Existing and Projected Infrastructure Capacities Motivate Alternatives to "All-Electric" Heating Decarbonization

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SUMMARY

We investigate implications of building space heating decarbonization pathways across the climate-diverse United States. We provide key insights that challenge the emerging consensus around an "All-Electric" approach, estimating this would require a 70% minimum increase in nationwide electricity system capacity. New capacity additions would be highly heterogeneous (e.g. fourfold increases in some states) and highly underutilized (66 equivalent full load hours annually). Fossil fuel system replacement by electric heat pumps without increasing peak loads can only reduce fossil fuels to 43% of heating energy supply (currently 70%). We show that by retaining a subset of existing fossil fuel equipment for use during the coldest weather in dual source systems that also include heat pumps, the additional heating electrification possible without exceeding current peak loads can reduce fossil fuels to 3.2% of heating energy supply. Therefore, strategic use of legacy infrastructure could facilitate a more flexible, cost-effective transition to low-carbon heating.

INTRODUCTION

Reducing greenhouse gas (GHG) emissions associated with heating buildings is an essential element of a larger energy transition. The primary – and in many cases *only* – approach being considered is "All-Electric": Converting all existing fossil fuel-based heating systems that currently prevail[1] to high efficiency electric heat pumps (HPs) and expanding renewable electricity supply[2–5]. 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[6] highlights a particular issue in the current research and policy consensus: Widespread heating electrification has significant implications for distribution systems that are largely absent from the many deep decarbonization studies conducted to date[7].

Even where nearly comprehensive studies have included some distribution system considerations, they have assumed no future changes to electricity delivery pricing[8] or that such costs will scale with generation and transmission[9]. Detailed generation and transmission models are standard for such studies[10], which allow researchers to capture the benefits of smoothing intermittent renewable output over large distances[11]. However, no such effect is available at the local scale where the All-Electric approach is likely to only increase capacity requirements[12] and delivery already constitutes 25-50% of electricity costs[13]. Understanding the load implications of heating electrification is thus essential to future system planning and operation[14].

Evaluating the roles of different generation resources is critical as intermittent renewable energy supply (i.e. from wind and solar) increases[15], 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. Whereas air-conditioning drives current peak electricity demands in much of the developed world[16] and while

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future electricity demand profiles are difficult to project[17], two primary factors can drive higher heating-induced peak electricity demands. First, winter indoor-outdoor temperature differentials are generally higher than in the summer: Averaged over the continental United States, peak winter temperature differentials are approximately twice those of the summer[18]. Second, HP coefficient of performance (COP) – the amount of heat delivered per unit electricity consumed – reduces as temperature decreases: Even the most advanced cold climate HP prototypes operate with low-temperature COP less than half the COP at rated conditions[19]; despite this, heating electrification studies typically use an average COP[10,20]. Although cooling energy growth is an emerging challenge in the developing world[21], properly assessing heating effects is essential where massive, complex and robust infrastructure systems already exist.

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[22], existing heating equipment[23], fuel availability[24], and renewable energy resource potential[25]; and (2) a transition largely dependent on converting existing systems, with over 75% of existing commercial building area[26] and over 80% of existing housing units[13] estimated to remain in 2050, while total building energy demands are expected to be stable[13].

Different pathways to decarbonizing heating will require different energy infrastructure changes[27], but current understanding of the implications for such strategies is limited due to incomplete or unavailable information on existing energy systems[28] and high spatial variability of the underlying drivers of heating demands. Heating fuels[29], climate[21] and building stock[30–32] can all be highly diverse across a region. While electricity grid data is 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[33] despite being essential to projecting future electricity demands.

For the study described in this paper, a methodology was developed to obtain high fidelity census tract-level estimates of current and potential temperature-dependent residential and commercial building energy demands using several disparate public datasets. This represents the first known attempt to quantify the relative capacities of fossil fuel 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 potentially low utilization of new capacity, we also estimate the HP penetration possible with current electricity delivery capacity. While there are several potential alternatives to All-Electric approaches[34], here we investigate the use of dual source systems (DSSs) that maintain existing fossil fuel heating equipment in addition to new HPs[35]. While a future low-emission energy system may include some amount of residual fossil fuel usage[36], this paper analyzes its role in facilitating widespread heating electrification and anticipates that economical use of existing infrastructure is likely to provide the most flexibility for a range of future innovations to eliminate GHG emissions from heating.

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We compute that an All-Electric heating approach would result in a minimum 70% aggregate increase in electricity delivery capacity; nearly one-third of the U.S. would need to double electricity capacity. This represents a highly expensive proposition with new capacity used for fewer than 100 annual equivalent full load hours. If one aims to replace existing fossil fuel systems with HPs and does not want to exceed the current peak electricity demands, the computed heating energy provided by fossil fuels reduces to only 43% (70% currently). 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, 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. Therefore, this approach would avoid a very large increase in highly underutilized electricity capacity for an All-Electric approach that would replace only the last 3% of fossil fuel-based heating.

A central broader conclusion of this study is thus that a transition to a low-carbon future could be most effectively achieved by leveraging the distinct advantages of existing fossil fuel systems to achieve future GHG goals. A dedicated All-Electric pathway could also preclude future viable alternatives; for example, hydrogen produced from renewable energy is already emerging as a potential cost-effective alternative fuel[37] and issues with blending it into existing natural gas pipelines have been identified and evaluated[38]. While analyzing this and other approaches is beyond our scope, we provide key counterintuitive 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

It is important to first establish the effects of much larger potential heating demands than cooling demands and to understand the implications of current system topography for an energy transition. The temperature-dependent fossil fuel and electricity demand models described in the Experimental Procedures underly the computations described throughout the Results section. An example showing these models applied to a typical residential building is shown in Figure S1.

We first 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 between the two systems; census tract-level computations are shown in Figure 1. Census tract land area varies considerably due to population densities; as this is not necessarily

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clear in Figure 1, a histogram of census tracts by current fossil fuel to electricity peak ratio is shown in Figure S2.

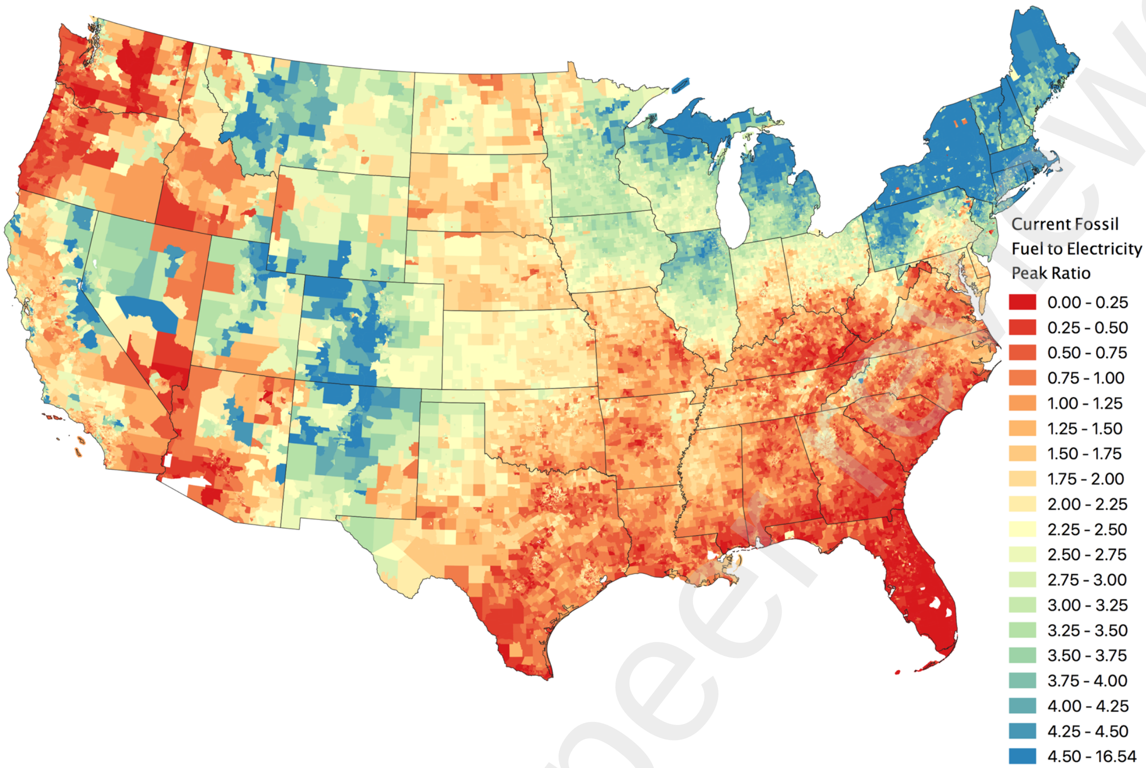

Figure 1 I Census Tract-Level Ratios of Current Peak Fossil Fuel Demand to Current Peak Electricity Demand. All values are computed at the census tract level for years 2008-2017. Census tracts with white fill have no residential or commercial building square footage in the source data. Figure S2 shows a histogram of census tracts by current fossil fuel to electricity peak ratio.

In aggregate, fossil fuel delivery capacity is computed to be 91% greater than electricity delivery capacity; however, the scale of this ratio is highly geographically heterogeneous. Much of the Northeast, the Upper Midwest and the Rocky Mountains have more than four times greater fossil fuel delivery capacity than electricity capacity. This implies the possibility of abandoning large infrastructure systems in an All-Electric approach without considering how such infrastructure might support an energy transition.

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, we must consider what is most likely to achieve the goals of reduced fossil fuel usage in practice given what is currently in place. As such, let us first consider the potential for an All-Electric approach within existing system constraints before evaluating two broad strategies to further expand electrification in the following subsections. We designate this the “Current Peak-Limited” (CPL) scenario and computed the maximum electric heating possible without exceeding the current peak

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electricity demand in all census tracts; this would represent fully replacing existing fossil fuel-based heating systems with HPs in a subset of buildings within each census tract. The computed CPL heat pump penetrations, HP_{CPL}, shown in Figure 2 represent maximum values because they can include both conversion of existing fossil fuel-based heating and existing electric heating to high-COP HPs.

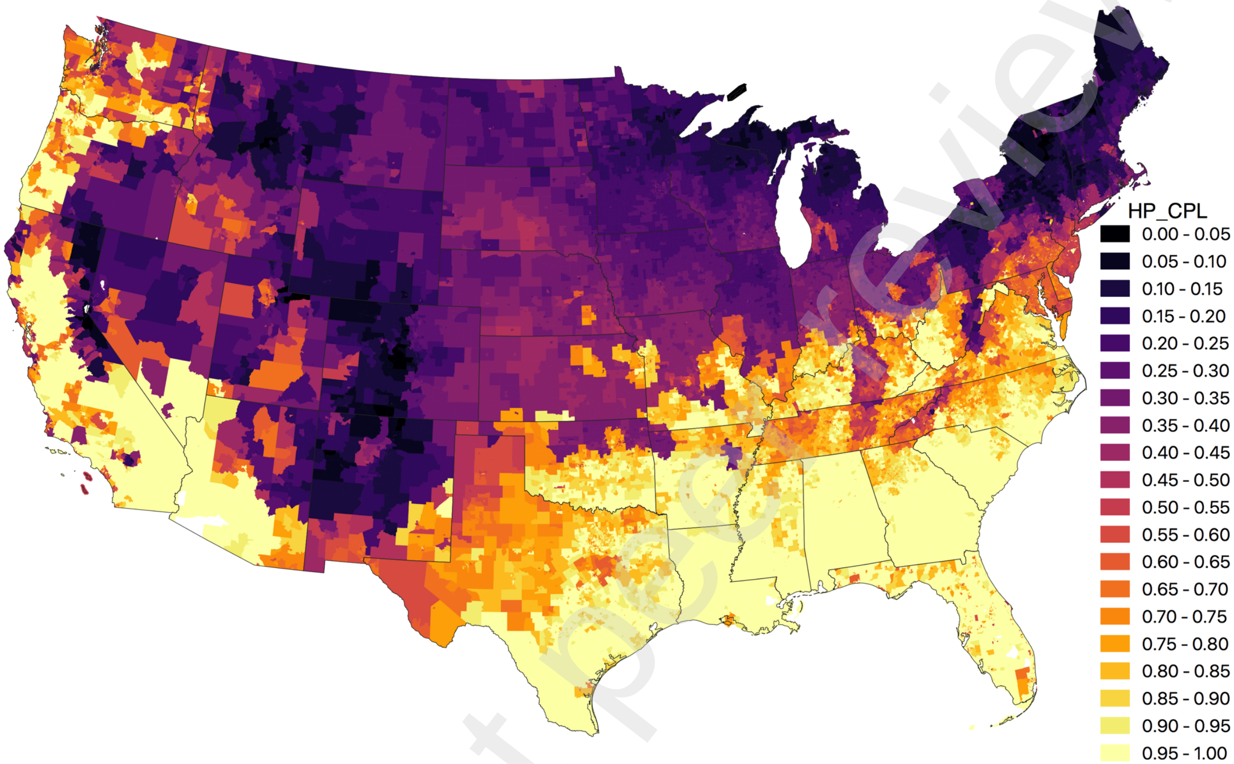

Figure 2 I Current Peak-Limited Heating Electrification. Computed maximum penetration of high-COP heat pumps without exceeding current peak electricity demands (HP_{CPL}). All values are computed at the census tract level for years 2008-2017. Census tracts with white fill have no residential or commercial building square footage in the source data. Figure S4 shows a histogram of census tracts by HP_{CPL}.

Aggregating across all census tracts, we compute that a maximum 54% of all U.S. residential and commercial heating can be met by electricity; this is achieved by replacing 39% of all U.S. residential and commercial fossil fuel heating with HPs. There are several factors that contribute to the geographical heterogeneity. 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} than other areas at the same latitude due to relatively high summer temperatures. This is different than the effect in California where higher CPL heating electrification is possible because of mild climates without extreme minimum or maximum temperatures.

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One further differentiating factor is that some cooler areas already have deep penetration of electric heating (see Figure S17). 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 current 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 CPL constraint while others can achieve 100% or near to it. There are 24 states in all with less than 50% computed aggregate HP_{CPL}. Relevant computations for these states are summarized in Table S1. 16 of these states are unable to reach even one-third electric heating penetration in the CPL scenario; among these states, the computed fossil fuel heating replacement ranged from 6.3% to 26%.

