the fossil fuel system. This, in effect, creates a “dual source system” or DSS that allows supplemental or combined use of the existing fossil fuel system along with the EHP. Figure 4 can help us understand the motivation for such an approach.

Figure 4(a) shows model electricity and natural gas demands vs. outside temperature for an average 2000 sf home in western Virginia. The electric demand is shown for the currently available EHP used elsewhere in this report; it assumes there is no gas heat and the “Gas Demand w/ Heating” line assumes no electric heating. Both the heating and cooling demands are shown for the heat pump. Vertical lines indicate the temperatures below which GHG emissions from natural gas heating are less than from EHP heating in the current local grid (dashed line) and with 25% of the current fossil fuel electricity generation mix shifting to low-carbon sources (dotted line). The solid line shows the temperature below which the home’s EHP-driven winter peak electric load would be higher than the home’s current cooling-driven summer peak electric load. While this perspective makes it seem that natural gas heating should be maintained until the electricity grid is “cleaner,” it is important to understand that the very low temperatures that cause these high heating loads are infrequent.

Figure 4(b) scales the x-axis to reflect the fraction of hours in our ten-year analysis in which each temperature occurs; to maintain clarity, this figure includes only the dashed line for the temperature below which GHG emissions from natural gas heating are less than from EHP heating in the current grid. This view shows that the total amount of heating energy – and associated natural gas or electricity use – is relatively small at these low temperatures compared to total heating energy needs. We compute that 19% of the average annual heating energy is at temperatures less than 20.6°F (dashed line); the lowest emission option would be to use a DSS that heats with EHPs above 20.6°F and with the existing natural gas system below 20.6°F. Note that such an approach would not just reduce emissions but has the potential to also (1) keep EHP size and investment modest and (2) ensure that impact on the electric distribution system is modest.

Figure 4(c) zooms in on the coldest 6.5% of the analyzed temperature time series, representing an average of approximately 570 hours per year; this allows us to better see the other temperature-based DSS control scenarios. As the grid incorporates cleaner electricity generation, the temperature below which a DSS should shift to natural gas heating decreases: 1°F (dotted line) with 25% of the current fossil fuel electricity generation mix shifting to low-carbon sources in our computations. At this point, we compute only 1% of heating would be provided by natural gas burned on site.

