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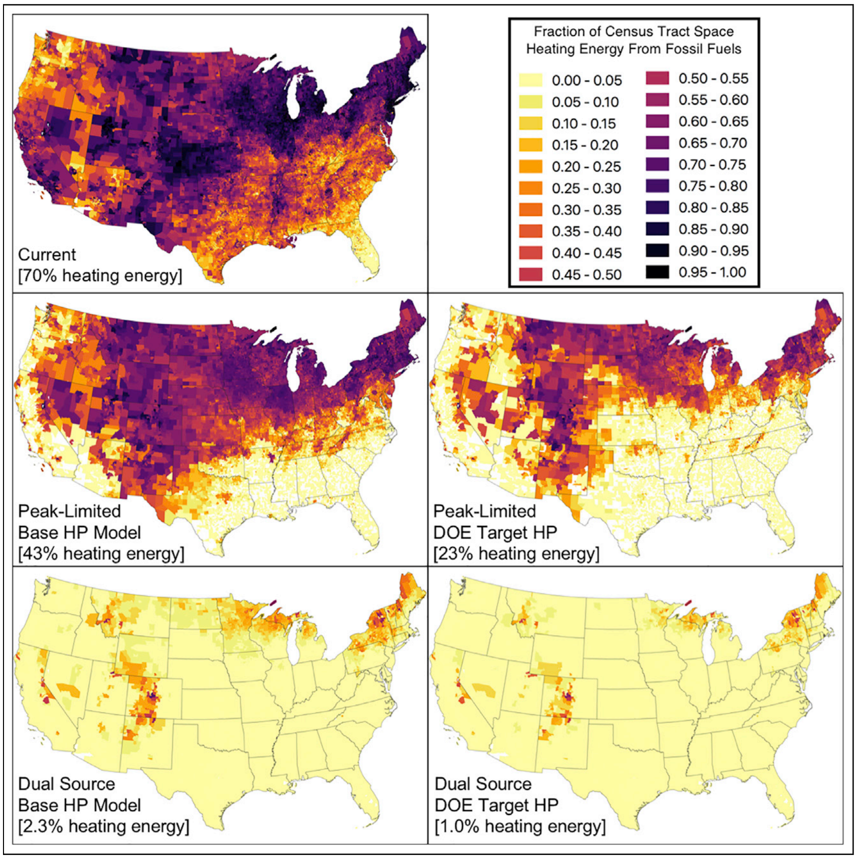
Electricity Load Implications of Space Heating Decarbonization Pathways



We model building space heating electrification across the United States, computing a potential 70% increase in nationwide electricity delivery capacity with very low capacity factors. Without increasing peak electric loads, fossil fuels can be reduced to 43% of total heating energy using current heat pump technology and 23% with future advances. Dual source systems with heat pumps and some fossil fuel equipment retained for the coldest weather could reduce fossil fuels to 1%–3% of heating energy without electricity capacity upgrades.

Michael Waite, Vijay Modi

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HIGHLIGHTS

53% of U.S. space heating energy can be electric without exceeding current peak loads

Electrification increases aggregated peak loads by 70%, more than double in 23 states

Targeted heat pump advances mitigate load issues, but challenging regions remain

Some fossil fuel backup supports 97% heating electrification without new peak loads

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Electricity Load Implications of Space Heating Decarbonization Pathways

Michael Waite[1,2,*] and Vijay Modi[1]

SUMMARY

We investigate implications of building space heating decarbonization pathways across the climate-diverse United States. We compute that an "all-electric" approach could require a 70% increase in nationwide electricity system capacity. New peak loads would be highly heterogeneous (e.g., 4-fold increase in some states) with very low load factors (fewer than 100 full load hours annually). Without increasing peak loads, currently available electric heat pumps can reduce fossil fuels to 43% of total heating energy supply (currently 70%). Future advances in heat pump technology could reduce this further to 23%; however, several challenging regions would remain. We show that installing heat pumps and retaining some fossil fuel equipment for use in only the coldest weather could reduce fossil fuels to 1%–3% of heating energy while progressively reducing fossil fuel heating capacity and avoiding electricity capacity upgrades. Therefore, strategic use of legacy infrastructure could facilitate a more flexible transition to low-carbon heating.

INTRODUCTION

Reducing greenhouse gas (GHG) emissions associated with heating buildings is an essential element of a larger energy transition. Although the path forward is not yet settled, the primary approach in the deep decarbonization research literature[1–4] and emerging U.S. state policies[5,6] is "all-electric," converting all existing fossil fuel-based heating systems that currently prevail[7] to high efficiency electric heat pumps (HPs) and expanding renewable electricity supply. Setting aside the challenges of replacing systems in tens of millions of existing buildings, the lack of recognition of the difficulty of eliminating building emissions[8] highlights a particular issue in the emerging consensus: widespread heating electrification has significant capacity implications that are largely absent from the many deep decarbonization studies conducted to date.[9]

Even where nearly comprehensive studies have included some distribution system considerations, they have assumed no future changes to electricity delivery pricing[10] or that such costs will scale with generation and transmission.[11] Detailed generation and transmission models are standard for such studies,[12] which allow computational analyses to capture the benefits of smoothing intermittent renewable production over large distances.[13] However, no such effect is available at the local scale where the all-electric approach is likely to only increase capacity requirements[14] and delivery already constitutes 25%–50% of electricity costs.[15] Understanding the load implications of heating electrification is thus essential to future system planning and operation.[16]

Context & Scale

Building heating decarbonization is essential, but the prominent "all-electric" proposal—replace all fossil fuel heating with electric heat pumps and expanded renewable electricity supply—could require massive buildouts of underutilized electricity infrastructure according to the analysis presented in this paper. Future heat pump advances could mitigate these issues, but some regions could still require more than double the current delivery capacity. Because it is imperative to start rapidly reducing emissions now, this paper evaluates a viable transitional approach: dual source systems that maintain existing fossil fuel equipment with new heat pumps. Because the highest heating needs are infrequent, using fossil fuels for only 3% of total U.S. heating energy could avoid any increase in local peak electricity demands. Such an approach would further allow the flexibility to adapt to future developments, such as viable alternative fuels or unanticipated major heating technology advances.

Evaluating the roles of different generation resources is critical as intermittent renewable energy supply (i.e., from wind and solar) increases,[17] but capacity and operational requirements will be highly sensitive to a demand-side transition away from fossil fuel sources and will be largely set by future peak loads. While air conditioning drives current peak electricity demands in much of the developed world[18] and future electricity demand profiles are difficult to project,[19] two primary factors can cause higher heating-induced peak electricity demands. First, winter indoor-outdoor temperature differentials are generally higher than in the summer, which are averaged over the continental United States, peak winter temperature differentials are approximately twice those of the summer.[20] Second, the HP coefficient of performance (COP)—the amount of heat delivered per unit electricity consumed—reduces as temperature decreases and must eventually switch to electric resistance heating at the lowest temperatures. Even the most advanced cold climate HP prototypes operate with low-temperature COP that is less than half the COP at rated conditions.[21] Despite this, heating electrification studies typically use an average COP based on rated performance.[12,22] Although cooling energy growth is an emerging challenge in the developing world,[23] properly assessing heating effects is essential where massive, complex, and robust infrastructure systems already exist. Although potential effects of transport electrification are beyond the scope of this study, peak thermal comfort demands can be far higher,[24] do not have the range of integration and control opportunities of electric vehicles,[25] and are highly seasonal.

The United States provides a useful study area because it has two general features consistent with the overall heating electrification challenge: (1) geographical heterogeneity of space heating energy demands,[26] existing heating equipment,[27] fuel availability,[28] and renewable energy resource potential[29]; and (2) a transition largely dependent on converting existing systems, with over 75% of existing commercial building area[30] and over 80% of existing housing units[15] estimated to remain in 2050, while total building energy demands are expected to be stable.[15]

Different pathways to decarbonizing heating will require different energy infrastructure changes,[31] but current understanding of the implications for such strategies is limited due to incomplete or unavailable information on existing energy systems[32] and high spatial variability of the underlying drivers of heating demands. Heating fuels,[33] climate,[23] and building stock[34–36] can all be highly diverse across a region. While electricity grid data are not widely available at high spatial resolution, time-dependent fossil fuel usage is essentially non-existent. As such, estimating current temporal heating fuel usage has remained intractable[37] despite being essential to projecting future electricity demands.