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

Many decarbonization studies and state-level policy goals envision an All-Electric (AE) heating approach (i.e. replacing all fossil fuel heating with HPs) that would require some buildout of electricity infrastructure capacity in most of the U.S. For each census tract, we computed the anticipated peak electricity demand if 100% of residential and commercial buildings adopted high-COP HPs. The computed ratio of the anticipated new peak in the AE 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; refer to Figure S1 for the effect of heating electrification on electricity peak at a single-family residential building level. Each peak ratio represents a minimum because it includes conversion of both existing fossil fuel-based heating and existing electric heating to high-COP HPs.

In general, and as one would expect, the same areas with limited heating electrification potential under computed current capacity constraints (Figure 2) would require a significant buildout of electricity capacity to accommodate the heating-driven peak electricity demand increases shown in Figure 3. However, the immense scale of the infrastructure challenge is clear in this view: Some areas could see new peak electricity demands more than 3 or 4 times their current peaks, implying a vast expansion of electricity capacity. We find that 32% of census tracts were computed to have an AE peak ratio exceeding 2 (representing 44% of nationwide heating), with 15% of census tracts exceeding 3 (22% of total nationwide heating). It is important to note that Figure 3 does not clearly show concentration of energy demands. For example, computed Peak Ratios on the order of 1.25-2.0 for densely populated areas of the East Coast could pose unique challenges due to their higher infrastructure costs.

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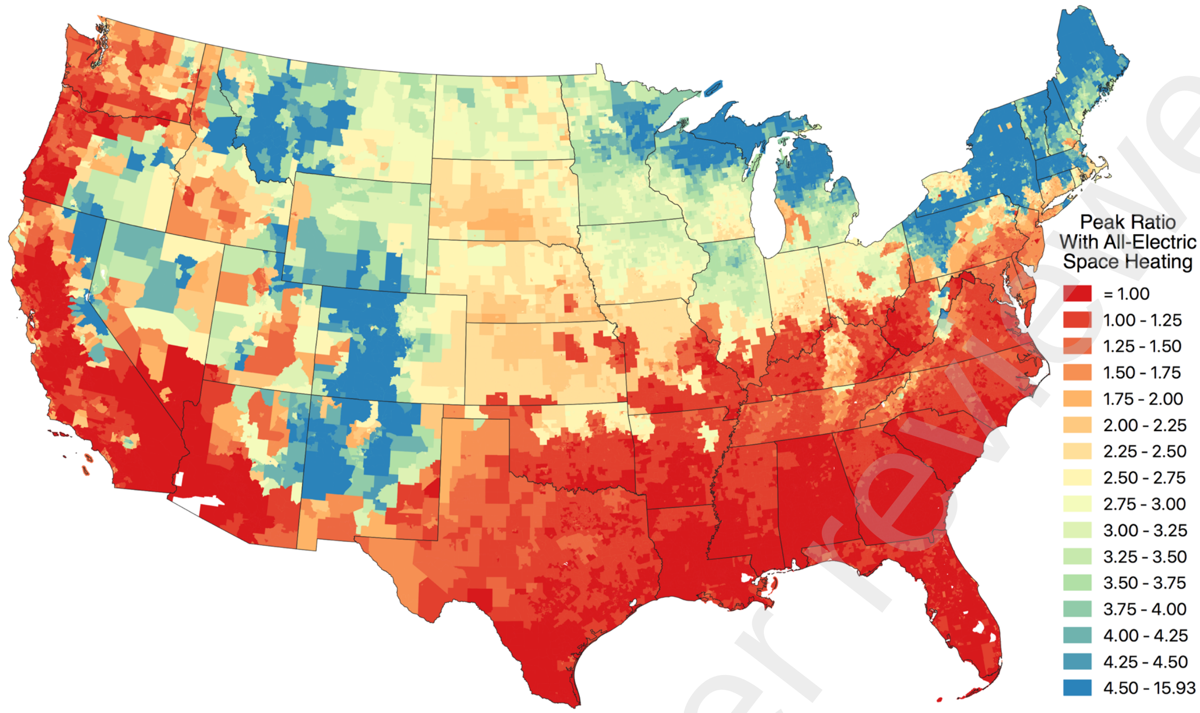

Figure 3 | Census Tract Electricity Peak Ratios in an All-Electric Space Heating Scenario. Computed ratio of peak electricity demand with 100% heat pumps to current peak electricity demand. All values are computed at the census tract level for years 2008-2017. Census tracts with white fill have no residential or commercial building square footage in the source data. Figure S6 shows a histogram of census tracts by All-Electric peak ratio.

High census tract AE peak ratios suggest potential distribution system capacity expansions whereas aggregate U.S. and state-level increases in peak ratio generally suggest potential investments in generation (and perhaps transmission). Figure 4(a) shows how incremental 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* because not all census tracts see a peak ratio this high before achieving full heating electrification; the dashed line shows the increase in U.S. aggregate peak ratio at the designated peak ratio limit.

Allowing unrestricted electricity load growth to achieve full heating electrification in the AE scenario, we compute an aggregate AE peak ratio of 1.70. State-level computations in Table S1 show the heterogeneity of electricity capacity expansion: AE peak ratios exceed 2 in 21 states and exceed 3 in 10 states; the corresponding capacity upgrades would be without precedent. That said, 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 and the effect on customer prices is largely dependent on the infrastructure's capacity factor (CF), the average capacity utilization. Continuing to use load computations as proxies for understanding capacity needs, we computed various load factors (LFs), the ratio of average load to peak load; aggregate values are shown in Figures 5(b) and 5(c), state-level computations are shown in Table S1, and census tract computations are shown in Figures S6 and S7.

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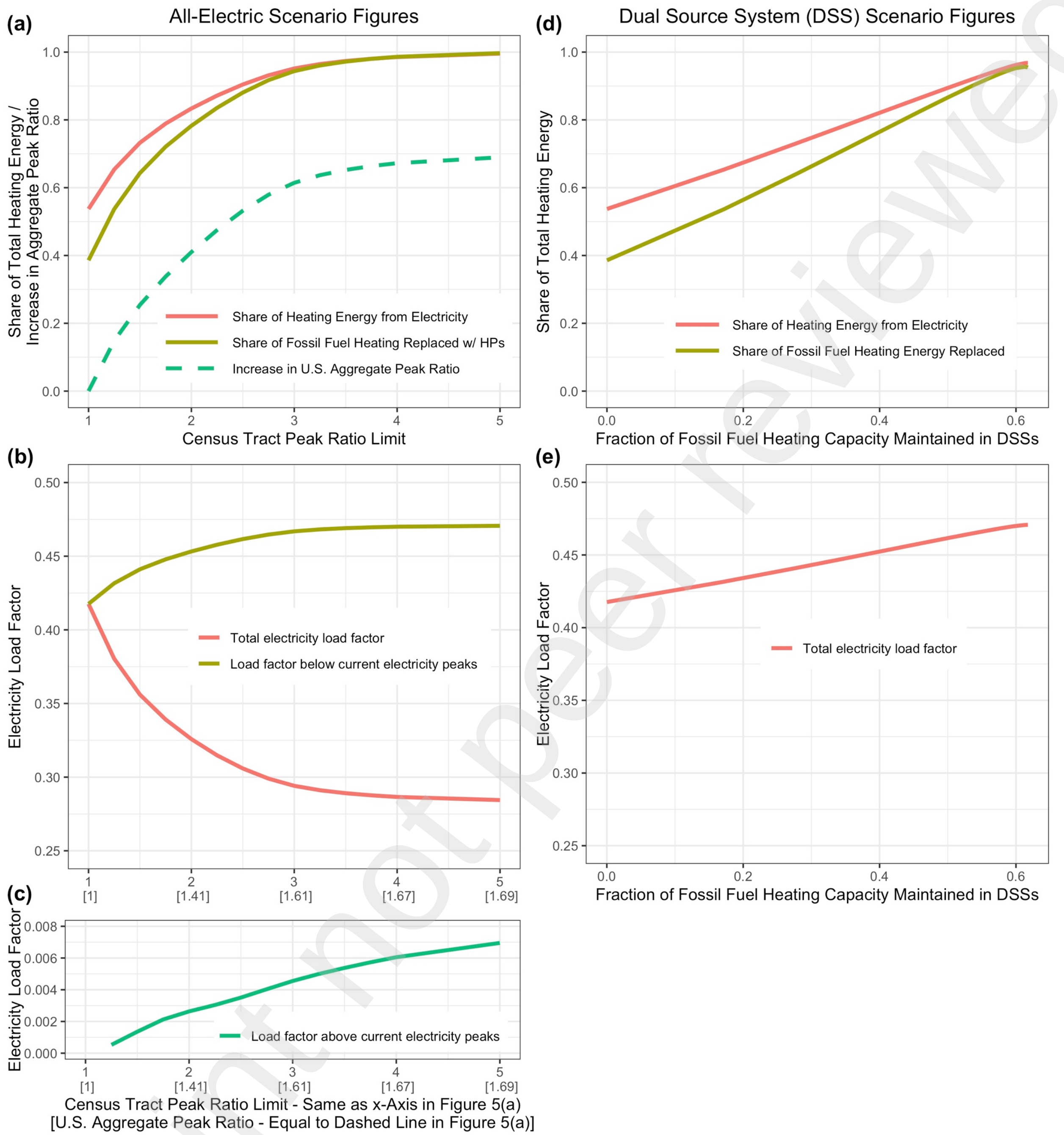

Figure 4 | Aggregate Effects of Pathways to Expanding Heating Electrification. (a) Maximum share of total heating energy from electricity and the maximum share of existing fossil fuel heating that can be replaced within each peak ratio limit using an All-Electric approach. Some census tracts achieve full heating electrification without reaching the designated peak ratio limit; the dashed line shows the corresponding increase in U.S. aggregate Peak Ratio. (b) 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. (c) Aggregate electricity load factor of only the electricity demands above current census tract peak demands in an All-Electric approach. (d) The maximum share of total heating energy from electricity and the maximum share of existing fossil fuel heating energy that can be replaced by maintaining a given fraction of current fossil fuel heating capacity in DSSs. (e) Aggregate total electricity load factor when maintaining a given fraction of current fossil fuel heating capacity in DSSs.

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The most consequential result for energy decarbonization pathways and the remainder of this paper is shown in Figure 4(c): The computed 0.75% aggregate LF above current electricity peaks is equivalent to only 66 annual full load hours: The new electricity infrastructure that would be required to accommodate All-Electric heating would be highly underutilized. The result of large load increases with low LFs would be *overall* electricity LFs less than half the current LFs in many states. If we assume that electricity distribution CF scales similarly to the computed LFs, this implies that average electricity delivery prices in some states – already the largest part of many customer's bill – could more than double for all electricity, not only that used for heating.

At the national level, an aggregate 28% total electricity LF was computed, compared to a computed current total electricity LF of 42%, as shown in Figure 4(b). The resulting decrease in capacity utilization has serious implications for utilities, particularly considering it would occur coincident with a vast renewable energy (RE) supply expansion and possible large transmission system upgrades that may also not be highly utilized. Further, the least efficient generators are likely to be used to meet these "peaky" heating-driven loads. Times of both high GHG emissions and high electricity prices would thus be likely 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 4(b) 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.

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 existing buildings' fossil fuel-based heating in a dual source system (DSS) with new HPs. The motivation for this approach is illustrated in Figure S1: The electricity requirements of a model residential HP would exceed current peak electricity demand at temperatures below -4°C whereas legacy fossil fuel infrastructure already provides the needed gas capacity at the lowest temperatures. Because extreme temperatures are infrequent, this low temperature operation could represent a relatively small portion of the aggregate space heating needs. For the building in Figure S1, the total heating energy that would exceed current peak electricity demand represents only 1.9% of all computed heating energy; the total heating energy required below -4°C represents 12.6% of all computed heating energy.

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 (AE scenario) 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

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constraint of limiting new peak electricity loads to current peak loads in all census tracts. We then estimated the maximum reduction in fossil fuel heating without exceeding current census tract peak loads. Figure 5 shows maps comparing the minimum fraction of census tract heating from fossil fuels for the CPL (Figure 5(b)) and DSS (Figure 5(c)) scenarios to existing fossil fuel usage for heating (Figure 5(a)).

In most of the country, fossil fuel-based heating can be reduced to less than 5% of all heating. In aggregate, we compute that 3.2% of all heating is provided by fossil fuels in the maximum DSS scenario as shown in Figure 4(d); compare this to 43% of all space heating from fossil fuels in the CPL scenario and 70% of all current space heating. Achieving these levels relies on total U.S. DSS capacity equal to 40% of all heating capacity (equivalent to maintaining 62% of current fossil fuel heating capacity in DSSs); the remaining 60% of heating capacity would be All-Electric.

While there remain some challenging geographical areas, the analysis indicates that all states shown in Table S1 could see very significant increases in heating electrification with DSSs. A particularly striking finding is that, in nearly all states, the widespread use of DSSs could result in an order eight or greater reduction in fossil fuel heating compared to the base case and an order six or greater reduction compared to the CPL scenario. Moreover, the widespread use of DSSs would actually increase the U.S. aggregate electricity LF from 42% to 47% as shown in Figure 4(e). The effects are even more striking at the state level shown in Table S1: Electricity LF increases of 8-19% were computed in colder states, compared to the 25-41% *decreases* in the AE scenario.

It is useful to select a reference point to compare increasing shares of DSS heating (Figure 4(d)) to an All-Electric pathway relying on electricity infrastructure capacity expansion (Figure 4(a)). Achieving 80% heating electrification in an AE approach results in a computed U.S. aggregate peak ratio of 1.36 (with individual census tract peak ratios up to 1.81); this corresponds to a 260 GW increase in noncoincident peak load nationwide. With DSS, we compute that this 80% heating electrification can be achieved without increasing census tract peak electricity loads if 37% of all existing fossil fuel heating capacity is maintained as part of a DSS (with 36% existing fossil fuel space heating capacity being replaced by HPs only and 27% remaining unchanged).

The DSS approach would also allow significantly smaller HPs to be used in cold climates than in an AE scenario. We compute that the total HP heating capacity with DSSs could be 60% of the capacity in the AE scenario by avoiding HP heating when its capacity degrades at low temperatures. The additional 2/3 HP heating capacity would only be needed infrequently to replace the remaining 3.2% of fossil fuel space heating. Because current electricity peaks are largely driven by air-conditioning, many buildings may be able to deploy DSSs by converting current cooling-only systems to HPs with heating and cooling capability for minimal cost. In addition to the economic implications for the heating systems and electricity infrastructure, issues specific to oversized HPs

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could be avoided: Cycling effects on maintenance requirements and equipment life, reduced COP, and increased potential freezing and electricity usage for defrosting.