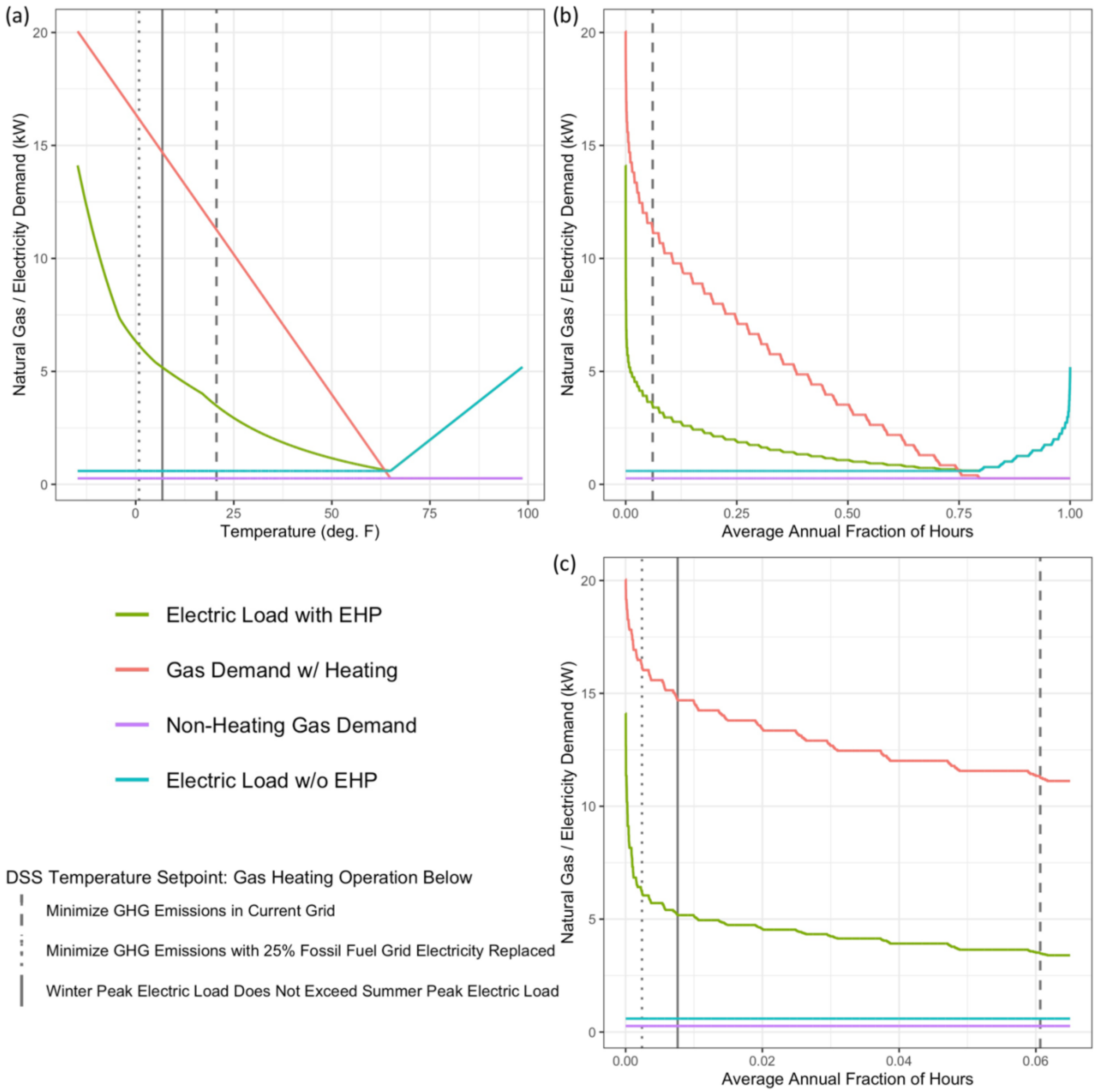


Figure 4 | Natural Gas and Electric Heat Pump Energy Demands for a Model Home. Computations for a model 2000 sf home in Virginia: (a) With outside air temperature on the x-axis, (b) with the average annual fraction of hours at which the temperatures and loads occur on the x-axis, and (c) isolating the coldest 6.5% of the analyzed temperature time series from (b). Vertical lines indicate model dual source system temperature settings for different conditions.

There is still a question of new peak electricity demands that would be caused by EHPs in much of the country[2]. For now, let us consider DSS operation that ensures the new EHP-induced peak electricity demand does not exceed the current cooling-induced

[2] This could strain the local distribution system or require a significant buildout of electricity distribution system capacity (and perhaps additional generation and transmission capacity, as well). As noted above, we go into great detail on the issues with large new infrastructure capacities that are infrequently utilized in a recent publication that serves as the basis for the computations presented in this report [5].

peak electricity demand as a proxy for avoiding these distribution system upgrades (at least in the near term). We can see from Figure 4(c) that this will prevent some GHG emissions savings, but the effect is rather small: Here, on-site natural gas use for heating would be at temperatures below 6.8°F (solid vertical line) and would amount to 3% of annual space heating energy needs. In any location what the temperature change-over point would be and the fraction of heating provided by natural gas (or for that matter, by fuel oil or propane) would depend on the local temperature regime, the cold temperature performance of the EHP and how the EHP is sized.

Dual Source Systems and a Progressively Cleaner Grid

We will return to the peak load control case below, but for now we will stay focused on GHG emissions. Figure 5 shows two columns of maps displaying computed values at the census tract level for environmentally beneficial heating electrification and DSS operation: The left column shows computed values for the ratio of residential DSS (or EHP only where environmentally beneficial) emissions to the emissions of natural gas heating alone across the U.S. For the current grid (top left panel) the weighted average of this ratio is 0.699. Lower panels show scenarios with progressively cleaner grids where increasing amounts of low-carbon generation replaces fossil fuel generation in the current electricity generation mix (analogous to the left column in Figure 3). Observe that at 50% replacement – a scenario that most analysts would agree is viable in the next decade or two – leads to weighted emissions with EHPs that become 37% of those from gas heating (i.e. a 53% reduction compared to the current grid).

The right column in Figure 5 shows the corresponding fraction of total heating energy provided by the EHPs for each scenario. The computed aggregate values at the national level for both *total* heating energy provided by EHPs and *peak* heating energy provided by EHPs for each scenario are also shown. Figure 5 shows that significant reductions in GHG emissions are possible with DSSs as the electricity grid evolves. Further, this can be achieved without requiring that EHPs be sized to meet a home's total heating capacity in much of the country; this is also seen in the example home shown in Figure 4, above. (Note that smaller EHP capacities in DSSs would also lower emissions, though not to the full extent computed and presented in Figure 5.)