This study represents the first known attempt to quantify the relative capacities of fossil fuels and electricity delivery infrastructure or to compute the load effects of heating electrification of all U.S. residential and commercial buildings. Given the cost of building new electricity infrastructure and the potential for its limited use to meet infrequent high loads, we also estimate the HP penetration possible with current electricity delivery capacity. While there are several potential alternatives to all-electric approaches,[38] here, we investigate the use of dual source systems (DSSs) that maintain existing fossil fuel heating equipment in addition to new HPs.[39]

For this study, an analytical methodology was developed that synthesized several disparate publicly available datasets (e.g., monthly state-level energy usage, local hourly temperatures, census tract-level heating fuel and building floor area) and

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applied several statistical techniques to obtain high fidelity census tract-level estimates of current and potential temperature-dependent residential and commercial building energy demands. Heating electrification models were developed based on currently available HPs and future performance targets. Given the large geographical scope and high spatial resolution of the model, we focus on heating energy delivery to serve statistically discernable temperature-dependent behavior of buildings; however, we have not attempted to model diurnal or other patterns of thermal comfort demands. Furthermore, we have not analyzed potential gains in building thermal performance, thermal energy storage, ground-source heat pumps (GSHPs) or energy sources. Analyzing low-carbon electricity supply is a robust area of research, here, we work from the proposition that regardless of electricity system developments, a central element of overall energy decarbonization will be a major reduction in fossil fuel usage for space heating.

We compute a 70% aggregate increase in peak electricity loads to accommodate an all-electric heating approach using state-of-the-art HPs (116% increase using median-performance ''cold climate HPs''); more than one-third of census tracts would see double their peak load. Significant future HP technology improvements can mitigate these effects in much of the country, but several challenging regions would remain. Furthermore, new capacity utilization is computed to be fewer than 100 annual equivalent full load hours. If each census tract installs the maximum HP capacity possible, without exceeding current peak electricity loads, the computed heating energy provided by fossil fuels reduces to 43% (70% currently). While our results suggest this can eventually be reduced to a promising 23% with future advanced technologies, we also find significant geographic heterogeneity with full or near-complete electrification within current peak loads in warmer regions and colder areas unable to achieve 50% reduction in fossil fuel heating.

Perhaps the most important finding of this study is that, if approximately 60% of existing fossil fuel-based heating capacity is maintained in DSSs for use only during the coldest weather, more than 97% of U.S. residential and commercial space heating energy can be provided by electricity without exceeding the current peak electricity demand of any census tract. Even deeper reductions in fossil fuel usage with approximately half the DSS capacity are computed for HP technology improvement scenario. Therefore, this approach could avoid a very large increase in electricity system capacity only to replace the last 1%–3% of fossil fuel-based heating.

A central broader conclusion of this study is that energy decarbonization could be most effectively achieved by leveraging the distinct advantages of existing fossil fuel systems to achieve future GHG goals. A future low-emission energy system may include some amount of residual fossil fuel usage,[40] but this paper analyzes its role in facilitating widespread heating electrification and to allow flexibility for possible future innovations. A dedicated all-electric pathway from the outset could preclude future viable alternatives and leave large buildouts of infrastructure capacity with limited utility over the long term. While this leads to several areas of research beyond this paper's scope, we provide key insights that can set planners and policymakers on a course that offers more flexibility as decarbonization progresses.

RESULTS AND DISCUSSION

Current Fossil Fuel Delivery Capacity Is Much Larger than Current Electricity Delivery Capacity

We first quantify current system topography that reflects much larger heating demands than cooling demands in most of the U.S. and the implications for a

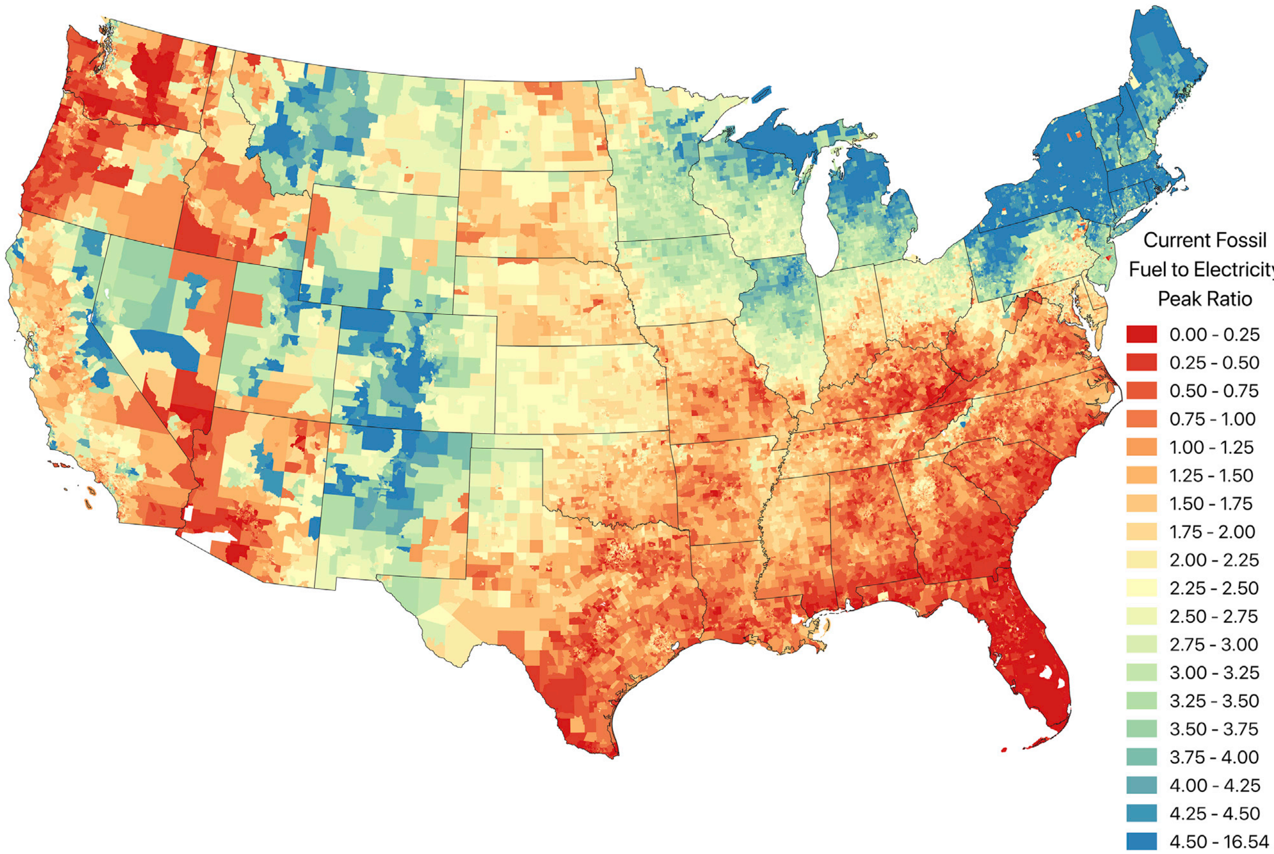

Figure 1. Census-Tract-Level Ratios of Current Peak Fossil Fuel Demand to Current Peak Electricity Demand

All values are computed at the census tract level for years 2008–2017. Census tracts with white fill have no residential or commercial building square footage in the source data. Figure S11 shows a histogram of census tracts by current fossil fuel to electricity peak ratio.

transitioning energy system. The temperature-dependent fossil fuel and electricity demand models, described in the Experimental Procedures underly the computations described throughout the Results section (for reference, an example showing these models applied to a typical residential building is shown in Figure S14).

We computed current hourly peak fossil fuel and electricity demands for all 72,198 census tracts with residential or commercial building floor area in the contiguous U.S. The specific physical infrastructure capacities being unknown, we use the ratio of peak fossil fuel demand to peak electricity demand as a proxy for scale differences. Census-tract-level computations are shown in Figure 1. Census tract land area varies considerably due to population densities; however, as this is not necessarily clear in Figure 1, a histogram of census tracts by current fossil fuel to electricity peak ratio is shown in Figure S11.