This sets up an energy planning decision between (a) wholesale heating system replacement and large investments in new electricity infrastructure capacity and (b) maintaining fossil fuel capacity to meet the same ends with only limited fuel usage. The latter approach also offers the flexibility to adapt to future advances in technology, such as the usage of RE-produced hydrogen in future generations of end-use equipment (e.g. furnaces and boilers). There may be mutual benefits for fossil fuel and electricity infrastructure if long-term storage accompanies the large-scale RE capacities in the electricity system likely needed to achieve deep GHG reductions.

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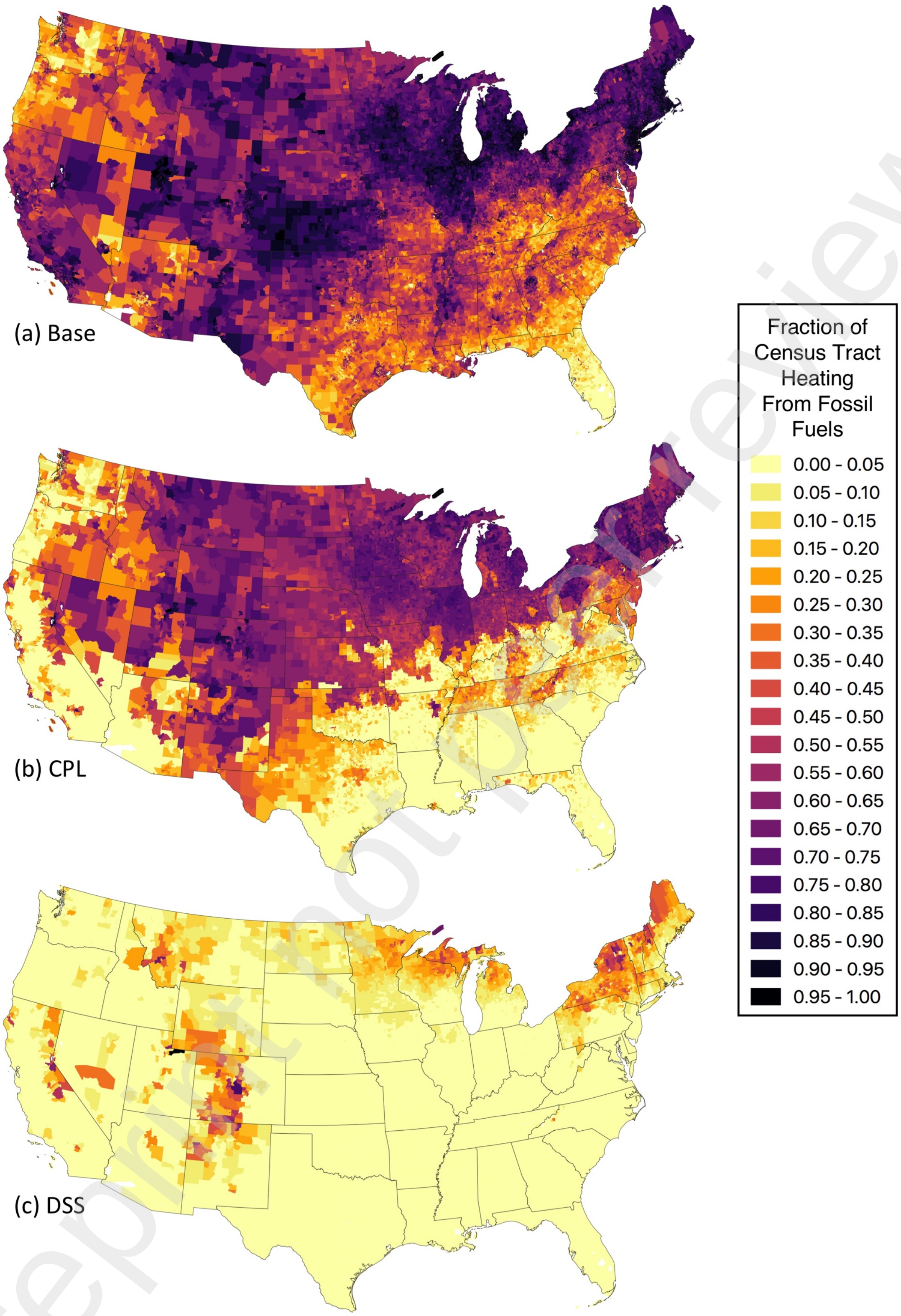

Figure 5 | Fraction of census tract heating from fossil fuels: (a) "Base" – current fossil fuel heating, (b) "CPL" – minimum fossil fuel heating with an HP-only approach without exceeding current census tract peak electricity demand, and (c) "DSS" – minimum fossil fuel heating achieved by deploying HPs in dual source heating systems where needed to prevent each census tract peak electricity demand from exceeding its current peak electricity demand. Figures S8-S10 show corresponding histograms.

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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 that challenge the emerging consensus around an All-Electric approach that would fully replace existing fossil fuel-based heating systems. 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 an All-Electric approach would result in an estimated minimum 70% increase in nationwide electricity delivery capacity, with 21 states seeing such capacity more than double. State-level load factors for only those loads above current peaks range from 0.1-2.3%, implying that such a proposition could be prohibitively expensive with the need for new underutilized electricity infrastructure, including distribution, generation and/or storage, and likely transmission.

We modeled two options that avoid such uneconomical investments: (1) A "current peak-limited" (CPL) scenario computing the maximum heat pump penetration without exceeding each census tract's current peak electricity demand, and (2) maintaining some amount of existing fossil fuel-based heating with new HPs in dual source systems (DSSs). For the CPL scenario, we compute a maximum possible electric HP penetration of 54%, reducing the total amount of space heating energy from fossil fuels to 43%. This national figure hides significant geographic heterogeneity; for example, fossil fuels would continue to provide more than 60% of space heating in 18 states.

This paper identifies a potentially powerful alternative pathway: Strategic deployment of DSSs can reduce the amount of heating provided by fossil fuels to 3.2% with no new electricity infrastructure capacity, let alone the highly underutilized large capacities necessary for an All-Electric pathway. Most cold-climate states are found capable of achieving an order five or greater reduction in space heating fossil fuel usage compared to using only HPs under the CPL constraint. This can all be achieved with a computed total HP heating capacity 60% of that needed in an All-Electric scenario, while also providing resilience and grid flexibility.

The most significant general finding of this study is thus that existing fossil fuel infrastructure should be leveraged, rather than ignored, in a transition to a low-carbon energy system. However, if the DSS approach is to be a part of this transition, it must be incorporated into energy planning now: The challenges identified here are likely to manifest later and abandoning existing fossil fuel infrastructure may preclude flexible

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adaptation to future technology and system advances (e.g. incorporation of renewable energy-produced hydrogen or biofuels into current fossil fuel-only systems).

We have not analyzed potential gains through building thermal efficiency measures, thermal energy storage or ground-source heat pumps (GSHPs); we do not suggest that those 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, evaluation of GSHPs 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.

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 is available. To capture year-to-year variations, weather data[39] for years 2008-2017 was 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[40]. 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[41]: Electricity (Figure S17); "utility gas" was assumed to be natural gas (Figure S18); "fuel oil, kerosene, etc." was assumed to be all fuel oils and kerosene (Figure S19); "bottled, tank or LP gas" was assumed to be propane (Figure

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S20); and "coal or coke," and "other fuel" were all grouped as "other fuels" (Figure S21). 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 S22 and S23, 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, $\hat{E}_{c,i,t}$, 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, $T_{i,t}$:

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

$T_{ref,res}$ is assumed to be 18.3°C based on common practice[42]; $T_{ref,com}$ is assumed to be 16.7°C based on a recent study[43]. $e_{c,s}^{+}$ 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[44].

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, $\hat{F}_{c,i,t}$, 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, $f_{c,s}^{-}$:

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

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

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.

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$f_{c,s}^{-}$, $f_{com,s}^{+}$ 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[45] and annual propane usage[46] were used and assumed to scale with monthly natural gas usage[47,48].

Heating Electrification Models

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

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

where $\eta_{FF} = 0.78$ is the assumed fossil fuel heating efficiency[49] and $COP_{HP}(T)$ is the HP's coefficient of performance, given by[50]:

$$COP_{HP}(T) = \begin{cases} 1, & T < -24.8 \\ 0.0344T + 2.7442, & -24.8 \leq T \leq 4.4 \\ 0.1562T + 2.733, & T > 4.4 \end{cases} \tag{9}$$

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AUTHOR CONTRIBUTIONS

M.W conceived of the study, developed all analytical methods, gathered and processed source data, implemented the methodology, analyzed the results, and developed figures; V.M. consulted in and reviewed all steps throughout these processes. M.W. was the primary author of the manuscript, which was prepared with V.M. V.M. provided institutional and material support for the research.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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SUPPLEMENTAL EXPERIMENTAL PROCEDURES

Overview

A model was developed for temperature-dependent residential and commercial building electricity and fuel usage to estimate current electricity peak loads and projected future peak loads under different heating electrification pathways at the census tract level for the United States. In this paper, “United States” is used to describe the contiguous 48 states and the District of Columbia, for conciseness. After initial model development, unique characteristics of Alaska and Hawaii led to intractable solutions and concerns of source data reliability; as such, these two states are excluded. There are 72,198 census tracts with residential or commercial building area in the U.S. (as so defined). While the model developed for this study is unique, initial approach formulation was informed by Gurney et al[1]. The underlying model for temperature-dependent energy demands used data for 2010, the most recent year for which all needed data is available. To capture year-to-year variations, weather data for years 2008-2017 was used for analyses of the three heating electrification scenarios. This model was then used to evaluate residential and commercial building space heating electrification scenarios involving high-coefficient of performance (COP) heat pumps (HPs) replacing current fossil fuel-based space heating, low-COP HPs and electric resistance heating.

All analyses were performed using the RStudio[2] interface for the computing software R[3]. All plots were created using R package “ggplot2”[4]. All map figures were created using QGIS[5]. Census tract geographical data was from 2010 TIGER/Line shapefiles[6].

Census Tract Temperature Time Series

For each census tract, *i*, a 2008-2017 hourly time series was developed for temperature, $T_{i,t}$, at each hourly time step, *t*. The basis for $T_{i,t}$ is the National Centers for Environmental Information (NCEI) of the U.S. National Oceanic and Atmospheric Administration (NOAA) Integrated Surface Dataset[7] (ISD). ISD data was accessed using the R package “rnoaa”[8]. The ISD is particularly useful because it aggregates data from more than 100 data sets and is provided after the use of automated quality control software. Outliers were further removed by the authors through inspection. Each census tract was assigned the temperature of the nearest ISD site for each hour. A spline fit was then used to fill data gaps of four hours or less. The next closest ISD site was then used followed by a new spline fit for data gaps of four hours or less. This process was repeated for the next nearest ISD sites until all census tracts had a full 2008-2017 temperature time series. After the first (i.e. nearest site) iteration, 49.8% of census tracts had complete data for all 87,672 hours in the time period; 23.3% of total tract-hours were incomplete where one “tract-hour” is one of the 87,672 hourly data points at one of the 72,198 census tracts. Subsequent iterations resulted in 75.4% complete census tracts (1.3% incomplete tract-hours), 97.9% complete census tracts (0.07% incomplete

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tract-hours), 99.6% complete census tracts (<0.01% incomplete tract-hours), and finally, 100% of census tract time series complete at the fifth iteration.

Building Stock Characterization

To determine building floor area, $A_{c,i}$, for each building class (i.e. residential, commercial and industrial), c, for each census tract, i, we used the U.S. Federal Emergency Management Agency (FEMA) Hazus General Building Stock (GBS) database[9], which contains Year 2010 census tract-level floor area for 33 occupancy classes; here we ignore the "industrial" occupancy classes. While most of Hazus's occupancy classes track closely to the larger building classes, the authors exercised some judgement based on typical classification for the energy usage data discussed below; these select occupancy classes are generally quite small compared to total floor area of the larger classes of which they are a part. Hazus's "Temporary Lodging (Hotel/Motel)," "Institutional Dormitories (Group Housing/Jails)," and "Nursing Homes" are residential sub-classes, but were classified under commercial for this study. Hazus's "Construction (Offices)" is an industrial sub-class, but was classified under commercial for this study. Some Hazus occupancy classes are not nested under residential, commercial or industrial. We included Hazus's "Agriculture" occupancy class in the industrial building class. The following were classified as commercial for this study: "Church/Non-Profit" religious structures, government "General Services (Office)" and "Emergency Response (Police/Fire/EOC)," and educational "Grade Schools" and "Colleges/Universities." Because of the vast array of industrial energy uses and this study's focus on building space heating, industrial floor area was excluded from the analysis; in the main text of this paper and in the rest of this Methods section, building classes refer only to residential and commercial.

Estimates of the number of households using each of the following heating fuels are available from the U.S. Census Bureau through statistical analysis of 2010 American Community Survey data[10]: Utility gas; bottled, tank or LP gas; electricity; fuel oil, kerosene, etc.; coal or coke; wood; solar energy; other fuel; and no fuel used. For the purposes of this study, "utility gas" was assumed to be natural gas and "bottled, tank or LP gas" was assumed to be propane. It was assumed that census tract residential floor area corresponding to each heating fuel scaled linearly with the fraction of households in each census tract. Based on computations in initial model development, it was the authors' judgement that the model significantly overestimated fuel oil, kerosene and propane usage vis-à-vis natural gas usage; as such, residential floor area using natural gas (Figure S18), fuel oil or kerosene (Figure S19) and propane (Figure S20) were used to determine the fraction of residential floor area in each census tract using fossil fuels for heating, $p_{FF,current,res,i}$ (Figure S22). This fraction of floor area using natural gas, fuel oil or propane was also assumed to apply to commercial building floor area; however, it was also assumed that commercial buildings used fossil fuels in place of wood, solar energy and other fuels (Figure S21) to determine the corresponding fraction of commercial floor area in each census tract using fossil fuels for heating, $p_{FF,current,com,i}$

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(Figure S23). It was assumed that the fraction of commercial floor area in each census tract using electricity for heating, $p_{elec,current,com,i}$, was equal to the fraction of residential floor area in each census tract using electricity for heating, $p_{elec,current,res,i}$ (Figure S17). The underlying data does not differentiate between households with electric resistance heating and those with electric HPs.