As mentioned above, the computations shown in Figure 5 do not restrict the peak electricity load to avoid distribution system strains or upgrades. These considerations are important in transitioning away from fossil fuel-based heating, but our analysis indicates that even a conservative load constraint does not significantly affect our overall computations: Table 3 shows the computed values in Figure 5, as well as the corresponding values if we constrain all homes' new peak electricity loads to current cooling-driven peak loads (if all homes were to have air conditioning).

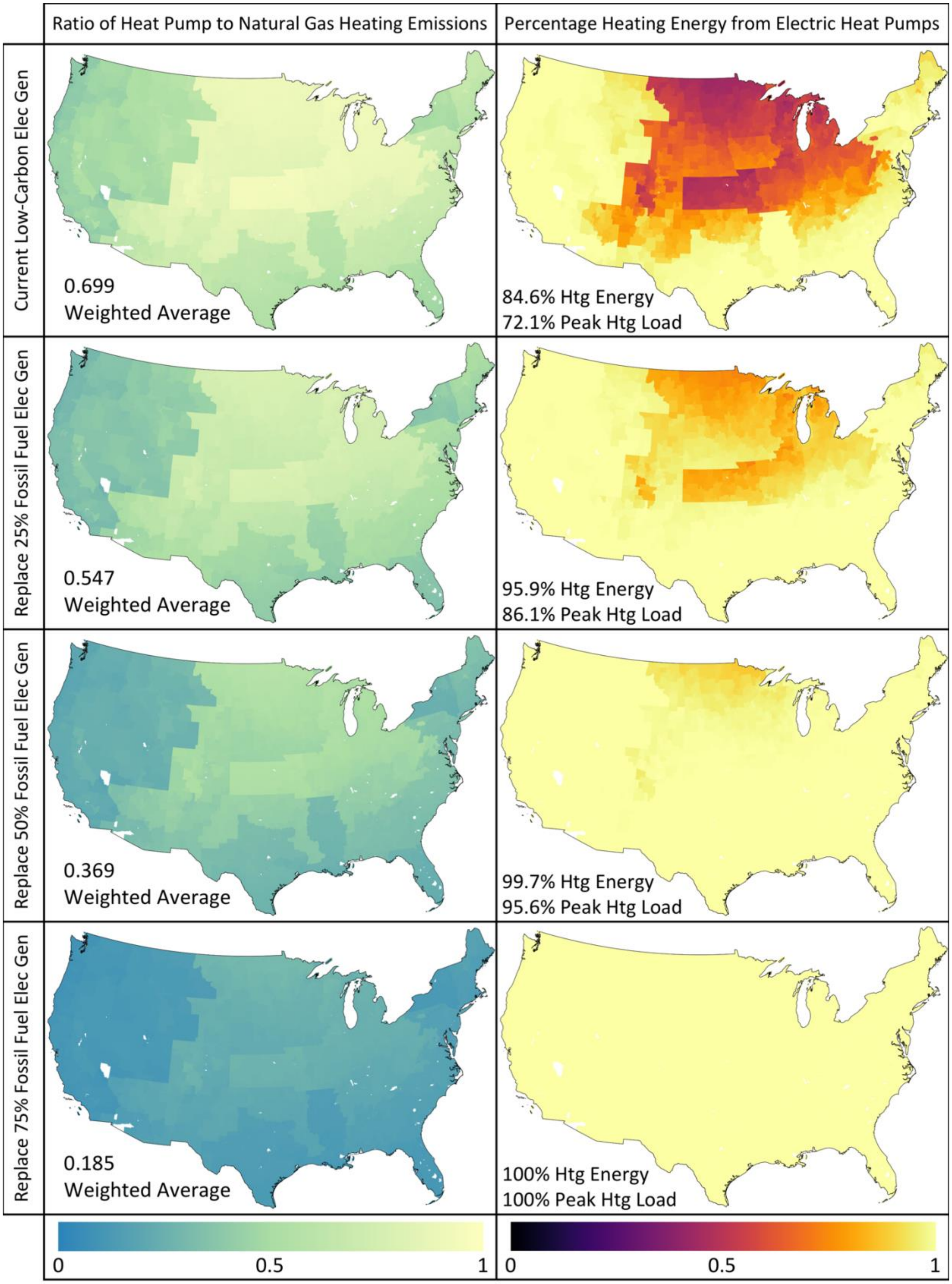


Figure 5 | Dual source systems at different low-carbon electricity supplies. Left column: Computed ratio of residential heat pump emissions to natural gas heating emissions; note ratio is always less than 1. Right column: Fraction of space heating from electricity.