In aggregate, peak fossil fuel loads are computed to be 91% greater than peak electricity loads, and at the census tract level, this ratio is highly geographically heterogeneous. Much of the Northeast, the Upper Midwest and the Rocky Mountains are estimated to have more than four times greater fossil fuel delivery capacity than electricity capacity (we use the term ''delivery'' throughout this paper largely to refer to distribution infrastructure which is nearest to the spatial resolution analyzed; however, we use the term generally in discussing the implications of our findings, including for generation and transmission).

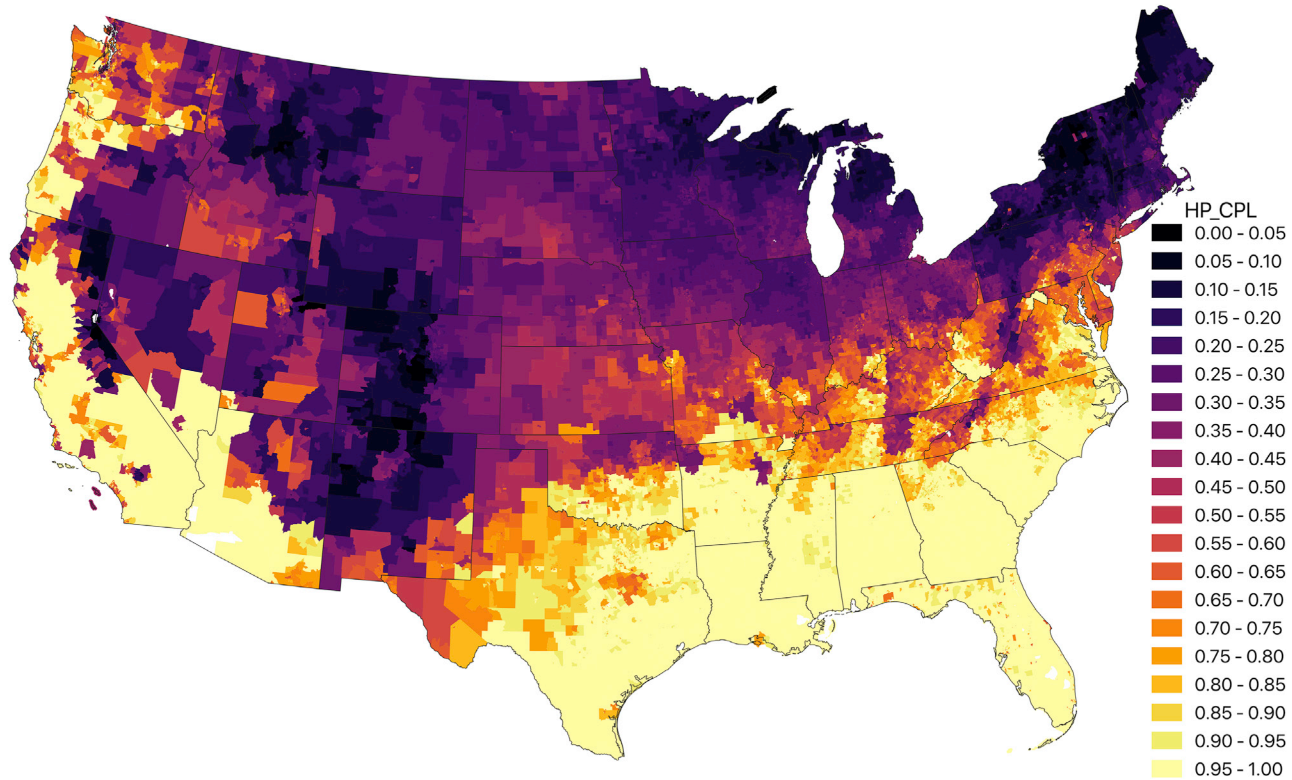

Figure 2. Current Peak-Limited Heating Electrification-Base Heat Pump Model

Computed maximum penetration of high-COP heat pumps without exceeding current peak electricity demands ($HP_{CPL}^{(base)}$). All values are computed at the census tract level for years 2008–2017. Census tracts with white fill have no residential or commercial building square footage in the source data. Figure S15 shows a histogram of census tracts by $HP_{CPL}^{(base)}$.

Heating Electrification within Current Electricity Capacity Limits Is Restricted

Considering that existing energy infrastructure systems are robust, complex, and highly reliable for their scale and complexity, it is prudent to consider potential HP penetration given what is currently in place. We designate this the "current peak-limited" (CPL) scenario and computed the maximum electric heating possible without exceeding the current peak electricity demand in all census tracts, this would represent fully replacing existing heating systems with HPs in a subset of buildings within each census tract. Here we use our "base HP model" described in Experimental Procedures and intended to reflect the current state-of-the-art HP performance. The Supplemental Information presents a sensitivity analysis using median-performance "cold climate HPs," but we are considering that high performance systems would be used in a serious effort to expand heating electrification. The computed peak-limited HP penetrations, $HP_{CPL}^{(base)}$, shown in Figure 2, include conversion of both existing fossil fuel-based heating and existing electric heating to high-COP HPs.

Aggregating across all census tracts, we compute 53% of all U.S. residential and commercial heating energy from electricity. This is achieved by replacing 38% of existing U.S. residential and commercial fossil fuel heating with HPs. There are several factors that contribute to the geographical heterogeneity shown in Figure 2. The largest single driver of heating electrification limitations is low winter temperatures that cause higher heating demands and lower HP COP. The coldest climates also tend to have lower current peak electricity demands because of lower air conditioning penetration. There are, however, areas that have both cold winters and warm or hot summers, for example, areas along the Atlantic coast have higher computed $HP_{CPL}^{(base)}$ than other areas at the same latitude due to relatively high summer temperatures. This is different than the effect in much of California where higher peak-limited heating electrification is possible because of mild climates without extreme minimum or maximum temperatures.

One further differentiating factor is that some cooler areas already have deep penetration of electric heating (see Figure S3). The clearest example is the Pacific Northwest with inexpensive hydroelectric supply. Low-COP or electric resistance heating, can set current peak demands, so conversion to high-COP HPs can make existing electricity delivery capacity available for more fossil fuel heating replacement.

In combination, these factors result in large areas of the U.S. falling short of 50% heating electrification within the current peak constraint, while others can achieve 100% or near to it. There are 24 states in all with less than 50% computed aggregate $HP_{CPL}^{(base)}$. Eighteen of these states are unable to reach even one-third electric heating penetration in the peak-limited scenario. Among these states, computed fossil fuel heating replacement ranges from 2.1% to 24% (state-level computations are summarized in Table S2).

All-Electric Heating with Current Technologies Would Require a Large Buildout of Highly Underutilized Electricity Capacity

Many deep decarbonization studies and state-level policy goals envision replacing fossil fuel heating with electricity (primarily HPs) and achieving 100% renewable electricity supply. Again, using our base HP model, we computed the anticipated peak electricity demand for each census tract if 100% of residential and commercial buildings adopted HPs. The computed ratio of the anticipated new peak in the all-electric scenario to the current peak can be considered a proxy for the increase in electricity delivery capacity to accommodate heating electrification. Computed electricity peak ratios for all U.S. census tracts are shown in Figure 3. Each peak ratio considers conversion of both existing fossil fuel-based heating and electric heating to high-COP HPs.

In general, and as one would expect, the same areas with limited heating electrification potential under the peak-limited constraint (Figure 2) would require a significant buildout of electricity capacity to accommodate heating-driven peak electricity demands. However, the immense scale of potential new electricity capacity is clear in this view: some areas could see new peak electricity loads more than four times their current peaks. We find 33% of census tracts (representing 45% of nationwide heating) to have a computed all-electric peak ratio exceeding 2, with 14% of census tracts (22% of total nationwide heating) exceeding 3. It is important to note that Figure 3 does not clearly show concentration of energy demands. For example, computed peak ratios of 1.25–2.0 for densely populated areas of the East Coast could pose unique challenges due to their higher infrastructure costs.