Current Temperature-Dependent Electricity Usage Model

The model estimate for temperature-dependent electricity usage, $\hat{E}_{c,i,t}$, for each building class, *c*, in each census tract, *i*, 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, $e_{c,s}^{-}$; the fraction of building class floor area in each census tract using electricity for heating, $p_{elec,current,c,i}$; the reference temperature for each building class, $T_{ref,c}$; and the temperature for each census tract at each time step, $T_{i,t}$:

$$\hat{E}_{c,i,t} = A_{c,i}\left[e_{c,s}^{const} + p_{AC,c,i}e_{c,s}^{+}\left(T_{i,t} - T_{ref,c}\right)^{+} + p_{elec,current,c,i}e_{c,s}^{-}\left(T_{ref,c} - T_{i,t}\right)^{+}\right] \quad \text{(S1)}$$

Note that the "+" outside the parentheses indicates the value of the term is zero if the value inside the parentheses is negative. In Eq. S1, the decreasing-temperature dependence is weighted by the fraction of building class floor area using electricity for heating; this approach will not necessarily capture temperature-dependent pump and fan electricity usage for some heating systems, which is uncertain in the underlying data. The reference temperature for residential buildings is $T_{ref,res} = 18.3℃$ and based on common practice[11]. The reference temperature for actual commercial buildings varies significantly depending on the type of building and many other factors, but a value of $T_{ref,com} = 16.7℃$ was used based on the average found in a recent study of commercial building balance point temperatures[12].

The fraction of commercial floor area with air-conditioning in each census tract, $p_{AC,com,i}$, was assumed to be 1 for all census tracts due to the lack of an adequate reference data source. Residential air-conditioning penetration was estimated based on a curve fit of households with air-conditioning in select metropolitan areas[13] versus cooling degree day "normals" with a 65°F (18.3°C) basis, *CDD65*, for the same metropolitan areas[14]. The resulting curve fit equation was then used to compute the fraction of residential floor area with air-conditioning in each census tract, $p_{AC,res,i}$, based on the $CDD65_i$ for each census tract:

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$$p_{AC,res,i} = 1 - e^{-b(CDD65_i)^n} \tag{S2}$$

where b = 1.17796 x 10^{-3} and n = 1.1243

Eq. S1 decision variables, $e^+_{c,s}$ and $e^-_{c,s}$, are selected for each state and building class so as to minimize the residual sum of squares, $RSS_{elec,c,s}$, with respect to the actual state monthly electricity usage for each building class in 2010, $E^{(act,2010)}_{c,s,m}$, as obtained from publicly available retail sales data of the U.S. Energy Information Administration (EIA)[15]:

$$RSS_{elec,c,s} = \sum_{m=25}^{36} \left[E^{(act,2010)}_{c,s,m} - \sum_{i \in s} \sum_{t \in m} \hat{E}_{c,i,t} \right]^2 \tag{S3}$$

where $m \in \{25{:}\,36\}$ represent the months of 2010 in the 2008-2017 data set

The estimated current peak electricity demand for each census tract, $P_{existing,i}$, thus becomes the maximum of the estimated current electricity demand, summed across all building area for each building class:

$$P_{current,i} = \max_t \sum_c \hat{E}_{c,i,t} \tag{S4}$$

Current Temperature-Dependent Fossil Fuel Usage Model

The model estimate for temperature-dependent fossil fuel usage, $\hat{F}_{c,i,t}$, for each building class, *c*, in each census tract, *I*, at each time step, *t*, is defined by the temperature-independent fuel usage per unit floor area, $f^{const}_{c,s}$, for each building class for each state, *s*; the decreasing-temperature-dependent fuel usage per unit floor area for each building class for each state, $f^-_{c,s}$; the fraction of building class floor area in each census tract using fossil fuels for heating, $p_{FF,current,c,i}$; the reference temperature for each building class, $T_{ref,c}$; and the temperature for each census tract at each time step, $T_{i,t}$:

$$\hat{F}_{res,i,t} = A_{res,i} p_{FF,current,res,i} \left[f^{const}_{res,s} + f^-_{res,s} \left(T_{ref,res} - T_{i,t} \right)^+ \right] \tag{S5}$$

$$\hat{F}_{com,i,t} = A_{com,i} p_{FF,current,com,i} \left[f^{const}_{com,s} + f^+_{com,s} \left(T_{i,t} - T^+_{ref,com,s} \right)^+ + f^-_{com,s} \left(T_{ref,com} - T_{i,t} \right)^+ \right] \tag{S6}$$

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Although fossil fuels are primarily used for space heating, hot water and cooking, some increasing-temperature dependence was observed for commercial buildings in the source data; therefore, a term to capture this effect was included for commercial buildings only (Eq. S6) with the increasing-temperature-dependent electricity usage per unit floor area for each state, $f^{+}_{com,s}$, and the increasing-temperature-dependent commercial building reference temperature, $T^{+}_{ref,com,s}$, included as decision variables.

Eqs. 5 and 6 decision variables ($f^{-}_{c,s}$, $f^{+}_{com,s}$ and $T^{+}_{ref,com,s}$) , are selected for each state and building class so as to minimize the residual sum of squares, $RSS_{FF,c,s}$, with respect to the monthly state fossil fuel usage for each building class in 2010, $F^{(2010)}_{c,s,m}$

$$RSS_{FF,c,s} = \sum_{m=25}^{36} \left[F^{(2010)}_{c,s,m} - \sum_{i \in s} \sum_{t \in m} \hat{F}_{c,i,t} \right]^2 \quad \text{(S7)}$$

Because fuel oil and propane are delivered in bulk and stored on site, sometimes for a full season or multiple years, while natural gas usage is based on actual monthly values, the total fossil fuel usage was assumed to scale by month with the natural gas usage. As such, the monthly fuel usage for each building class in each state, $F^{(2010)}_{c,s,m}$, is computed from EIA data for monthly natural gas usage[16,17], $F^{(act,2010)}_{NG,c,s,m}$, annual fuel oil and kerosene usage[18], $F^{(act,2010)}_{FOK,c,s}$, and annual propane usage[19], $F^{(act,2010)}_{prop,c,s}$:

$$F^{(2010)}_{c,s,m} = \frac{F^{(act,2010)}_{NG,c,s,m}}{\sum_{m=25}^{36} F^{(act,2010)}_{NG,c,s,m}} \left[\sum_{m=25}^{36} \left(F^{(act,2010)}_{NG,c,s,m} \right) + F^{(act,2010)}_{FOK,c,s} + F^{(act,2010)}_{prop,c,s} \right] \quad \text{(S8)}$$

Heating Electrification Models

We made several simplifying assumptions in developing our heating electrification models: (1) The building thermal response to temperature to be the same for regardless of heating fuel type. (2) A single existing heating system efficiency, $\eta_{FF} = 0.78$, was assumed largely based on the authors' judgment and the performance of traditional heating systems and corresponds to average early-1990's era equipment as documented for the Lawrence Berkeley National Laboratory (LBNL) Home Energy Saver tool[20] with some reduction for part-load operation effects. (3) As the heating electrification computations in this study envision a medium-term transition that begins immediately, a particularly high-performing, currently commercially available HP system[21] was assumed rather than vintage equipment or higher performing systems that may become available in the future. The temperature-dependent coefficient of performance, $COP_{HP}(T)$, was computed by the following, which includes technology limits that necessitate electric resistance heating below -24.8°C:

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$$COP_{HP}(T) = \begin{cases} 1, & T < -24.8 \\ 0.0344T + 2.7442, & -24.8 \le T \le 4.4 \\ 0.1562T + 2.733, & T > 4.4 \end{cases}$$

(S9)

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

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

(S10)

To compute the projected new census tract-level temperature-dependent electricity demand for each building class it is necessary to know how much existing electric heating and how much existing fossil fuel heating is being replaced. As this study is primarily interested in assessing the maximum possible heating electrification, for computation purposes it was assumed that new HPs will first replace existing electric resistance and low-efficiency HPs; this will be the condition to achieve maximum HP penetration in capacity-constrained census tracts. This does not necessarily mean that such a sequence would be necessary in practice for all census tracts, but for methodological consistency, the electricity demand, $E_{c,i,t}$, for a given building class HP penetration, $p_{HP,c,i}$, is computed by:

$$\begin{aligned} E_{c,i,t}(p_{HP,c,i}) = A_{c,i} \Bigg[& e_{c,s}^{const} + p_{AC,c,i} e_{c,s}^{+} \left(T_{i,t} - T_{ref,c} \right)^{+} + p_{elec,current,c,i} e_{c,s}^{-} \left(T_{ref,c} - T_{i,t} \right)^{+} \\ & + \left(p_{elec,current,c,i} - p_{HP,c,i} \right)^{+} e_{c,s \ni i}^{-} \left(T_{ref,c} - T_{i,t} \right)^{+} \\ & + p_{HP,c,i} A_{c,i} \frac{\left[f_{c,s}^{-} \left(T_{ref,c} - T_{i,t} \right)^{+} \right] \eta_{FF}}{COP_{HP}\left(T_{i,t} \right)} \Bigg] \end{aligned}$$

(S11)

Census tracts have some mix of residential and commercial building area. To simplify most analyses presented in this paper, we considered the same HP penetration in both building classes in computing the peak electricity demand, P_i, for a given HP penetration, $p_{HP,i}$:

$$P_i(p_{HP,i}) = \max_t \sum_c E_{c,i,t}\left(p_{HP,c,i}\right)$$

(S12)

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We also compute the electricity load factor, LF_i, the load factor below current peaks, $LF_i^{(below)}$, and the load factor above current peaks, $LF_i^{(above)}$, for each census tract, i, from the electricity demand and peak loads computed as above, and using the number of hours in the 10-year analysis period, n_{hrs}=87,672:

$$LF_i = \frac{\sum_{c,t} E_{c,i,t}}{n_{hrs} \times P_i} \tag{S13}$$

$$LF_i^{(below)} = \frac{\sum_{c,t} \min\left(E_{c,i,t}, P_{current,i}\right)}{n_{hrs} \times P_{current,i}} \tag{S14}$$

$$LF_i^{(above)} = \frac{\sum_{c,t} \max\left(0, E_{c,i,t} - P_{current,i}\right)}{n_{hrs} \times \max\left(0, P_i - P_{current,i}\right)} \tag{S15}$$

This study is particularly interested in the heating electrification potential without requiring new electricity infrastructure. As such, the current peak-limited (CPL) HP penetration, $p_{HP.CPL,i}$, was computed from the following:

$$p_{HP.CPL,i} = max(x) \mid P_i(x) \leq P_{current,i} \tag{S16}$$

The remaining fossil fuel usage for heating is also of interest as some portion of current heating is provided by non-fossil fuel sources (i.e. electricity or other sources, such as wood). Without a DSS, the computation of the portion of heating provided by fossil fuels, $p_{FF,noDSS,i}$, is fairly straightforward assuming, as above, that high-COP HPs first replace existing electric resistance heating and low-COP HPs, followed by fossil fuel-based heating and, finally, other heating sources:

$$p_{FF,noDSS,i} = \max\begin{cases} 0 \\ p_{FF,current,c,i} - \left(p_{HP,i} - p_{elec,current,c,i}\right) \end{cases} \tag{S17}$$

The computation for fossil fuel usage for heating is more complex when considering DSSs as fossil fuels are only used for heating that cannot be met by HPs. The heating provided by the DSS fossil fuel component for each census tract at each time step, $H_{DSS,i,t}$, is the lesser of (a) the avoided heating by HPs that would have exceeded the current peak electricity demand and (b) the heating that could be provided by existing fossil fuel-based systems in the absence of an HP or DSS:

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$$H_{DSS,i,t} = \min \begin{cases} \sum_c \left[E_{c,i,t}^{(HP)}(p_{HP,c,i}) - P_{current,i} \right] COP_{HP}(T_{i,t}) \\ \sum_c \left[\eta_{FF} A_{c,i} p_{FF,current,c,i} f_{c,s}^{-} \left(T_{ref,c} - T_{i,t} \right)^{+} \right] \end{cases}$$

(S18)

The portion of heating provided by fossil fuels with DSSs, $p_{FF,DSS,i}$, thus becomes a straightforward computation based on the earlier assumption that the thermal behavior of buildings without fossil fuel heating is the same as those with fossil fuel heating:

$$p_{FF,DSS,i} = \frac{\sum_t H_{DSS,i,t}}{\sum_t \eta_{FF} A_{c,i} f_{c,s}^{-} \left(T_{ref,c} - T_{i,t} \right)^{+}}$$

(S19)

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SUPPLEMENTAL DATA ITEMS

Table S1 I Summary of State-Level Computations[a]

State	Base[b] FF-Elec Peak Ratio	AE[c] Elec. Peak Ratio	CPL[d] (%)	% of All Heating by Fossil Fuels				Electricity Load Factor (%)					Fossil Fuel Load Factor (%)			
				Base[b]	AE[c]	CPL[d]	DSS[e]	Base[b]	AE[c] Total[f]	AE[c] New[g]	CPL[d]	DSS[e]	Base[b]	AE[c]	CPL[d]	DSS[e]
VT	3.98	3.92	17.9	83.1	0	69.6	13.8	47.2	17.7	1.7	45.2	64.3	26.1	4.5	22.6	8.1
ME	3.82	3.62	20.4	85.9	0	70.4	8.4	42.7	17.4	1.1	41.4	60.1	26.7	4.9	22.8	7.0
MA	4.54	3.84	21.3	84.7	0	74.1	9.1	42.0	16.5	1.1	41.6	60.4	24.4	5.0	22.0	7.1
WY	2.75	3.25	21.4	72.6	0	69.9	9.9	55.0	20.5	1.4	47.9	63.7	24.4	2.2	23.6	5.2
MT	2.96	3.40	22.4	73.4	0	68.1	8.3	45.6	17.8	1.3	39.9	57.4	23.5	0.8	21.9	3.4
CO	3.14	3.30	22.6	80.1	0	71.8	7.8	42.8	18.0	0.9	41.9	57.1	22.1	1.2	20.0	3.2
MN	3.02	3.13	23.1	81.5	0	71.4	9.6	46.5	20.7	1.6	45.6	61.5	26.0	3.8	23.2	6.5
NH	3.59	3.19	24.8	86.0	0	68.7	9.1	47.3	20.5	1.3	46.7	62.6	24.8	3.3	20.5	5.6
MI	3.53	3.10	26.1	89.3	0	70.2	5.1	40.6	18.7	0.7	41.3	56.5	25.0	4.4	20.6	5.6
NM	3.40	3.04	26.5	80.0	0	65.9	6.3	49.5	19.9	0.6	48.4	59.1	19.7	4.8	17.1	5.9
WI	2.77	2.89	26.7	82.0	0	67.8	5.4	41.3	19.8	0.9	40.9	55.4	24.9	2.3	21.0	3.8
ND	1.96	2.73	27.5	62.3	0	60.2	7.3	50.6	22.3	1.6	43.8	58.1	25.5	2.1	24.8	4.8
IA	2.75	2.80	28.8	81.4	0	68.2	3.0	40.7	18.5	0.4	38.6	51.1	23.3	4.1	20.2	4.8
IL	3.17	2.92	28.9	85.8	0	69.4	2.3	37.3	17.0	0.3	36.6	49.2	23.5	5.2	20.0	5.7
SD	2.05	2.48	30.7	72.1	0	64.7	3.1	48.9	22.9	0.6	44.2	55.9	24.7	3.1	22.5	4.0
RI	4.72	2.40	31.5	90.0	0	66.9	10.0	44.5	28.0	2.3	48.6	63.8	23.0	3.3	17.9	5.5
NY	4.03	2.50	34.2	86.8	0	62.1	10.5	46.5	25.9	2.0	49.5	61.7	26.7	8.0	21.4	10.3
NE	2.10	2.33	35.6	73.9	0	60.8	0.9	42.4	21.0	0.1	39.3	48.8	25.2	6.3	21.8	6.6
CT	3.71	2.16	39.0	83.3	0	59.0	4.9	43.9	27.5	1.2	45.9	58.1	24.7	5.5	19.1	6.7
OH	2.51	2.38	39.3	77.9	0	57.3	1.0	37.6	19.3	0.2	36.1	45.6	21.3	2.8	16.4	3.0
IN	2.15	2.28	41.1	73.7	0	55.1	0.5	35.7	18.3	0.1	33.3	41.7	20.3	2.1	15.7	2.2
UT	2.92	1.96	46.2	88.4	0	51.9	3.9	46.6	30.1	0.9	49.3	58.1	26.0	5.8	17.6	6.7
PA	2.84	1.96	47.6	76.6	0	48.1	3.8	43.8	27.5	0.9	44.1	53.1	23.5	4.1	16.3	5.1
ID	1.72	1.95	49.6	60.2	0	40.7	1.1	40.7	22.5	0.3	35.6	43.7	22.3	1.0	15.4	1.4
NJ	3.27	1.61	53.8	89.1	0	45.4	1.7	41.5	33.4	0.6	45.9	53.3	25.1	7.2	16.3	7.5
KS	2.06	1.81	55.2	79.2	0	42.7	0.1	37.2	23.8	0.0	38.0	43.1	19.6	2.9	11.9	2.9
NV	1.62	1.53	55.9	71.4	0	39.1	3.6	40.0	28.9	0.9	39.5	43.7	23.5	6.2	15.7	7.0