Table 3 – Select Aggregate Computed Values with Dual Source Systems with and without Peak Load Control[1]

Percentage of Current Fossil Fuel Electricity Generation Replaced by Low-Carbon Sources	Ratio of DSS/EHP to Natural Gas Emissions		Percentage of Heating Energy from EHPs		Percentage of Peak Heating from EHPs[2]	
	Without Peak Load Control	With Peak Load Control	Without Peak Load Control	With Peak Load Control	Without Peak Load Control	With Peak Load Control
0%	0.699	0.704	84.6%	82.6%	72.1%	68.3%
25%	0.547	0.557	95.9%	93.5%	86.1%	79.0%
50%	0.369	0.385	99.7%	96.3%	95.6%	84.5%
75%	0.185	0.211	100%	96.3%	100%	84.5%
100%	0	0.037	100%	96.3%	100%	84.5%

[1]Values without peak load control correspond to those in Figure 5. Values with peak load control reflect computations that constrain all homes' new peak electricity loads to the current peak loads computed for homes with air conditioning.
[2]Computed aggregate peak heating output from EHPs as a percentage of the total peak heating output.

The values in Table 3 do indicate that at very deep penetrations of low-carbon electricity generation, the peak load control constraint has an impact on computed GHG emissions (which are quite low at this point). Here even a benefit emerges from the simulated peak load control: Only moderately lesser emissions reductions are possible with significantly less aggregate peak heating provided by EHPs. Further, we stress that DSSs are likely to be a transitional approach as infrastructure investments are assessed, grid-interactive controls are developed and new EHP technologies emerge.

Summary of Individual and Combined Effects of Emissions Reduction Options

It is useful to synthesize the combined effects of EHPs, DSSs and an evolving grid, similar to our exploration of current electric heating in Table 2. This synthesis is shown in Table 4 where the first row shows the computed effects on GHG emissions for the "current situation", from Table 2. (Here 20% of the heating from electric resistance is assumed.) Forms of heating considered here add to 96% as the analyses exclude other minor contributors (e.g. wood, solar-thermal).

All other scenarios shown include converting all current electric heating to EHPs and all environmentally beneficial electrification of current fossil fuel heating. All percentages shown in brackets are relative to the "current situation" value of the corresponding column. For these scenarios the options considered are:

- With or without DSS: In the scenarios with DSS, DSS operation is assumed to ensure the EHP-induced peak electricity demand does not exceed what the cooling-induced peak electricity demand would be with air conditioning.
- "Coal to gas": Coal in current grid is replaced with natural gas.
- "Shift to DOE Target EHPs": All EHPs meet DOE performance targets.
- "Coal to gas + 50% fossil fuel generation replaced by low-carbon": In addition to coal in the current grid being replaced by natural gas, 50% of *all* fossil fuel generation after this switch is replaced by low-carbon resources.

Table 4 – Environmentally Beneficial Electrification of Current Fossil Fuel Heating[1]

Description			Fraction of All Residential Space Heating Energy		Residential Greenhouse Gas Emissions (MMtCO2e)					
					Space Heating Only			All Energy-Related Emissions		
FF Heating	DSS[2]	Electricity Grid	Electric HPs[3]	Fossil Fuels	Elec.	Fossil Fuels[4]	All Sources	Elec.	Fossil Fuels[4]	All Sources
Current situation	N/A	Current situation / fuel mix	7%	69%	250	339	589	636	402	1037
Shift to EHPs	No	Current situation / fuel mix	85%	11%	237 [-5.0%]	43 [-87%]	280 [-52%]	623 [-2.0%]	106 [-74%]	729 [-30%]
Shift to EHPs	Yes	Current situation / fuel mix	83%	14%	217 [-13%]	54 [-84%]	272 [-54%]	603 [-5.1%]	117 [-71%]	721 [-31%]
Shift to EHPs	No	Coal to gas	96%	0%	205 [-18%]	0	205 [-65%]	454 [-29%]	63 [-84%]	517 [-50%]
Shift to EHPs	Yes	Coal to gas	93%	3.1%	194 [-22%]	13 [-96%]	207 [-65%]	443 [-30%]	76 [-81%]	518 [-50%]
Shift to DOE Target EHPs	No	Coal to gas	96%	0%	189 [-24%]	0	189 [-68%]	437 [-31%]	63 [-84%]	500 [-52%]
Shift to DOE Target EHPs	Yes	Coal to gas	95%	1.3%	186 [-26%]	5.5 [-98%]	191 [-68%]	434 [-32%]	68 [-83%]	502 [-52%]
Shift to EHPs	No	Coal to gas **+** 50% fossil fuel gen. replaced by low-carbon	96%	0%	103 [-59%]	0	103 [-83%]	227 [-64%]	63 [-84%]	290 [-72%]
Shift to EHPs	Yes	Coal to gas **+** 50% fossil fuel gen. replaced by low-carbon	93%	3.0%	97 [-61%]	13 [-96%]	110 [-81%]	222 [-65%]	75 [-81%]	297 [-71%]
Shift to DOE Target EHPs	No	Coal to gas **+** 50% fossil fuel gen. replaced by low-carbon	96%	0%	94 [-62%]	0	94 [-84%]	218 [-66%]	63 [-84%]	281 [-73%]
Shift to DOE Target EHPs	Yes	Coal to gas **+** 50% fossil fuel gen. replaced by low-carbon	95%	1.3%	93 [-63%]	5.5 [-98%]	98 [-83%]	217 [-66%]	68 [-83%]	285 [-72%]