High census tract all-electric peak ratios suggest potential distribution system capacity expansions whereas aggregate U.S. and state-level increases in peak ratio generally suggest potential investments in some combination of generation and transmission. Figure 4A shows how increases in allowable peak electricity load enable expanded heating electrification across the U.S. Note that the x axis here represents the census tract peak ratio limit; however, not all census tracts see a peak ratio this high before achieving full heating electrification. Figure 4B shows the

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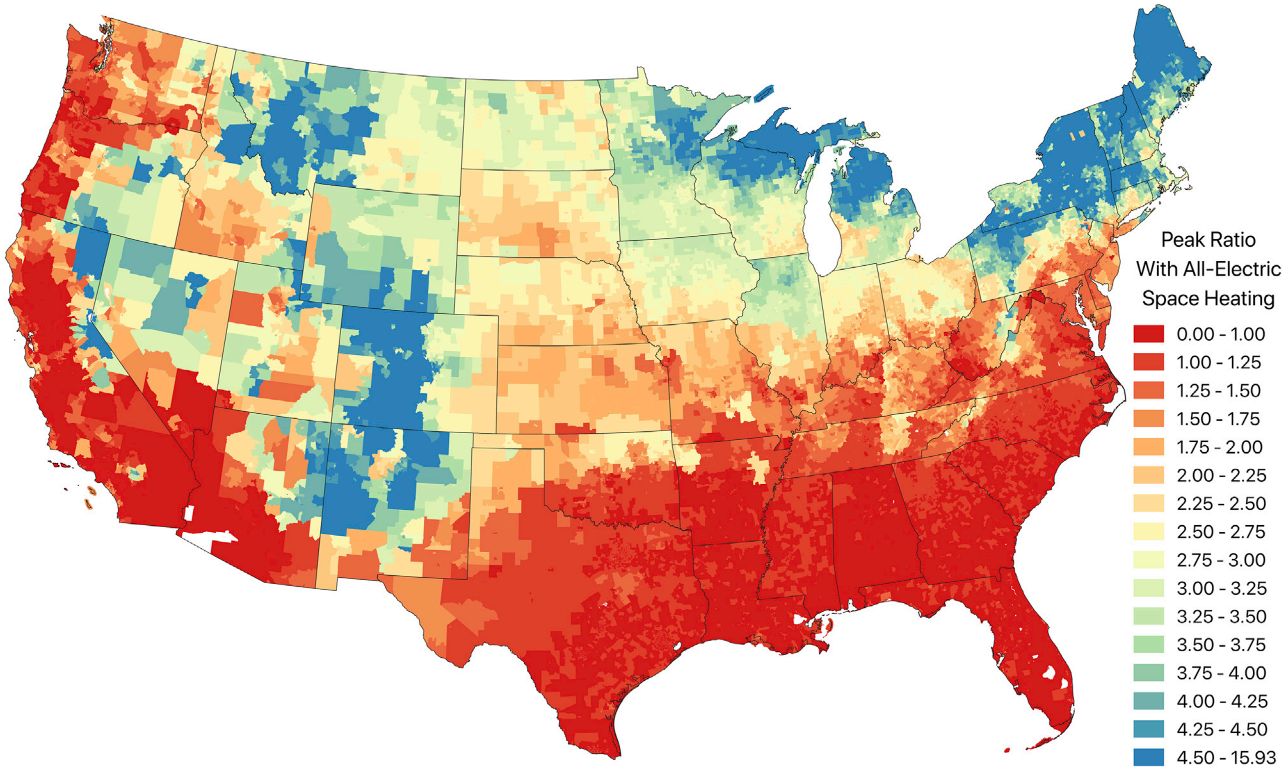

Figure 3. Census Tract Electricity Peak Ratios in an All-Electric Space Heating Scenario-Base Heat Pump Model

Computed ratio of peak electricity demand with 100% heat pumps to current peak electricity demand. All values are computed at the census tract level for years 2008–2017. Census tracts with white fill have no residential or commercial building square footage in the source data. Figure S17 shows a histogram of census tracts by all-electric peak ratio.

increase in U.S. aggregate peak ratio at the designated peak ratio limit. Note also that we continue to discuss the base HP model in this section. The following section relates to the other lines shown in Figure 4.

Allowing unrestricted electricity load growth to achieve full heating electrification in the all-electric scenario, we compute an aggregate electricity peak ratio of 1.70. This corresponds to a 506 GW nationwide increase in noncoincident peak load (i.e., the summation of peak loads in all census tracts, though they do not necessarily occur at the same time). State-level computations show the heterogeneity of electricity capacity expansion, peak ratios exceed 2 in 23 states and exceed 3 in 10 states (see Table S2). Capacity expansions of the scale implied by these results are not necessarily problematic if needed to meet new demands. However, the economics of such an investment are likely to be largely dependent on the infrastructure's capacity utilization. Continuing to use load computations as proxies for understanding capacity needs, we computed various load factors (LFs), which is the ratio of average load to peak load. Aggregate values are shown in Figures 4C and 4D, state-level computations are shown in Table S2, and census tract computations are shown in Figures S16, S18, and S19.

We note that a 506 GW increase in noncoincident load would not necessarily correspond to an equal increase in generation capacity; for example, if perfect aggregation of loads within North American Electric Reliability Corporation (NERC) subregions were possible, we compute the noncoincident peak load increase could

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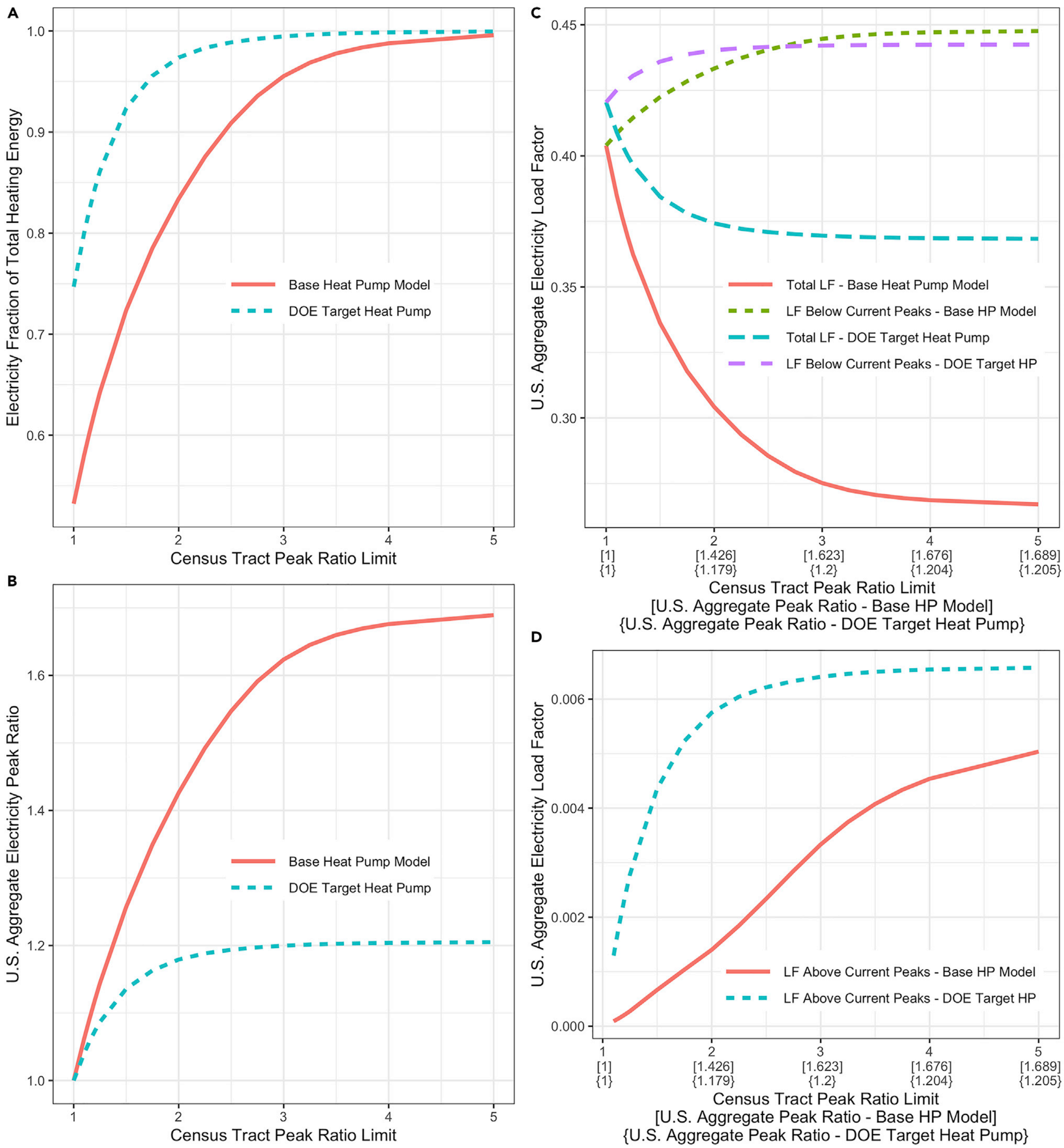


Figure 4. Aggregate Electricity Effects of Pathways to Expanding Heating Electrification

(A) Computed fraction of total heating energy from electricity within each peak ratio limit with an all-electric approach using the Base Heat Pump Model and a model that reflects U.S. Department of Energy heat pump performance targets. Some census tracts achieve full heating electrification without reaching the designated peak ratio limit.