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State	Base[b] FF-Elec Peak Ratio	AE[c] Elec. Peak Ratio	CPL[d] (%)	% of All Heating by Fossil Fuels				Electricity Load Factor (%)					Fossil Fuel Load Factor (%)			
				Base[b]	AE[c]	CPL[d]	DSS[e]	Base[b]	AE[c] Total[f]	AE[c] New[g]	CPL[d]	DSS[e]	Base[b]	AE[c]	CPL[d]	DSS[e]
DC	2.06	1.44	56.0	65.1	0	42.5	1.7	56.1	44.4	0.6	58.5	63.8	25.3	9.1	19.6	9.5
WA	1.34	1.53	58.8	42.6	0	31.2	1.8	49.1	33.6	0.7	44.6	51.0	25.0	2.2	18.9	3.1
MD	1.91	1.37	65.3	60.4	0	33.0	0.8	45.3	36.6	0.4	45.7	50.2	22.7	5.8	15.0	6.1
DE	1.97	1.31	69.1	68.8	0	29.7	0.3	45.8	38.8	0.2	47.0	50.7	23.8	6.6	14.0	6.7
KY	1.29	1.46	71.1	51.4	0	22.5	0.1	35.7	24.8	0.0	33.3	36.2	17.2	1.7	8.5	1.7
MO	1.61	1.40	71.8	65.5	0	24.4	0.1	38.8	29.4	0.0	38.1	41.0	20.3	4.5	10.4	4.5
OK	1.82	1.41	72.2	66.7	0	25.2	0.1	38.5	29.1	0.0	38.5	41.0	17.2	4.5	9.3	4.5
TN	1.24	1.27	74.2	42.0	0	21.3	0.2	41.3	34.0	0.1	40.7	43.4	19.1	4.7	12.0	4.8
AR	1.47	1.34	79.1	54.3	0	17.1	0.1	40.9	31.6	0.0	40.3	42.2	22.5	9.4	13.5	9.4
OR	1.12	1.29	79.7	45.6	0	13.9	0.3	38.6	30.1	0.2	36.3	38.9	22.5	0.9	7.5	1.1
WV	1.34	1.18	82.9	55.6	0	13.1	0.2	35.5	28.9	0.1	32.4	34.2	22.7	5.7	9.7	5.7
NC	1.11	1.14	83.4	43.5	0	14.4	0.2	42.8	38.1	0.2	42.0	43.5	16.9	1.9	6.9	2.0
AZ	0.84	1.09	84.0	46.2	0	11.4	1.4	43.7	38.4	0.9	41.1	41.7	18.8	8.7	11.2	9.0
VA	1.24	1.15	84.5	49.4	0	13.0	0.1	40.6	36.0	0.1	39.7	41.2	20.3	4.3	8.5	4.3
CA	1.68	1.11	85.5	72.3	0	12.1	1.3	39.3	37.6	1.0	41.0	41.8	24.1	10.8	13.0	11.0
TX	1.21	1.09	87.9	46.2	0	11.3	0.1	45.5	41.7	0.1	44.8	45.5	18.3	8.9	11.2	8.9
GA	1.27	1.07	91.4	54.2	0	7.9	0.0	40.7	38.0	0.0	39.9	40.5	17.2	4.7	6.5	4.7
FL	0.21	1.05	92.5	9.8	0	3.7	0.2	49.0	45.5	0.1	47.5	47.6	28.4	24.2	25.8	24.3
MS	1.16	1.03	94.9	51.8	0	4.3	0.0	44.4	42.1	0.0	43.2	43.5	18.7	7.0	7.9	7.0
SC	0.76	1.02	97.8	34.3	0	1.8	0.0	41.4	39.5	0.0	39.9	40.1	18.1	5.6	6.3	5.6
AL	0.87	1.00	99.5	42.6	0	0.4	0.0	39.7	36.7	0.0	36.8	36.9	17.8	6.1	6.2	6.1
LA	0.97	1.00	99.7	43.3	0	0.2	0.0	48.9	47.3	0.0	47.4	47.4	18.7	9.7	9.8	9.7
U.S.	**1.91**	**1.70**	**53.7**	**69.5**	**0**	**42.7**	**3.2**	**42.3**	**28.4**	**0.1**	**41.8**	**47.1**	**22.7**	**5.6**	**16.1**	**6.4**

[a]Corresponding census tract-level computations are shown in Figures 1-5, S3, S5, S7, S9 and S12-S16

[b]Base scenario is current model electricity and fossil fuel loads

[c]All-Electric (AE) is 100% heating electrification with high-COP heat pumps

[d]Current peak-limited (CPL) scenario is the maximum heat pump penetration without exceeding each census tract's current peak demand

[e]DSS scenario is the minimum fossil fuel-based heating achieved by deploying heat pumps in dual source heating systems where needed and operating DSS to prevent each census tract's new peak electricity demand from exceeding the current peak demand.

[f]Total electricity load factor for All-Electric scenario

[g]Load factor above current electricity peaks for All-Electric scenario

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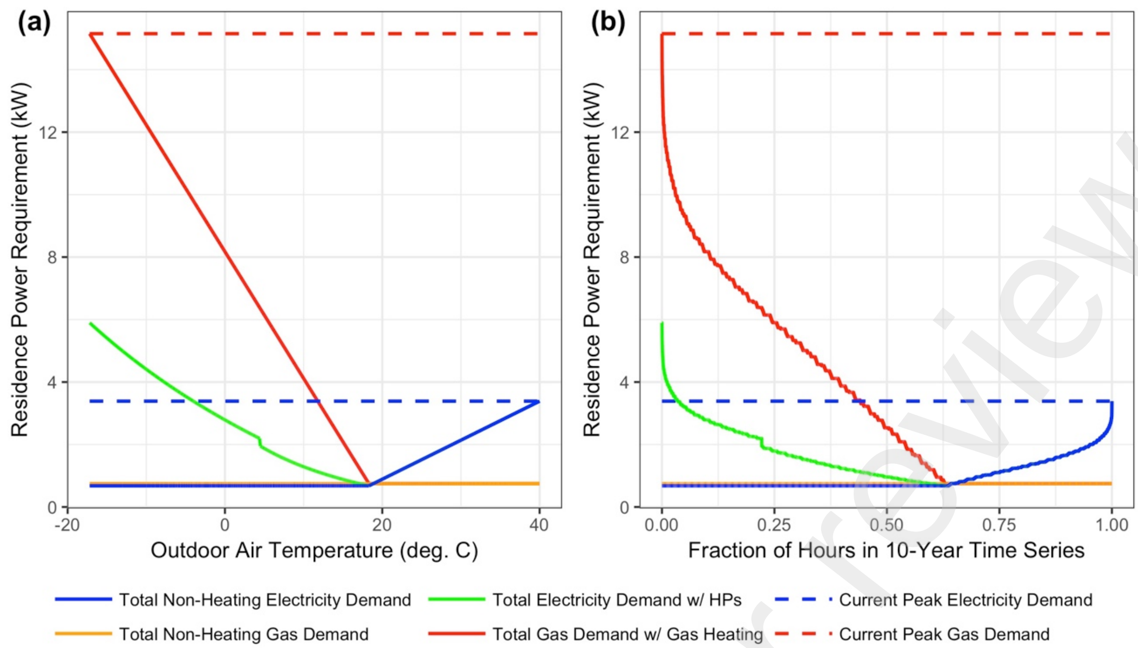

Figure S1 | Single-family residential building energy model. The figure shows (a) simulated residential building natural gas and electricity demand with and without heat pumps vs. outdoor air temperature; (b) simulated energy usage output from (a) with x-axis reflecting the fraction of annual hours during which such conditions occur. Computations are for a 1765 sq. ft. residence in Census Tract 36085018902 using weather data for 2008-2017. The census tract has a computed All-Electric scenario electricity peak ratio closest to the U.S. aggregate peak ratio. The census tract is also representative of a mixed heating and cooling climate: The ratio of heating degree days to cooling degree days is 4.03 whereas the U.S. median equivalent ratio is 4.09.

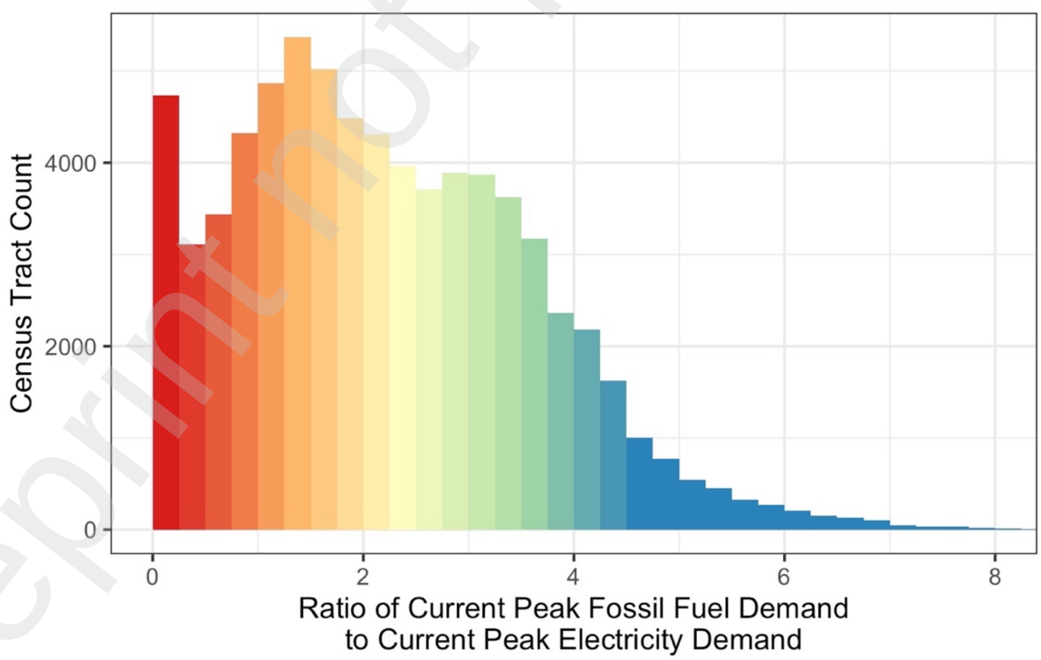

Figure S2 | Histogram of Census Tracts by Current Fossil Fuel to Electricity Peak Ratio, Related to Figure 1. For clarity, the x-axis is limited to a ratio of 8. The maximum computed ratio is 16.54; 56 census tracts (0.08% of all census tracts) have computed ratios greater than 8.

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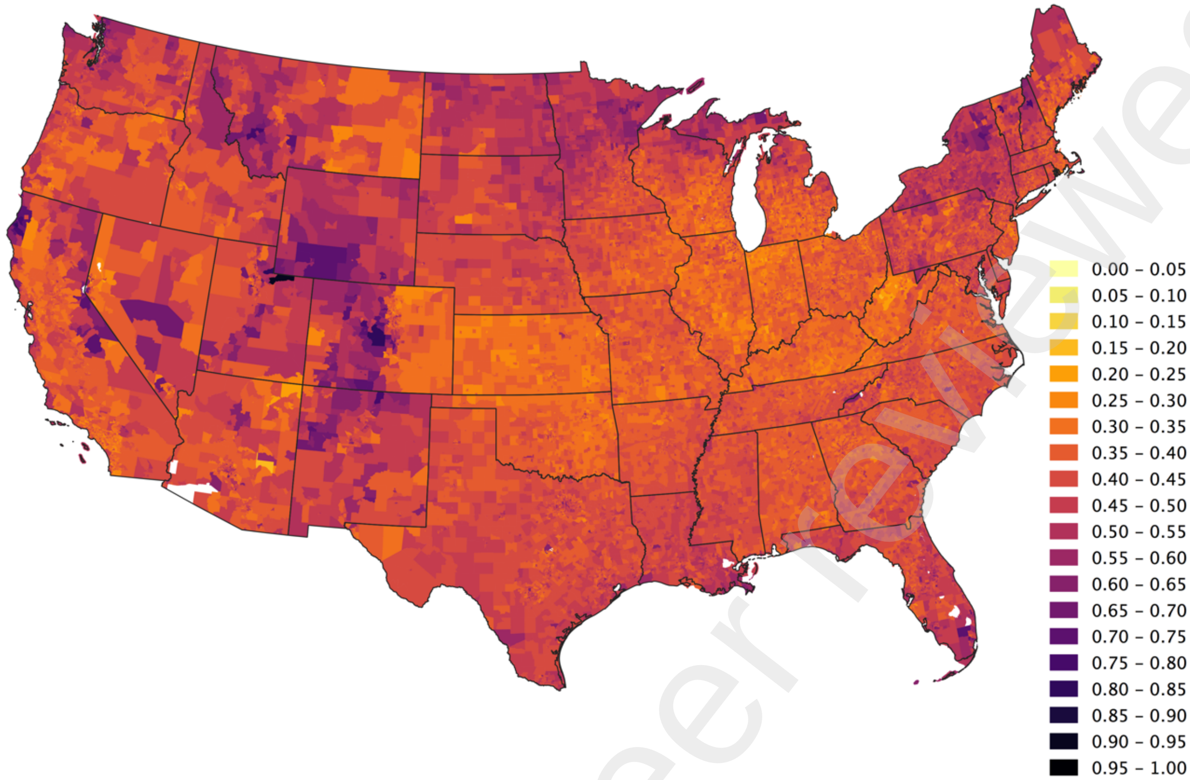

Figure S3 I Current electricity load factors. All values are computed at the census tract level for years 2008-2017. Census tracts with white fill have no residential or commercial building square footage in the source data.