1 All percentages shown in brackets are relative to first row values of corresponding column (current situation).
2 DSS operates when environmentally beneficial and to ensure the EHP-induced peak electricity demand does not exceed what the cooling-induced peak electricity demand would be with full penetration of air conditioning.
3 First row (current heating and grid situation) includes 20% heating energy from electric resistance. All others assume all current electric heating converts to electric heat pumps. See Table 2 for more detail on electric heating. Maximum value is 96% as the analyses here exclude minor contributors to heating (e.g. wood and solar-thermal).
4 Refers to on-site combustion of fossil fuels. “Electricity” columns account for fossil fuel use in electricity generation.

From Table 4, we can again see the effect of the shift to new EHPs even with the current electricity generation mix described earlier in this report: 52% reduction in overall heating emissions (and 30% of total residential energy-related emissions). Allowing for the use of EHPs in DSSs that retain some amount of existing fossil fuel heating capacity slightly further reduces space heating GHG emissions (even with the constraint that the DSSs operate to ensure the EHP-induced peak electricity demand does not exceed what the cooling-induced peak electricity demand would be with full penetration of air conditioning). One important thing to note is that the shift away from fossil fuels for most heating energy would result in significantly more electricity flowing to residential buildings, so the total electricity-related emissions do not dramatically decrease. However, on-site fossil fuel use decreases significantly, which is the primary contributor to overall emissions reductions. Further, this electrification allows for significantly greater emissions reduction as the grid itself becomes “greener.”

If current non-natural gas fossil fuel electricity generation (primarily coal) were to be replaced with natural gas, even more electrification of current fossil fuel-based heating becomes environmentally beneficial; in fact, EHPs would result in lower emissions than fossil fuel heating across the U.S. With this change in the grid, we do compute broader emissions reduction effects: 50% reduction in overall residential emissions and even 30% in electricity-related emissions despite the added electricity demand from heating electrification. The use of DSSs vs. EHPs alone has minimal impact on these aggregate numbers, so at this point one could consider constraints of peak load without affecting GHG emissions. Future EHPs that meet DOE performance targets have only a marginal effect on emissions, but would reduce by nearly 60% the fossil fuel usage needed to avoid violating the peak load constraint (1.3% vs. 3.0% of heating energy). This also reflects that future EHP advances could mitigate – and in some places eliminate – upgrades to infrastructure capacity or home electricity service.

The relative effects of DSSs and DOE performance targets generally hold for scenarios in which half of the current share of fossil fuel-based electricity generation (supplying both heating alone and overall electricity usage) shifts to low-carbon sources. In all cases, we compute space heating-related GHG emissions reductions of more than 80% and total residential energy-related GHG emissions reductions of more than 70%. We have not considered here electrification of other fossil fuel uses (primarily domestic hot water and cooking), but shifting these to electric equipment would further reduce emissions, though they would also have some impact on peak electricity loads.

Space Heating Emissions Reduction Pathways

In this report we have addressed five major elements of space heating decarbonization:

1. Replacing current electric resistance heating with EHPs.
2. Replacing current fossil fuel heating with EHPs.
3. Achieving DOE performance targets for future EHPs.

4. Cleaning the electricity grid through (a) shifting from coal to gas and (b) increasing low-carbon generation (e.g. renewable energy). In practice both of these are likely to proceed in tandem, as investigated in this report.
5. Using DSSs as a means to lower peak EHP electric power draw and/or minimize heating emissions.

Pathways are likely to include concurrent shifts of space heating to EHPs (from all current heating sources) and a cleaner grid over time (with the latter also more broadly reducing energy-related emissions). Here we take a simplified approach – assuming a percentage shift to EHPs is evenly distributed across the U.S. without optimizing for location or existing heating fuel replaced – to get a handle on the scale of transformations needed.