(B) Computed U.S. aggregate peak ratio within each peak ratio limit with an all-electric approach and both heating models.

(C) Aggregate total electricity load factor and aggregate electricity load factor of only the electricity demands below current census tract peak demands in an all-electric approach. The x axis values in brackets reflect aggregate peak ratio values from (B) for both heating models.

(D) Aggregate electricity load factor of only the electricity demands above current census tract peak demands using an all-electric approach and both heating models.

be reduced to 393 GW (see Table S4). However, we have also shown previously that a large intraregional transmission expansion with low capacity utilization is not likely economical[41] and, more broadly, more detailed additional research is needed in this area that is beyond the scope of this paper.

The most consequential result for energy infrastructure is shown in Figure 4D, the computed 0.5% aggregate LF above current electricity peaks is equivalent to fewer than 50 annual full load hours. The result of large load increases with low LFs would be overall electricity LFs less than half the current LFs in many states. This has serious implications for utilities, particularly considering it would occur coincident with a vast renewable energy (RE) supply expansion and other possible infrastructure upgrades. Furthermore, the least efficient generators are likely to be used to meet these "peaky" heating-driven loads, at least while the economics of energy storage continues to progress. Times of both high GHG emissions and high electricity prices are thus possible in the medium term. Over the longer term, it may be prohibitively costly to meet such loads with RE and storage; this must be further studied as decarbonizing the energy system is the primary motivator for heating electrification.

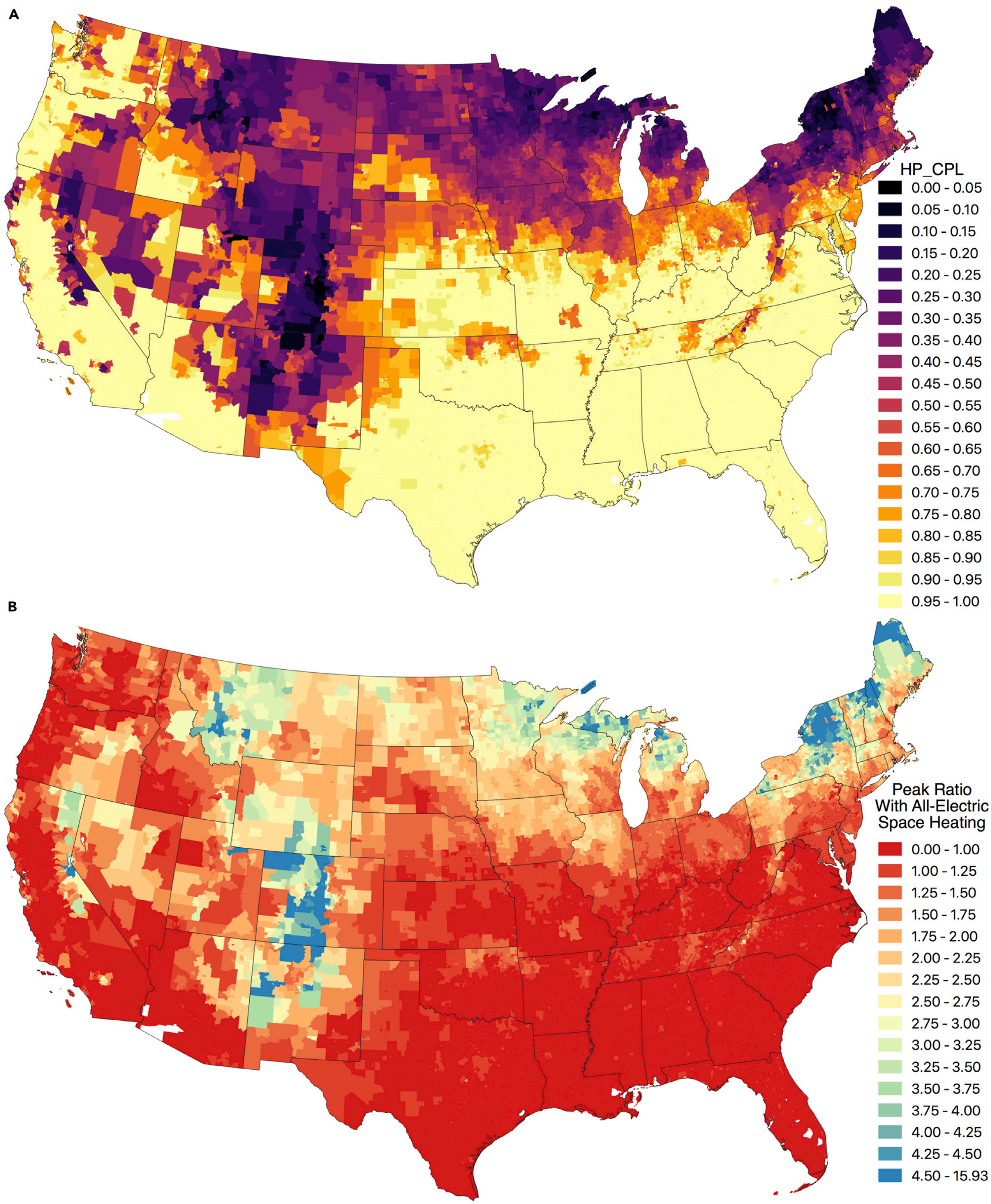
There is a silver lining, as HP penetration grows, the LF below current peaks shown in Figure 4C increases, resulting in higher utilization of existing electricity capacity. This motivates an alternative approach to avoid electric heating during times that would otherwise require new capacity, the dual source system explored in a later section.

Heat Pump Technology Improvements Can Mitigate Load Implications but Challenging Regions Remain

Heating electrification would occur over a period of time during which continued HP performance improvement is expected. The Experimental Procedures section describes an electric heating model based on U.S. Department of Energy HP performance targets (a sensitivity analysis presented in the Supplemental Information also includes potential effects of reduced heating loads due to climate change; however, Figures S37 and S38 show HP COP has a much more significant impact on our analysis, so we explore the climate effects only in the Supplemental Information). Figure 4 clearly shows that, in aggregate, achieving DOE HP performance targets has the potential to significantly increase the penetration of electric heating within current peak loads and to reduce the scale of peak load increases to accommodate full heating electrification. We compute 75% of all heating energy can be provided by electricity without exceeding current electricity peaks (compared to 53% with currently available HPs). This is achieved by replacing 66% of existing fossil fuel heating energy (38% with currently available HPs).

Despite the improved outlook in aggregation, Figure 5 shows significant regional heterogeneity remaining with the same challenging regions (Northeast, Upper Midwest, and Rocky Mountains) even while a much larger part of the country can fully electrify within current peak loads (or with modest increases). We compute that 48% of census tracts can achieve full heating electrification within current peak loads, and 56% of census tracts could be fully covered with local peak load increases of 10% or less. At the same time, when aggregated across full states, 17 states in the identified challenging regions would require peak load increases of more than 50% to achieve full heating electrification even with future advanced technologies (see Table S3 for full state-level computations).