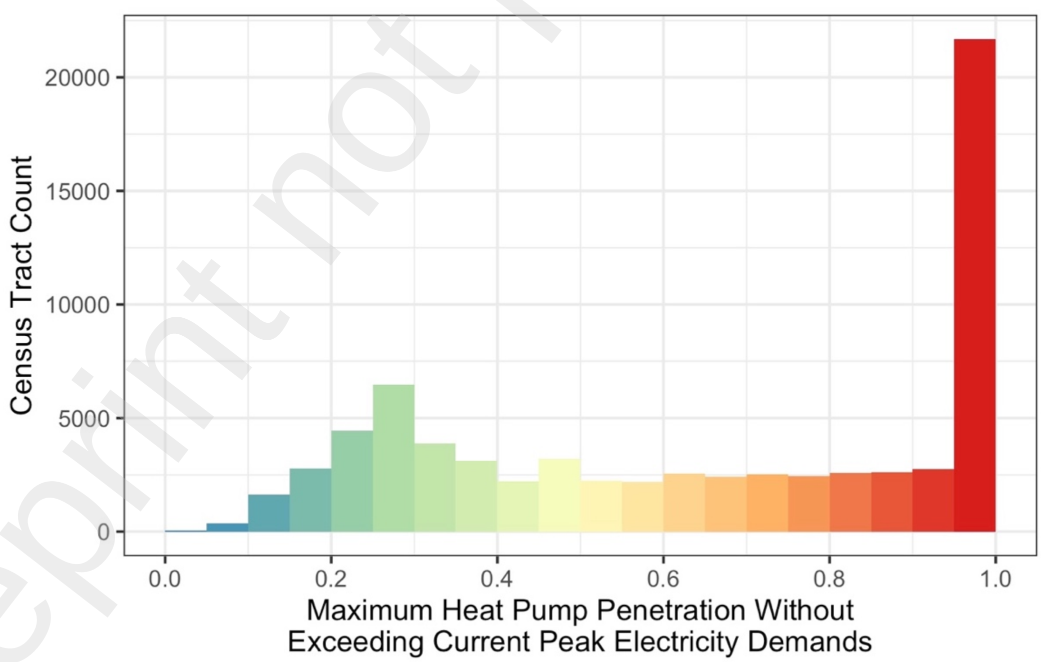

Figure S4 I Histogram of Census Tracts by Maximum Current Peak-Limited (CPL) Heating Electrification Potential, Related to Figure 2. Computed maximum penetration of high-COP heat pumps without exceeding current census tract peak electricity demands (HP_{CPL})

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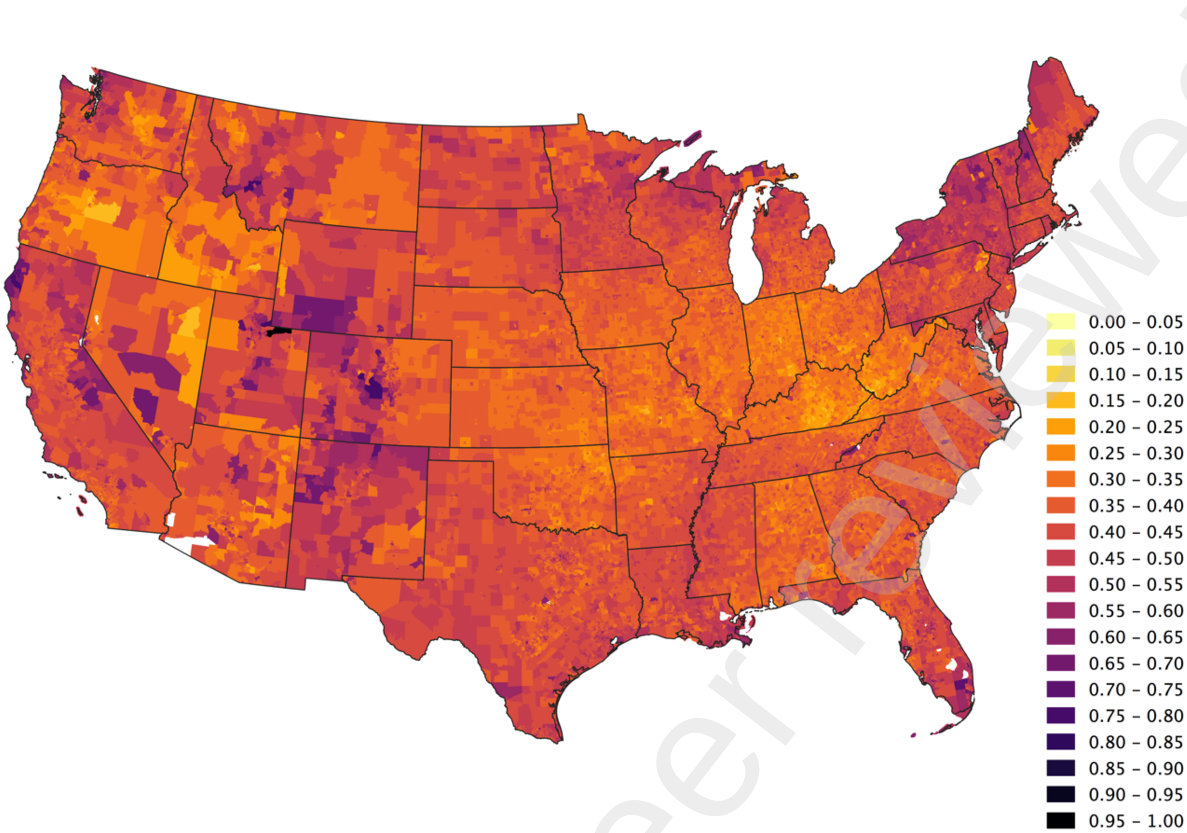

Figure S5 | Electricity Load Factors – Current Peak-Limited (CPL) Scenario. All values are computed at the census tract level for years 2008-2017. Census tracts with white fill have no residential or commercial building square footage in the source data.

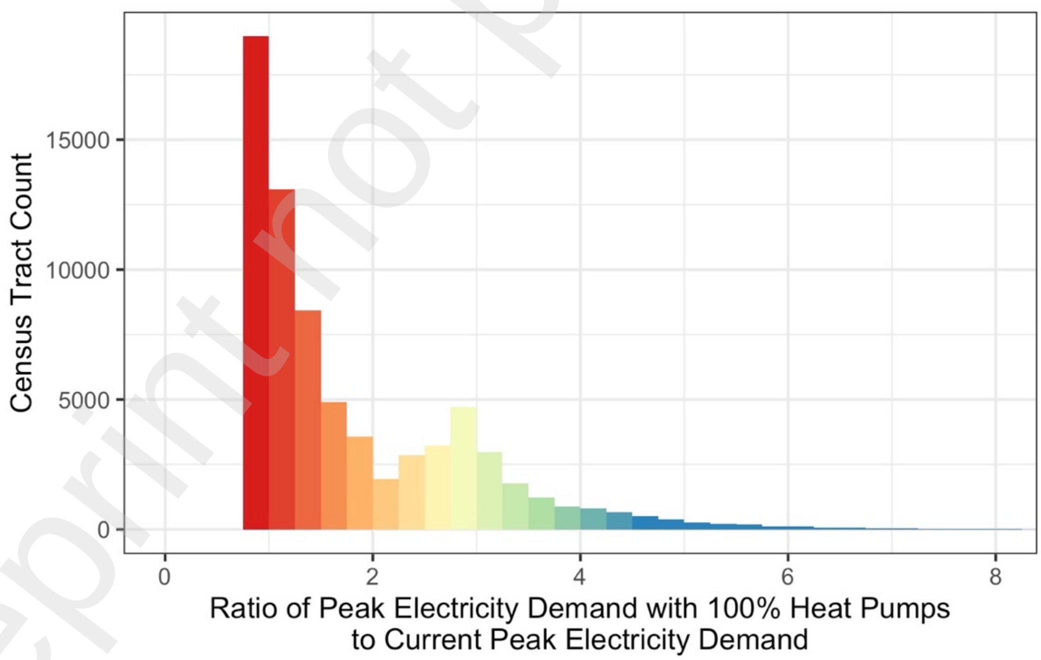

Figure S6 | Histogram of Census Tracts by Ratio of Peak Electricity Demand in All-Electric Heating Scenario to Current Peak Electricity Demand, Related to Figure 3. For clarity, the x-axis is limited to a ratio of 8. The maximum computed ratio is 15.93; 62 census tracts (0.08% of all census tracts) have computed ratios greater than 8.

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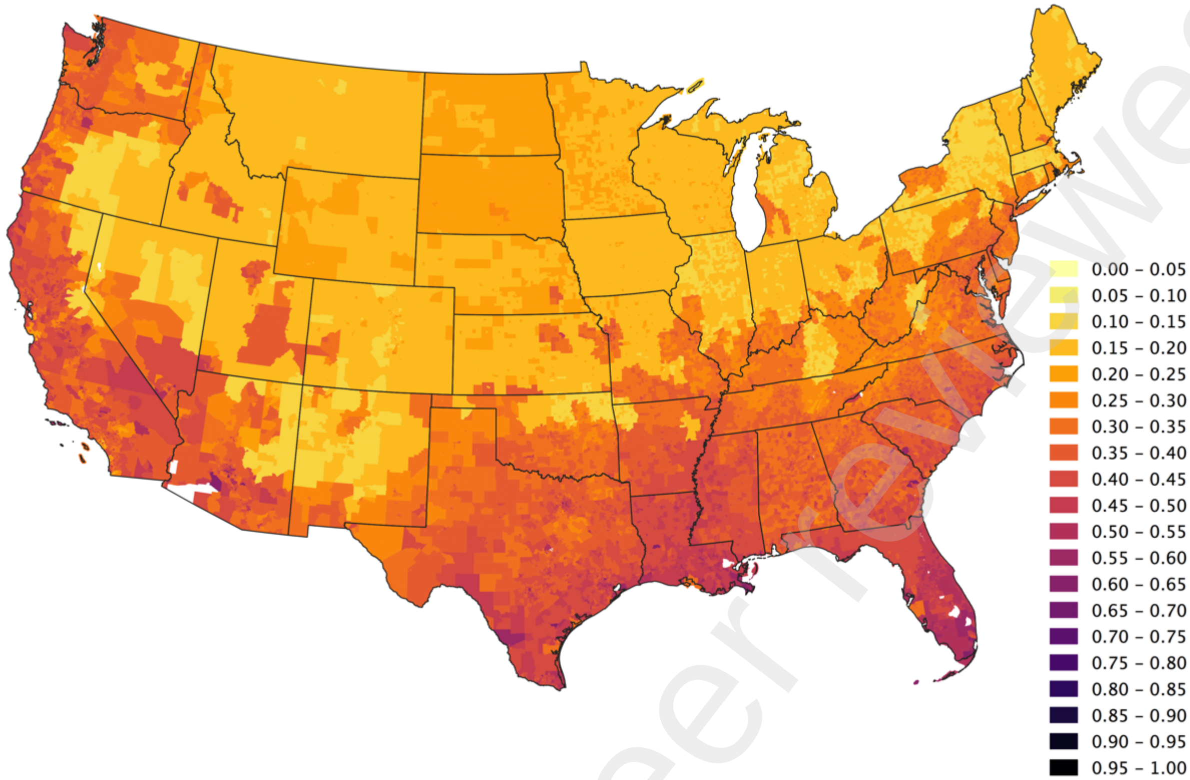

Figure S7 | Electricity Load Factors – All-Electric Heating Scenario, Related to Figure 4(b). All values are computed at the census tract level for years 2008-2017. Census tracts with white fill have no residential or commercial building square footage in the source data.

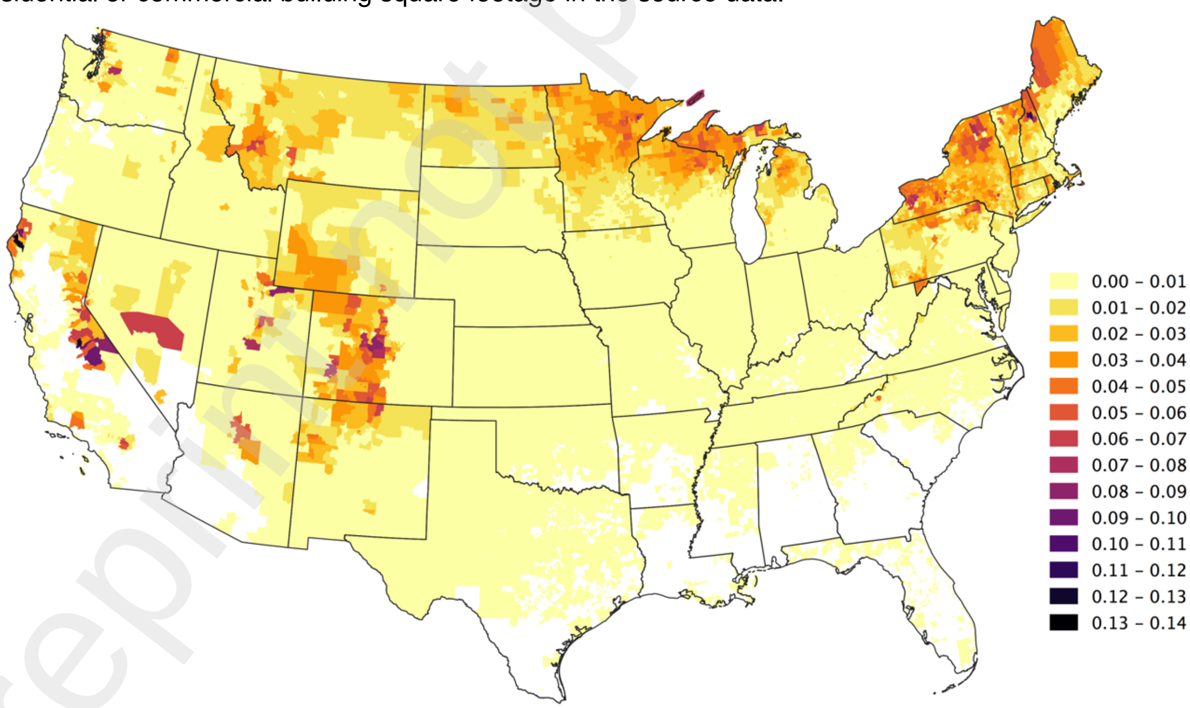

Figure S8 | Electricity Load Factors for Load Above Current Census Tract Peak Loads – All-Electric Heating Scenario, Related to Figure 4(c). All values are computed at the census tract level for years 2008-2017. Census tracts with white fill have no residential or commercial building square footage in the source data or have no increased peak load in the All-Electric scenario.