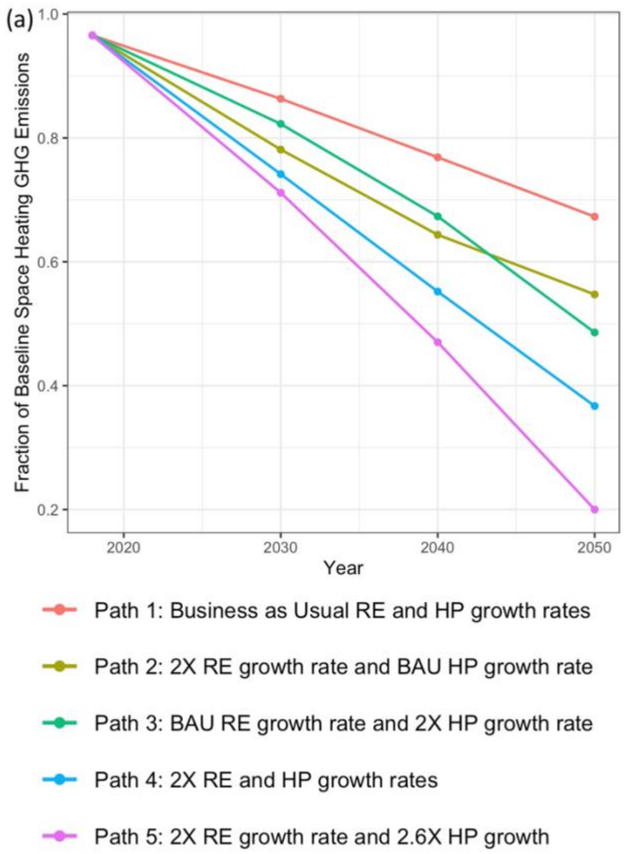
We first estimate a reasonable “business as usual” (BAU) rate of renewable energy penetration based on the growth in percentage of U.S. electricity generation from renewable energy since 2001 [1] and of EHP adoption based on U.S. Energy Information Administration surveys in 2005 [10], 2009 [11] and 2015 [4]. In order to compute reductions in total U.S. space heating emissions for the years 2030, 2040 and 2050 for different scenarios (Figure 6(a)), we assume a typical S-shaped technology adoption curve – fit to the historical electricity generation and survey data – to project the share of fossil fuel-based electricity shifting to low-carbon resources (Figure 6(b)) and the fraction of residential floor area using EHPs (Figure 6(c)). These figures also show computations that assume adoption rates of EHPs and/or renewable energy double.[3] (Note again that emission reductions shown in Figure 6(a) are for space heating only and do not include reductions from the other electricity uses. Nor do we investigate how renewable energy penetration may occur differentially between baseload and non-baseload electricity generation.)

We compute that a BAU pathway (Path 1 in Figure 6) can achieve a 33% reduction in space heating emissions in 2050. While this is significant, it does not nearly approach the minimum 80% reduction needed by this point in time. We next consider two scenarios: One, doubling the BAU renewable adoption rate and keeping BAU EHP adoption (Path 2); two, doubling EHP adoption and keeping BAU renewable adoption rate (Path 3). The relative effects of each are similar and emissions reductions remain short of our targets.

Doubling the adoption rates of both renewable energy and EHPs (Path 4) results in a computed 63% reduction in emissions in 2050. One combination of measures that can achieve 80% emissions reduction from heating in 2050 (Path 5), is a doubling of the renewable adoption rate and an EHP adoption rate that is 2.6 times BAU. This path

[3] Other relevant assumptions: Coal-based electricity generation is assumed to be eliminated by 2030. EHPs are adopted in DSSs where environmentally beneficial; we impose the peak load control discussed above. We assume 1/3 of installed EHPs meet DOE performance targets in 2030, 2/3 of EHPs in 2040 and all EHPs in 2050. Eliminating coal has a significant impact on computed values; higher renewable energy and EHP adoption rates would otherwise be required. The EHP performance assumptions (i.e. currently available EHPs versus those that meet DOE performance targets) do have some effect on computed GHG emissions reductions, but do not substantively affect the presented results or findings.

implies for 2050: 90% of all electricity generated for space heating loads from low-carbon resources, the remaining 10% of electricity generation from natural gas, and 77% of residential floor area heated by EHPs. Note that based on computations shown in the previous section, we would find a similar space heating GHG emission reduction with 96% EHPs (excluding current wood and solar-thermal heating) and slightly less than 50% of the current fossil fuel share of electricity generation being replaced by low-carbon sources.