It should be stressed that this represents a possible future scenario, dependent on full adoption of HPs with energy efficiency performance that are goals at the


A
HP_CPL
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0.05 - 0.10
0.10 - 0.15
0.15 - 0.20
0.20 - 0.25
0.25 - 0.30
0.30 - 0.35
0.35 - 0.40
0.40 - 0.45
0.45 - 0.50
0.50 - 0.55
0.55 - 0.60
0.60 - 0.65
0.65 - 0.70
0.70 - 0.75
0.75 - 0.80
0.80 - 0.85
0.85 - 0.90
0.90 - 0.95
0.95 - 1.00
B
Peak Ratio With All-Electric Space Heating
0.00 - 1.00
1.00 - 1.25
1.25 - 1.50
1.50 - 1.75
1.75 - 2.00
2.00 - 2.25
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Figure 5. Census Tract-Level Computations for Heating Model Reflecting Heat Pump Performance Advances

(A) Current Peak-Limited heat pump penetration, $HP_{CPL}^{(DOE)}$.

(B) Electricity peak ratios in an all-electric space heating scenario. All values are computed using a U.S. DOE heat pump performance target heating model at the census tract level for years 2008–2017. Census tracts with white fill have no residential or commercial building square footage in the source data. Figure S26 shows a histogram of census tracts by $HP_{CPL}^{(DOE)}$. Figure S28 shows a histogram of census tracts by all-electric peak ratio.

moment, thus motivating a pathway to such a future that significantly reduces fossil fuel usage with current technology. That said, previous DOE technology initiatives have proven successful, so optimism is warranted for improved HP performance with a dedicated focus and the shifts in market forces that would accompany deep heating electrification. These results further support pathways to heating electrification that do not rely on massive electricity delivery infrastructure to accommodate current HP technology.

The potential easing of electrification challenges from technology improvements does not address two remaining core issues: (1) some regions remain unable to approach full heating electrification without large-capacity upgrades, and (2) electricity load increases that would accompany full electrification would have very low LFs. Because the coldest temperatures are infrequent, the heating energy that would necessitate significant capacity upgrades for full electrification is a small portion of total heating energy. This is implicit in the low computed electricity LF above current peak loads discussed earlier and shown in Figure 4D.

Limited Fossil Fuel Usage Can Enable Deeper Heating Electrification

One alternative to decarbonize space heating while managing the implications of 100% heating electrification is to maintain some existing buildings' fossil fuel-based heating in a DSS with new HPs. We now consider three options for existing residential and commercial building space heating systems: (1) remain in place and provide all heating, (2) be fully replaced by HPs, or (3) remain in place as part of a DSS with HPs, but only operate to avoid electricity peaks in excess of current peaks. We therefore maintain the earlier constraint of limiting census tract peak electricity loads to current peak loads. We then computed the maximum reduction in fossil fuel heating without exceeding current census tract peak loads. Figure 6 compares the computed fraction of census tract heating from fossil fuels for HP-only scenarios (Figure 5B shows the base HP model and Figure 5D shows the DOE, target HP model) and DSS scenarios (Figures 5C and 5E) to existing fossil fuel usage for heating (Figure 5A).

In most of the country, fossil fuel-based heating can be reduced to less than 5% of all heating using current state-of-the-art HP technology. In aggregate, we compute that 2.3% of all heating is provided by fossil fuels in the maximum DSS scenario,in comparison to 43% of all space heating from fossil fuels in the peak-limited scenario and 70% of all current space heating. While there remain some challenging geographical areas, the analysis indicates that all states could see very significant increases in heating electrification with DSSs (see Tables S2 and S3). A particularly striking finding is that, in nearly all states, the widespread use of DSSs could result in space heating fossil fuel usage less than 10% of the peak-limited HP-only approach. Moreover, the widespread use of DSSs would actually increase the U.S. aggregate electricity LF. The effects are even more striking at the state level: electricity LF increases of 10%–20% were computed in colder states, compared to the 25%–40% decreases in the all-electric scenario (see Tables S1 and S2 for specific computed values).

Computed remaining fossil fuel heating energy with DSSs are not dramatically different for currently available HPs and potential future advanced HP technology,

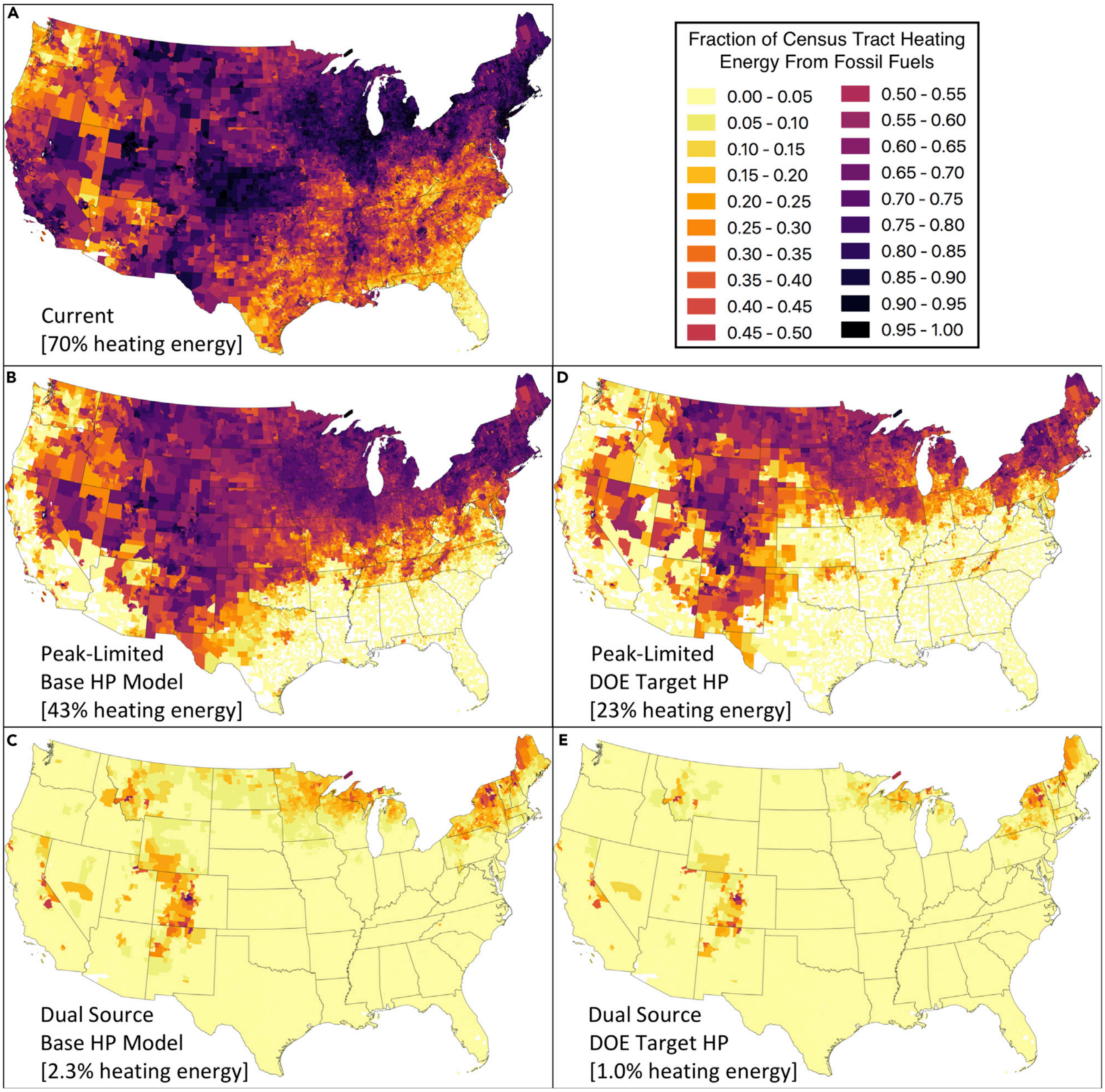

Figure 6. Fraction of Census Tract Heating from Fossil Fuels

(A) Current fossil fuel heating.

(B) Base Heat Pump Model without exceeding current census tract peak electricity demand.