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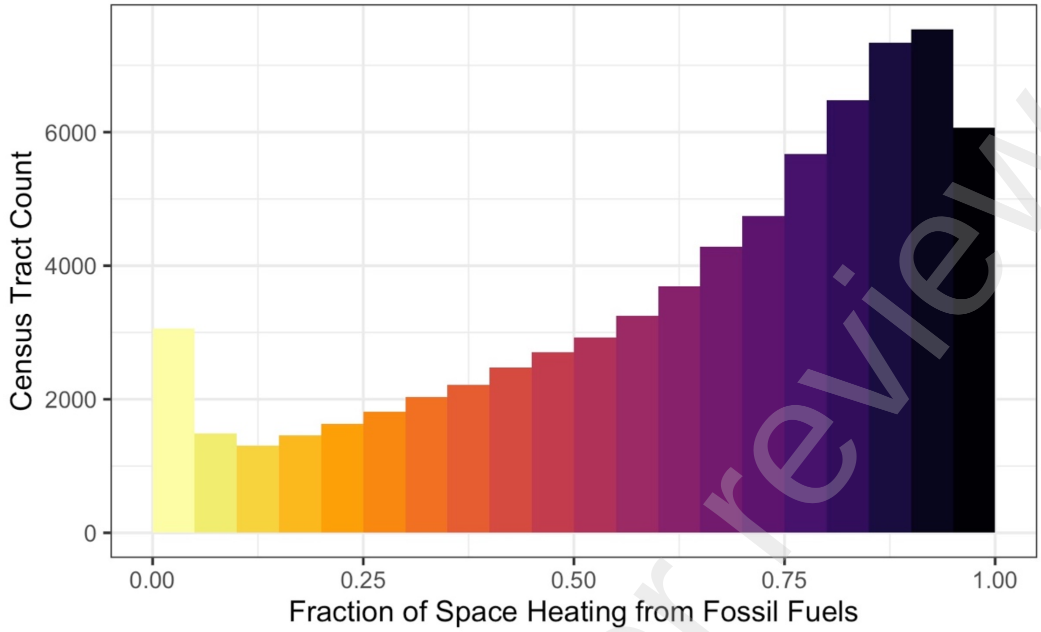

Figure S9 l Histogram of Computed Current Census Tract Fraction of Space Heating from Fossil Fuels, Related to Figure 5(a)

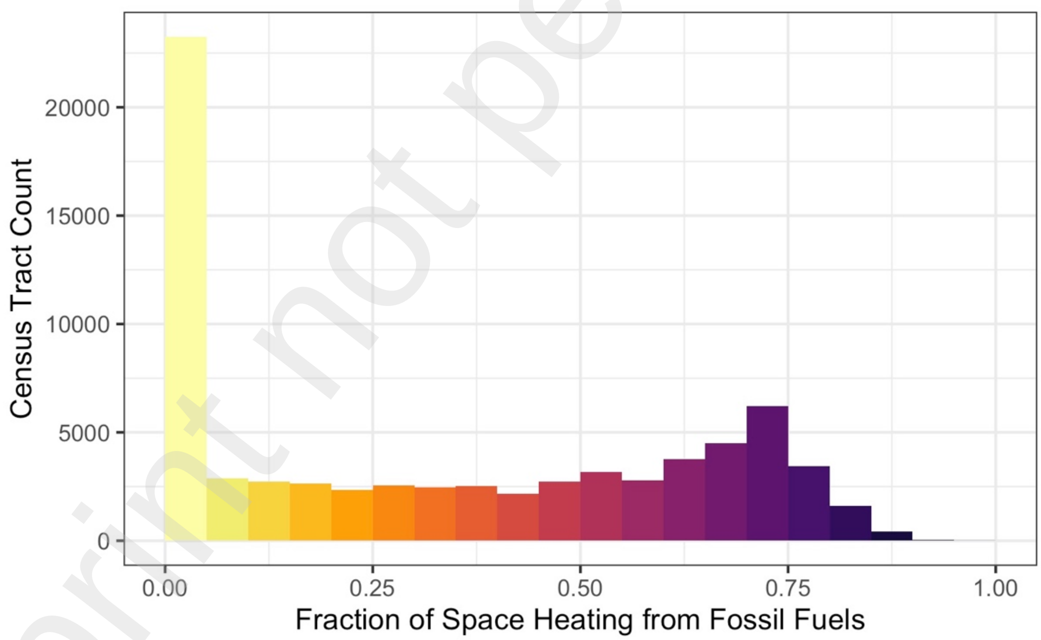

Figure S10 l Histogram of Computed Census Tract Fraction of Space Heating from Fossil Fuels in Current Peak-Limited Scenario, Related to Figure 5(b)

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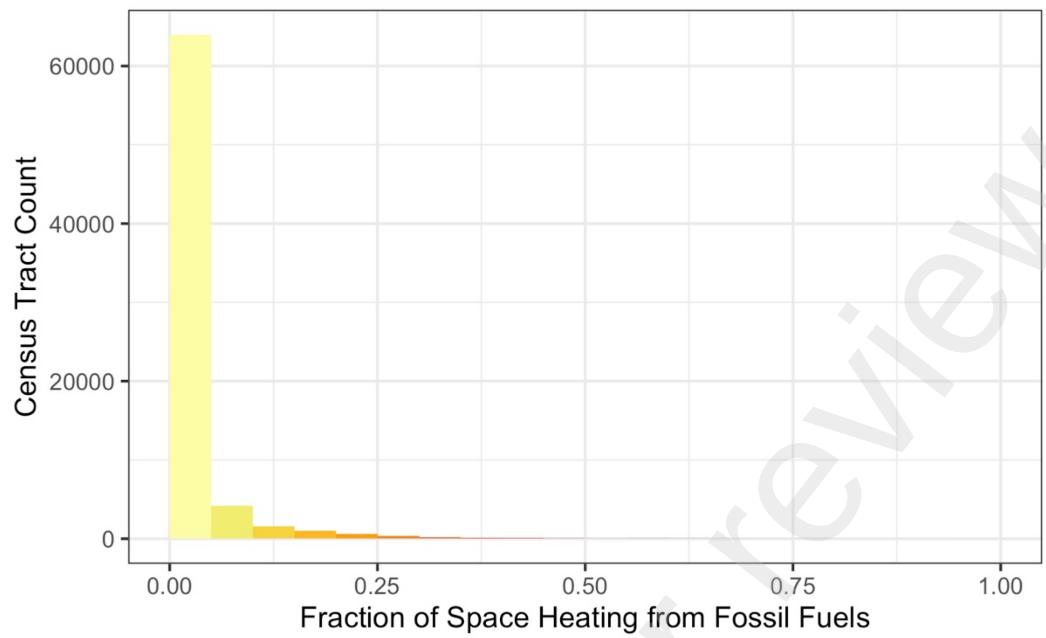

Figure S11 | Histogram of Computed Census Tract Fraction of Space Heating from Fossil Fuels in Dual Source System Scenario, Related to Figure 5(c)

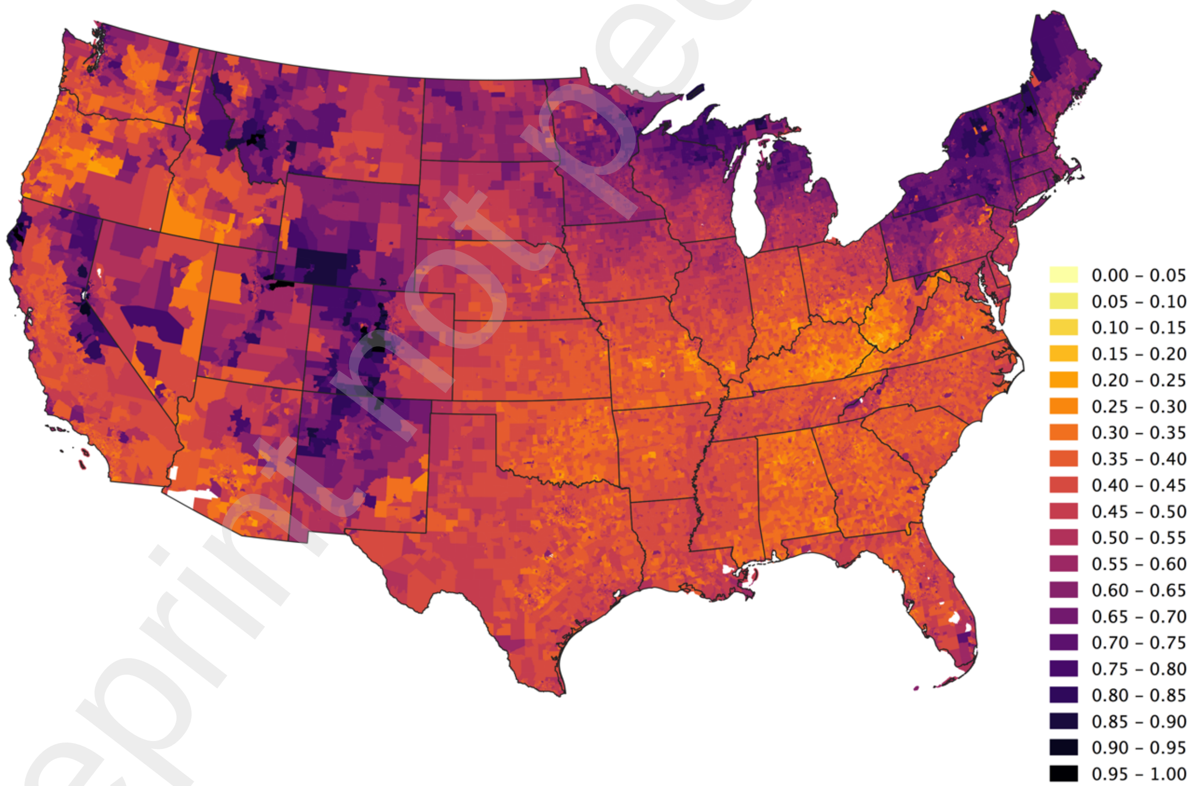

Figure S12 | Electricity Load Factors – Dual Source System (DSS) Scenario, Related to Figure 4(e). All values are computed at the census tract level for years 2008-2017. Census tracts with white fill have no residential or commercial building square footage in the source data.

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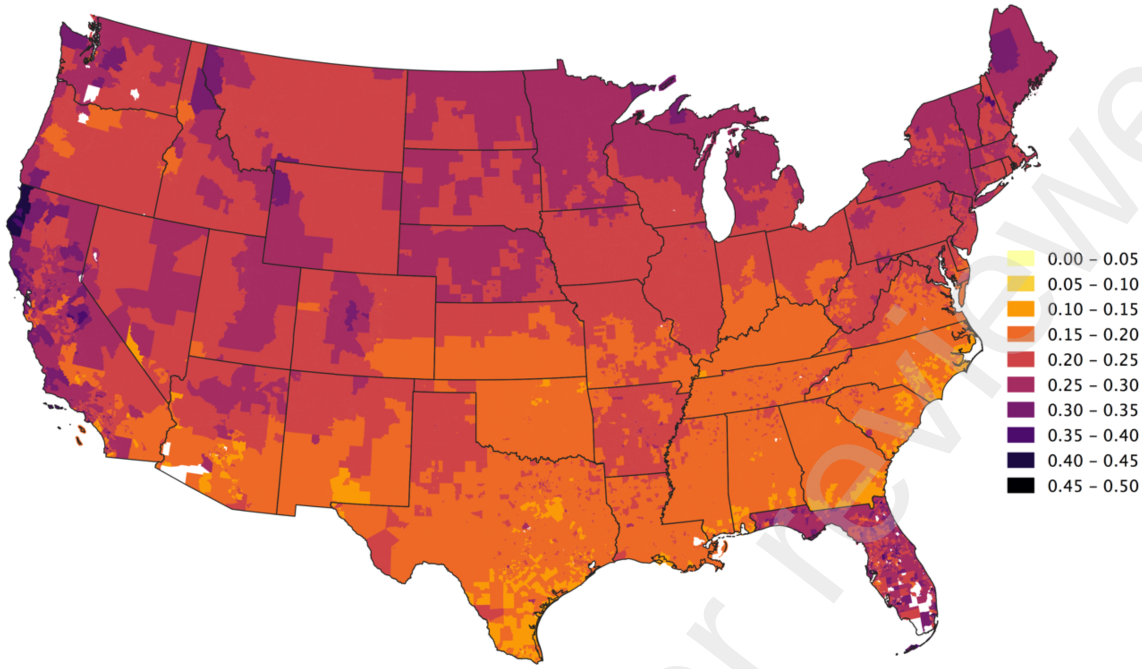

Figure S13 | Computed Current Fossil Fuel Load Factors. All values are computed at the census tract level for years 2008-2017. Census tracts with white fill have no residential or commercial building square footage with fossil fuel heating in the source data.