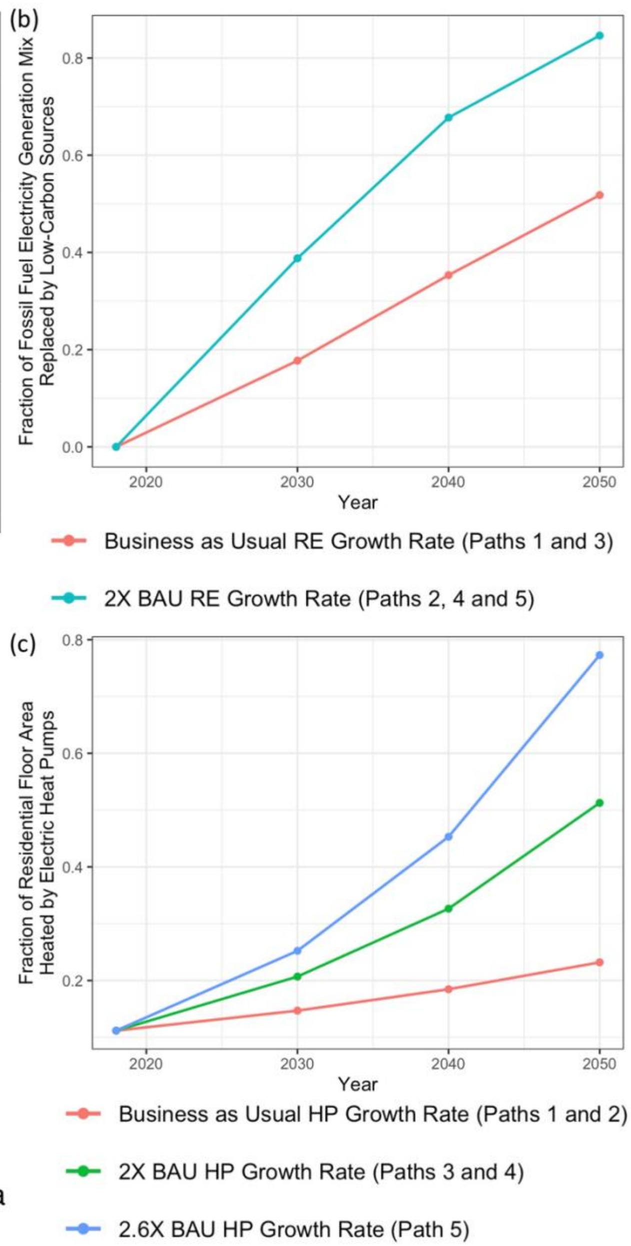


Figure 6 | Pathways to Space Heating GHG Emissions Reductions. Computed values for (a) total U.S. space heating emissions as a fraction of computed baseline, based on (b) projected fossil fuel electricity generation displaced by low-carbon sources and (c) projected EHP adoption. Note that the 2018 starting point of the plot includes some reduction from the baseline based on 2010 data and 2018 grid performance.

Discussion

In this report, we have presented computations that inform pathways to dramatically reduce GHG emissions from space heating across the U.S. Broadly, we can separate questions related to current electric heating (42% of residential heating emissions) that is dominated by electric resistance systems and current systems that burn fossil fuel on site to heat homes (remaining 58% residential heating emissions).

Electric resistance heating, currently the most prevalent electric heating approach, is technically nearly 100% efficient; current emissions from electric heating are due to high dependence on fossil fuels for electricity generation. Electric heat pumps (EHPs) can operate at much higher efficiency – called the coefficient of performance (COP) and given in raw numbers, not percentages – but the COP is highly dependent on outdoor air temperature and reduces significantly at low temperatures. We compute that currently available EHPs could achieve an average COP greater than 4 when averaged across the U.S.; we estimate current electric heating (comprised of electric resistance and some amount of legacy EHPs) to have an average COP of 1.2. We therefore compute that replacing current electric heating with currently available EHPs alone, even with the current grid, could lower total residential space heating emissions by 30%. The emissions would continue drop as the grid becomes cleaner. It is important to note that the contribution of electric heating to space heating emissions is not widely understood, so this opportunity for significant GHG emissions reductions is often missed[4]. Replacing electric resistance heating with EHPs would also reduce recurrent home heating costs. While there are upfront costs for converting to EHPs, no upgraded infrastructure capacity or home electricity service would be needed; thus, the benefits of such a shift are clear.