(C) Base Heat Pump Model HPs in all buildings, with dual source heating systems where needed to prevent each census tract peak electricity demand from exceeding its current peak electricity demand. (D) DOE Target Heat Pump Model without exceeding current census tract peak electricity demand. (E) DOE Target Heat Pump Model HPs in all buildings, with dual source heating systems where needed to prevent each census tract peak electricity demand from exceeding its current peak electricity demand. Figures S10, S20, S21, S31, and S32 show corresponding histograms.

but significantly less retained fossil fuel heating capacity would be needed with the latter, as shown in Figure 7 andthis is useful in identifying a path forward. With current HP technology, the minimum computed fossil fuel usage requires maintaining 59% of current fossil fuel heating capacity in DSSs with new HPs; 38% of total heating capacity would be from DSSs and the remaining 62% could already be all-electric

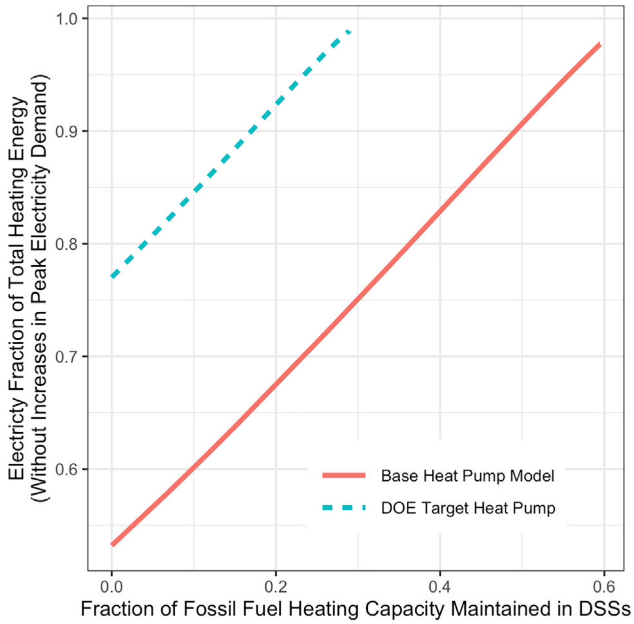

Figure 7. Aggregate DSS Capacity Effects on Heating Electrification

Fraction of total heating energy from electricity by maintaining a given fraction of fossil fuel heating capacity in dual source systems with new heat pumps. Computations use the Base Heat Pump Model and a model that reflects U.S. Department of Energy heat pump performance targets.

(i.e., HPs only) without exceeding current peak electricity demands (recalling this involves replacing both existing fossil fuel heating capacity and much of existing electric heating capacity). If DOE performance targets are met and such HPs are eventually widely deployed, the fossil fuel heating capacity in DSSs could be reduced to a computed 32% of current capacity, 20% of total heating capacity would then be in DSSs, and the remaining 80% of capacity could be all-electric within the peak load constraint. At this point, we compute that fossil fuels would only be required for 1% of heating energy.

It should be noted that while our analysis indicates that widespread use of DSSs can improve electricity LFs, it would also significantly reduce fossil fuel LFs. Regardless of the pathway to transition away from the current reliance on fossil fuels for heating, fossil fuel infrastructure will require continued maintenance to ensure safe and reliable operation. Our results imply limited use of such systems for buildings that rely primarily on electricity for heating is beneficial while future use of renewable produced fuels or full abandonment of current infrastructure are considered. Future research is necessary to determine if there is some utilization level below, which operational costs become prohibitive, particularly if utility cost recovery structures do not evolve (i.e., away from being primarily based on energy sales). This will be necessary understanding for many decarbonization planning decisions and not only those discussed in this paper.

Conclusions

While the challenge of decarbonizing building heating has been acknowledged, the underlying drivers of critical infrastructure considerations have not previously been analyzed across a wide range of climates and legacy systems. In this paper, we provide key insights into the challenges of an all-electric system rapidly replacing existing fossil fuel heating systems and a possible alternative pathway that could avoid significant infrastructure implications, while providing more flexibility to adapt to future technological developments. To do so, we developed a series of models that represent the first known attempt to quantify existing and potential future temperature-dependent building electricity demands at high spatial resolution across the United States.

The existing nationwide heating-driven fossil fuel delivery capacity, which provides 70% of all space heating energy, is computed to be 91% greater than the existing (largely) cooling-driven electricity delivery capacity. The result of replacing all fossil fuel-based heating with currently available HPs would result in an estimated 70%—equivalent to approximately 500 GW—increase in nationwide noncoincident peak load; 23 states see computed aggregate peak loads more than double. State-level LFs for only those loads above current peaks range from less than 0.1% to 1.7%, implying infrequent use of new large-capacity electricity infrastructure.

We modeled three options to avoid such issues: (1) a "current peak-limited" scenario computing the maximum HP penetration without exceeding each census tract's current peak electricity demand, (2) the peak-limited scenario with future technology that meets U.S. Department of Energy HP performance targets, and (3) maintaining some amount of existing fossil fuel-based heating with new HPs in DSSs. For the peak-limited scenario, we compute a maximum possible HP penetration of 54%, reducing the total amount of space heating energy from fossil fuels to 43%. This relies on current state-of-the-art heat pumps with lesser effect if more typical HPs are used. National figures elide significant geographic heterogeneity: fossil fuels would continue to provide more than 60% of space heating in 19 states primarily in the Northeast, Upper Midwest, and Rocky Mountains. Eventual achievement and widespread deployment of the advanced HPs targeted could increase peak-limited HP penetration to 75%, reducing fossil fuel space heating energy to 23%; heating in nearly half of census tracts could become all-electric with such technology improvements.

Strategic use of existing fossil fuel heating capacity in DSSs can be a potentially powerful pathway to deep heating electrification in much of the country, and underly a possible future hybrid approach in the coldest regions. We compute that the amount of heating provided by fossil fuels could be reduced to less than 3% with current HP technologies and no new electricity infrastructure capacity. With future advances in low-temperature HP efficiency, fossil fuel usage is reduced to a computed 1% of all heating energy with approximately half the total DSS capacity needed with current technology.

Taking all of our results together, we can classify three general modes of U.S. fossil fuel heating replacement without increasing peak loads: (1) approximately 1/3 of current fossil fuel heating capacity (primarily in warmer climates) can be fully replaced with a mix of currently available HPs, (2) an additional 1/3 of fossil fuel heating capacity (in moderate climates) could eventually be fully replaced with significant advances in low-temperature HP performance; fossil fuel usage could be dramatically reduced during this transition by using currently available HPs in DSSs, and (3) the remaining 1/3 of fossil fuel heating capacity (in cold climates) would be very challenging to replace even with advanced HP technology, but by retaining fossil fuel heating capacity as a "backup" in DSSs, the vast majority of fossil fuel usage for space heating could be eliminated. There are also potential benefits to a flexible pathway to decarbonizing this last 1/3 of fossil fuel-based heating in case of future breakthroughs, such as unanticipated major advances in HP technology or emergence of economical alternative fuels.

The most significant general finding of this study is that leveraging existing fossil fuel infrastructure during a transition to a low-carbon energy system can facilitate increased penetration of electric heating, while HP energy and thermal comfort performance improves and new technologies emerge. This suggests an ongoing role for current fossil fuel infrastructure but not necessarily fossil fuels. Even if the cost of renewable produced fuels may presently appear prohibitive as a primary fuel, their limited use may be attractive in a holistic GHG emissions reduction effort. That said, these findings should be balanced against considerations of whether allowing some residual role for fossil fuel systems may incentivize the continued use of fossil fuels—absent other mechanisms to eliminate their usage—especially where there are national, state, or local policies, intending to displace them as soon as possible.

We have also not analyzed potential gains from technologies outside the scope of this study, such as significant building efficiency improvements, energy storage, or ground-source heat pumps (GSHPs). We do not suggest that these approaches might not be important. There are also regional and local implications for electricity, gas and liquid fuel distribution, and supply chains, that warrant additional analysis to inform planning strategies. Future research will include, region-specific analyses, alternative heating technologies where possible, assessment of a gas infrastructure transition, and development of optimal and grid-responsive DSS control algorithms. The methods developed here, can also support future decarbonization studies by other researchers, system operators, and energy planners.