Shifting among different fossil fuel heating sources has limited or no impact on GHG emissions. We therefore focus here on the conversion of fossil fuel-based heating systems to electricity-based EHPs; we limit these conversions to where such a change would result in emissions reductions, broadly referred to as “environmentally beneficial electrification.” Such electrification would depend on (1) the GHG emissions caused by burning a particular fossil fuel; (2) the COP of available EHPs, including the COP-reducing effects of low temperatures; and (3) the emissions rate associated with the electricity supplied by the local grid. We presented the current fuel and grid emissions landscape in detail in a previous report. For a given fuel, the first item here is unlikely to vary significantly, though there is some benefit to improved equipment efficiency and shifting from fuel oil to natural gas or propane. The last two items warrant close attention and were analyzed in detail in this report.

As COP (particularly at low temperatures) has improved dramatically over time, EHPs have become viable in increasingly colder climates. Further, the DOE has set even

[4] This is likely due to the fact that most existing low-carbon electricity generation resources (primarily hydropower and nuclear power) meet baseload demands, whereas space heating should largely be considered a non-baseload electricity demand (being seasonal and highly temperature-dependent). The differential grid emissions rates are often not considered in assessing electric heating emissions.

higher performance targets that researchers and manufacturers are working to achieve. In this report, we have shown electrification with currently available EHPs to be environmentally beneficial in much of the U.S. with some further reduction in emissions (approximately 8%) if DOE performance targets are reached.

However, the biggest impact from EHPs comes with an increasingly clean grid. We compute that if 25% of the current fossil fuel generation mix is replaced by low-carbon sources and natural gas replaces all other fossil fuels in electricity generation – both trends that seem quite possible in the next 10-15 years – the U.S.-weighted average home emissions from EHPs would be 60% less than heating a home with natural gas.

One consideration is that the grid is not currently "green" enough for EHPs to be the lowest emission option in all locations or at all times, typically when temperatures are very low and where grid regions still rely on large amounts of fossil fuels (primarily significant amounts of coal). A second consideration is that in much of the country EHP-driven electricity loads are likely to be significantly higher than current cooling-driven peak electricity loads. Therefore, we see a strong role for an approach of installing EHPs while maintaining existing home fossil fuel-based heating in dual source systems (DSSs) in which the lowest emission option is used at a given time while also avoiding new large infrequent electric loads.

While advanced controls need to be developed for grid interactivity that takes advantage of intermittent wind and solar power supply, we can estimate the effects of DSSs using average grid supply emissions rates for space heating and operating EHPs only above temperatures at which the COP is sufficient to reduce emissions relative to those of fossil fuel heating. We can also impose peak load controls that avoid operating EHPs when high heating-driven electric loads would strain local distribution systems or require upgrades to infrastructure and home electricity service.

With the current grid in nearly the entirety of the U.S., we compute that DSSs would be the lowest emission option without requiring a complete shift to EHPs for all heating. Further, because the majority of heating is needed at relatively moderate temperatures, the amount of heating energy provided by EHPs would be significantly greater than that provided by fossil fuel heating, nearly 85% for environmentally beneficial operation in the current grid with natural gas as the secondary heating source. As the grid increasingly shifts away from coal and integrates more renewable energy, the amount of heating provided by EHPs could increase, further decreasing GHG emissions. Eventually the peak electric loads caused by EHPs could be a problem, but because the highest loads (i.e. the lowest temperatures) are infrequent, imposing peak load controls would only modestly increase GHG emissions. In such scenarios, EHPs could be sized to meet an even smaller percentage of a home's peak heating demand while EHP technology further improves.

We lastly charted possible paths to deep residential space heating emissions reductions that consider increased use of EHPs and renewable energy, coal being displaced in electricity generation, EHPs that eventually meet DOE performance targets, and environmentally beneficial and peak load-limiting DSS operation. One summary message is that using current EHP and renewable adoption rates to 2050, the aggregate annual residential space heating emissions would reduce by 33%. Doubling EHP and renewable energy growth rates, emission reductions could be 63%. Because of slow adoption of EHPs, even doubling growth rates would lead to EHPs (alone or as part of DSSs) heating only 51% of residential floor area in 2050, whereas 85% of the current fossil fuel mix would be replaced by renewables (for a total low-carbon electricity supply of 90%). In combination with a 90% low-carbon supply, a target 80% reduction in space heating emissions could be achieved in 2050 if an EHPs grow at a rate 2.6 times the current growth rate, resulting in EHPs in 77% of homes by that year.

The load and operational challenges associated with EHPs – and perhaps those of renewable energy integration – could be mitigated by widespread use of DSSs instead of completely eliminating existing fossil fuel heating systems, at least during a transition period. This approach would also provide flexibility as the grid changes, EHP performance further improves, advanced controls become available, and potentially unexpected viable alternative fuels or new heating technologies emerge.

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