EXPERIMENTAL PROCEDURES

This study uses an approach that synthesizes several publicly available data sets to develop new models for temperature-dependent residential and commercial building electricity and fuel usage to estimate current electricity peak demands and project future peak demands and load profiles under different heating electrification pathways at the census tract level for the contiguous United States. This section provides sufficient details to reproduce our model and calculations; the Supplemental Experimental Procedures (SEP) includes corresponding subsections with additional detail on computations underlying the results presented above and in the Supplemental Information as well as justification for model assumptions. Building energy demands depend on numerous factors, including diurnal patterns in non-space-heating (e.g., domestic hot water and cooking) and (numerous) non-cooling electricity end uses, occupant behavior and thermostat settings, and internal heat gains. Here, we focus on (1) the dependence of fossil fuel and electricity usage on outdoor air temperature as it decreases with the assumption that such energy usage is dominated by heating and (2) the dependence of electricity usage on outdoor air temperature as it increases with the assumption that such energy usage is dominated by cooling.

Census Tract Temperature Time Series

The underlying model for temperature-dependent energy demands, used data for 2010 the most recent year for which all needed data are available. To capture year-to-year variations, weather data[42] for years 2008–2017 were used for analyses of the three heating electrification scenarios; the SEP describes our procedure for filling data gaps.

Building Stock Characterization

Building floor area, $A_{c,i}$, for each building class (residential and commercial), c, and census tract, i, was determined using the U.S. Federal Emergency Management Agency (FEMA) Hazus General Building Stock (GBS) database.[43] While most of Hazus's occupancy classes track closely to building classes, the authors classified assigned building classes to some smaller occupancy classes as described in the SEP. Estimates of the number of households using heating fuels that aligned with energy usage data described below, were based on the U.S. Census 2010 American Community Survey data[44]: electricity (Figure S3); "utility gas" was assumed to be natural gas (Figure S4); "fuel oil, kerosene, etc." was assumed to be all fuel oils and kerosene (Figure S5); "bottled, tank, or LP gas" was assumed to be propane (Figure S6); and "coal or coke," and "other fuel" were all grouped as "other fuels" (Figure S7). It was assumed that the fraction of residential, $p_{FF,current,res,i}$, and commercial, $p_{FF,current,com,i}$, floor area using fossil fuels was equivalent to the fraction of households in each census tract using fossil fuels (Figures S8 and S9, respectively). The same approach was used for the fraction of residential, $p_{elec,current,res,i}$, and commercial, $p_{elec,current,com,i}$, floor area using electricity for heating.

Current Temperature-Dependent Electricity Usage Model

The model estimate for temperature-dependent electricity usage, $\widehat{E}_{c,i,t}$, for each building class and census tract at each time step, t, is defined by the temperature-independent electricity usage per unit floor area, $e_{c,s}^{const}$, for each building class for each state, s. The increasing-temperature-dependent electricity usage per unit floor area for each building class for each state, $e_{c,s}^{+}$; the fraction of building class floor area with air conditioning in each census tract, $p_{AC,c,i}$; the decreasing-temperature-dependent electricity usage per unit floor area for each building class for each state, $e_{c,s}^{-}$; $p_{elec,current,c,i}$; the reference temperature for each building class, $T_{ref,c}$; and the temperature for each census tract at each time step, $T_{i,t}$:

$$\widehat{E}_{c,i,t} = A_{c,i}\left[e_{c,s}^{const} + p_{AC,c,i}e_{c,s}^{+}(T_{i,t} - T_{ref,c})^{+} + p_{elec,current,c,i}e_{c,s}^{-}(T_{ref,c} - T_{i,t})^{+}\right]$$

$T_{ref,res}$ is assumed to be 18.3°C based on common practice[45] and $T_{ref,com}$ is assumed to be 16.7°C based on a recent study.[46] $e_{c,s}^{+}$ and $e_{c,s}^{-}$, are selected for each state and building class to minimize the residual sum of squares with respect to the actual 2010 state monthly electricity usage for each building class.[47]

Current Temperature-Dependent Fossil Fuel Usage Model

In addition to previously defined variables, the model estimate for temperature-dependent fossil fuel usage for each building class, census tract, and time step, $\widehat{F}_{c,i,t}$, is defined by the temperature-independent fuel usage per unit floor area, $f_{c,s}^{const}$, for each building class and state. The decreasing-temperature-dependent fuel usage per unit floor area for each building class and state, $f_{c,s}^{-}$:

$$\widehat{F}_{res,i,t} = A_{res,i}p_{FF,current,res,i}\left[f_{res,s}^{const} + f_{res,s}^{-}(T_{ref,res} - T_{i,t})^{+}\right]$$

$$\widehat{F}_{com,i,t} = A_{com,i}p_{FF,current,com,i}\left[f_{com,s}^{const} + f_{com,s}^{+}\left(T_{i,t} - T_{ref,com,s}^{+}\right)^{+} + f_{com,s}^{-}(T_{ref,com} - T_{i,t})^{+}\right]$$

A term to capture some increasing-temperature dependence observed for commercial buildings was included with the increasing-temperature-dependent electricity usage per unit floor area for each state, $f_{c,s}^{+}$, and the increasing-temperature-dependent commercial building reference temperature, $T_{ref,com,s}^{+}$, included as decision variables. $f_{c,s}^{-}$, $f_{com,s}^{+}$ and $T_{ref,com,s}^{+}$ are selected for each state and building class to minimize the residual sum of squares with respect to each state and building class's 2010 monthly fossil fuel usage. Because fuel oil and propane are delivered in bulk and stored on site, while natural gas usage is based on actual monthly values, annual fuel oil and kerosene usage[48] and annual propane usage[49] were used and assumed to scale with monthly natural gas usage.[50,51]

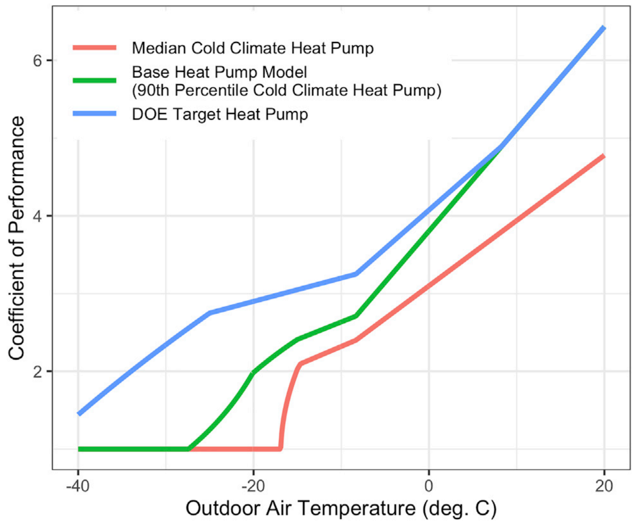

Figure 8. Heat Pump Model Temperature-Dependent Coefficient of Performance

Heating Electrification Models

The electricity demand for HPs for each building class in each census tract at each time step, $E^{(HP)}_{c,i,t}$, for a given HP penetration, $p_{HP,c,i} = \{0:1\}$, is given by:

$$E^{(HP)}_{c,i,t}\left(p_{HP,c,i}\right) = p_{HP,c,i}A_{c,i}\frac{\left[f^{-}_{c,s}\left(T_{ref,c} - T_{i,t}\right)^{+}\right]\eta_{FF}}{COP_{HP}(T_{i,t})}$$

Where $\eta_{FF} = 0.78$ is the assumed fossil fuel heating efficiency,[52] and $COP_{HP}(T)$ is the HP's COP. Three HP model COPs were developed based on the median performance of "cold climate" HPs in a regularly updated database, with more than 1000 available heat pumps[53] the 90th percentile performance of HPs in the same database (designated the "Base Heat Pump Model" for this study), and the midpoint between residential and commercial electric HP performance targets set by the U.S. Department of Energy[54] (designated the "DOE Target Heat Pump Model" for this study). The Supplemental Experimental Procedures details the assumptions and procedures used to develop the HP models, Figure 8 shows the resulting COPs.

DATA AND CODE AVAILABILITY

Various data reported in this paper are available at https://doi.org/10.7916/d8-4g8y-mv98. This dataset provides (1) the source data accessed, organized, and cleaned by the authors; (2) computed results used to develop this paper's figures; and (3) an R script that can be used to produce census tract electricity and fossil fuel time series for the various scenarios discussed in this paper.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.joule.2019.11.011.

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AUTHOR CONTRIBUTIONS

M.W. conceived the study, developed all analytical methods, gathered and processed source data, implemented the methodology, analyzed the results, and developed figures. V.M. provided expertise and feedback. M.W. was the primary author of the manuscript, which was reviewed and edited with V.M.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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