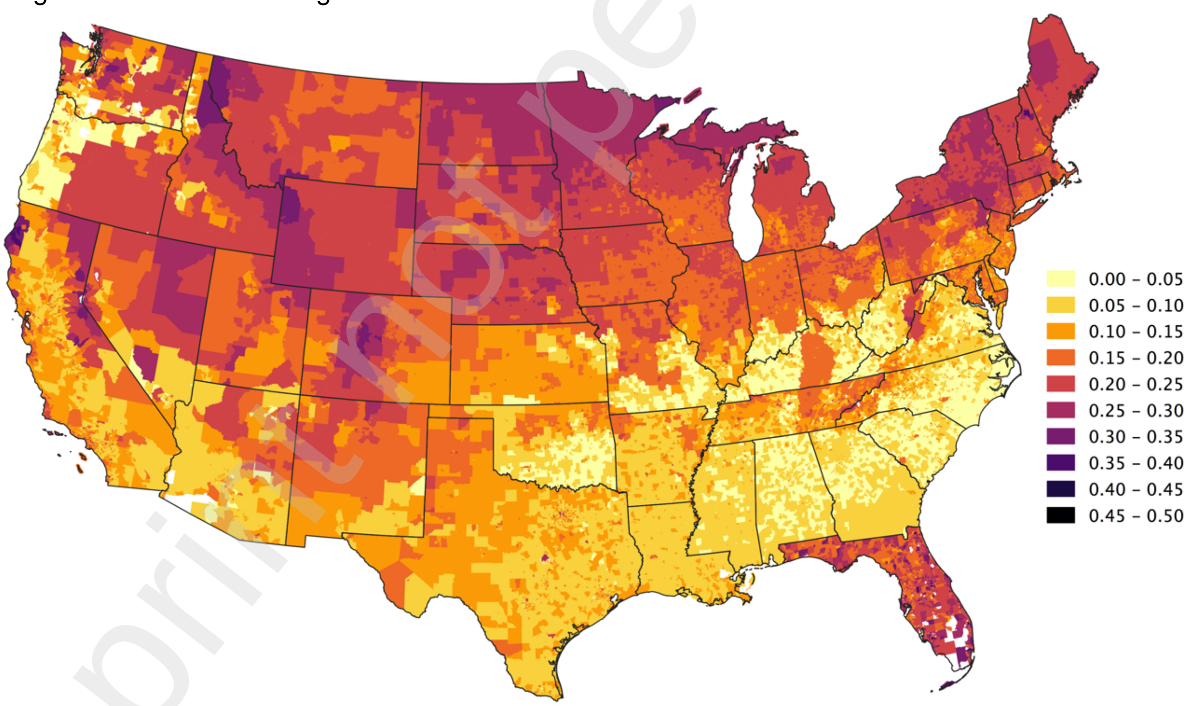

Figure S14 | Computed Fossil Fuel Load Factors – Current Peak-Limited (CPL) Scenario. All values are computed at the census tract level for years 2008-2017. Census tracts with white fill have no residential or commercial building square footage with fossil fuel heating in the source data.

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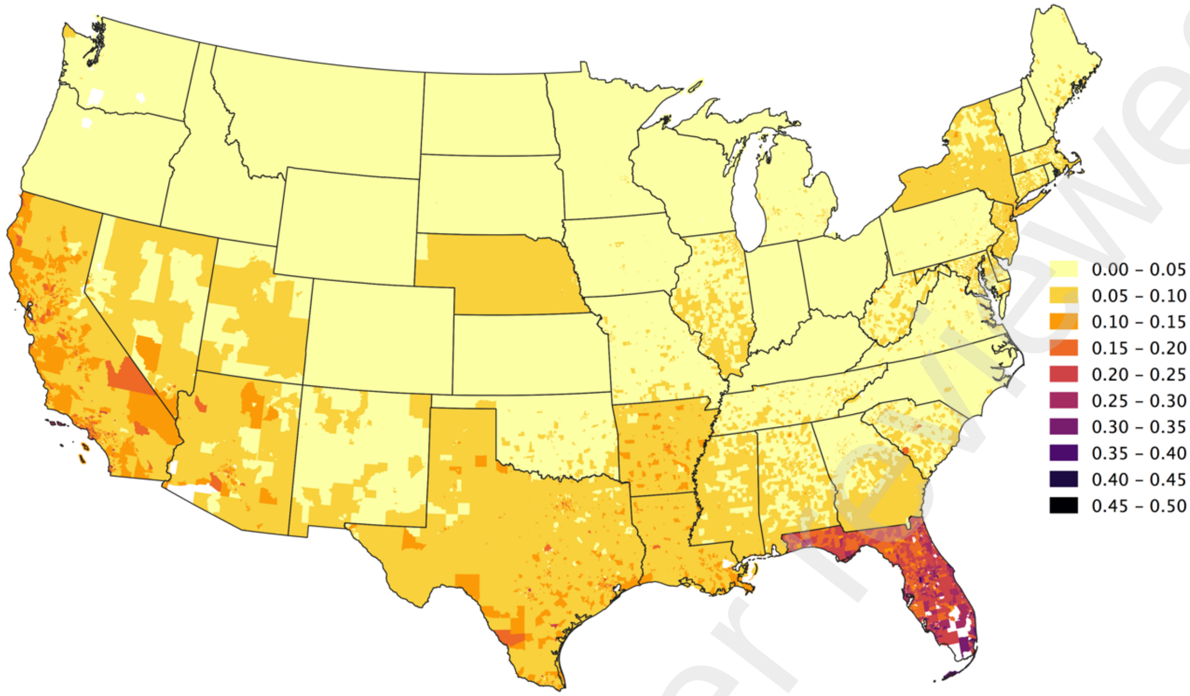

Figure S15 | Computed Fossil Fuel Load Factors – All-Electric Scenario. All values are computed at the census tract level for years 2008-2017. Census tracts with white fill have no residential or commercial building square footage with fossil fuel heating in the source data.

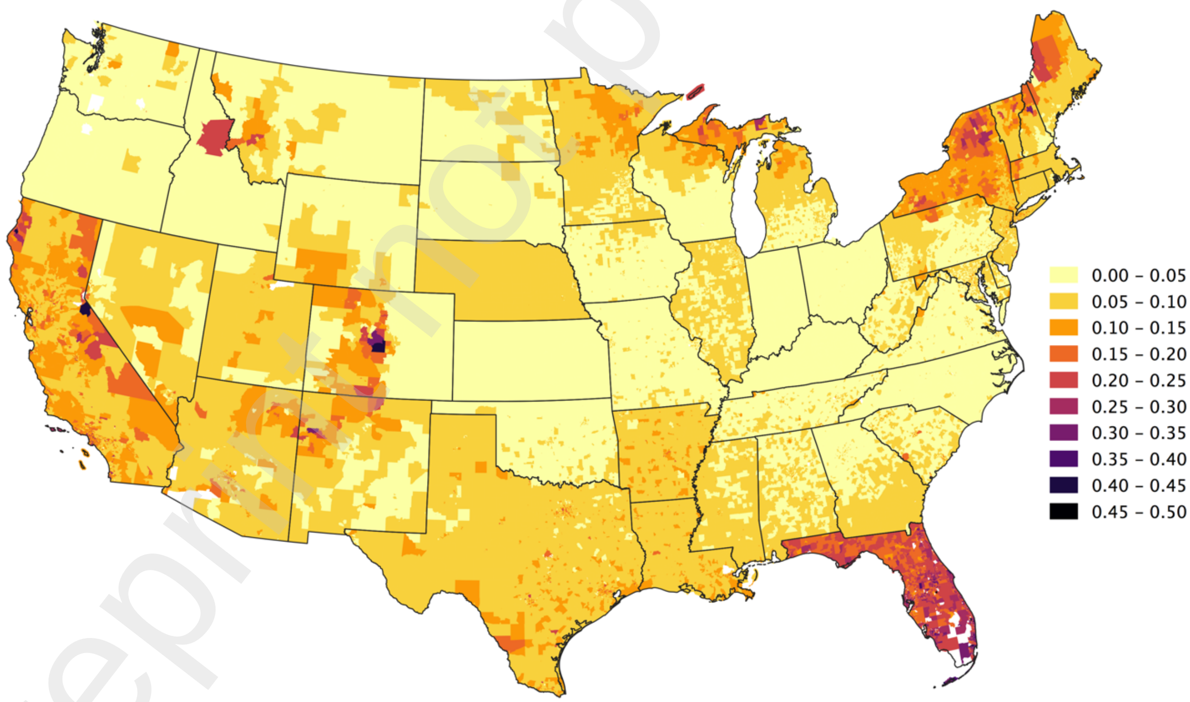

Figure S16 | Fossil Fuel Load Factors – Dual Source System (DSS) Scenario. All values are computed at the census tract level for years 2008-2017. Census tracts with white fill have no residential or commercial building square footage with fossil fuel heating in the source data.

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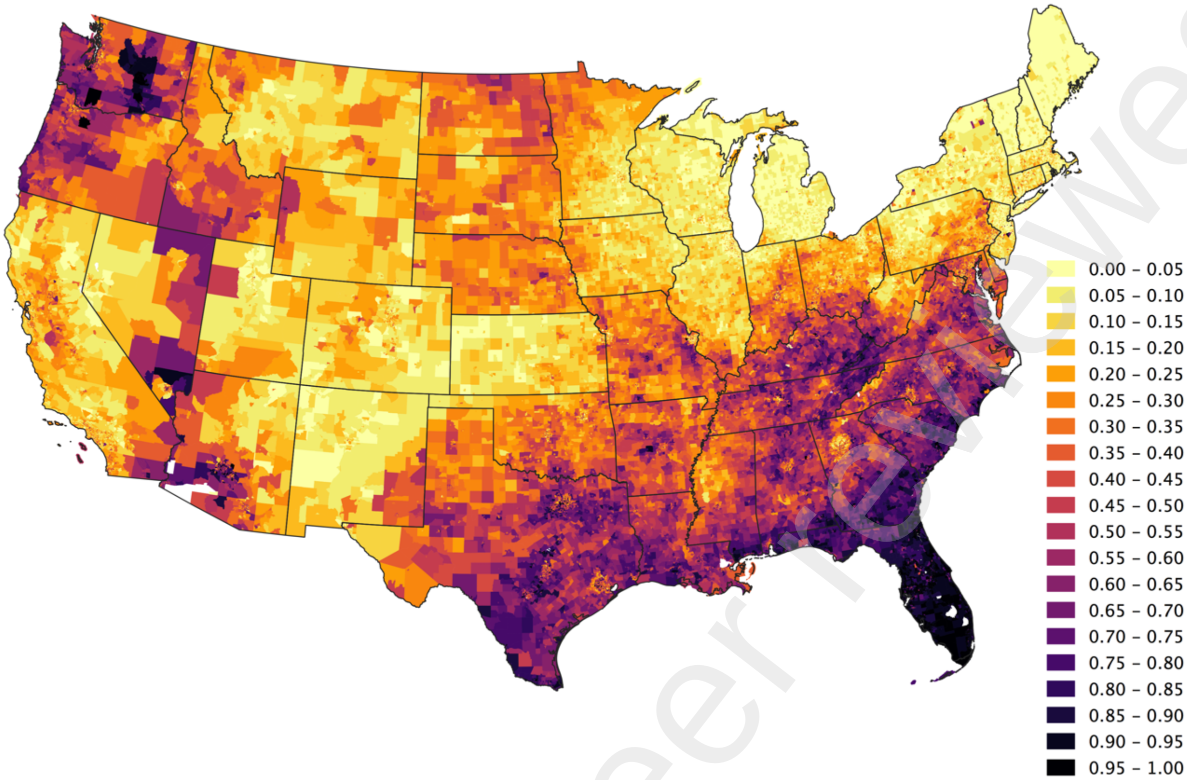

Figure S17 | Fraction of Households Using Electricity for Space Heating. Census tracts with white fill have no residential or commercial building square footage in the source data.

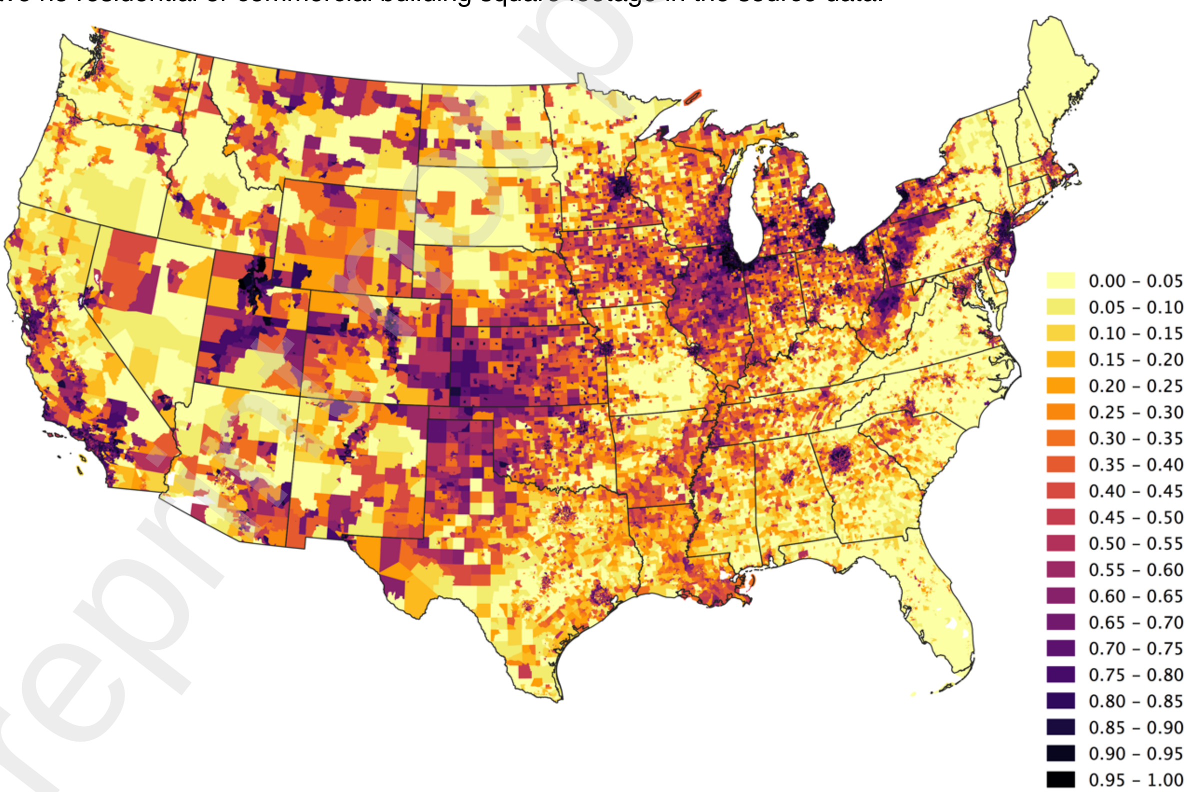

Figure S18 | Fraction of Households Using Natural Gas for Space Heating. Census tracts with white fill have no residential or commercial building square footage in the source data.

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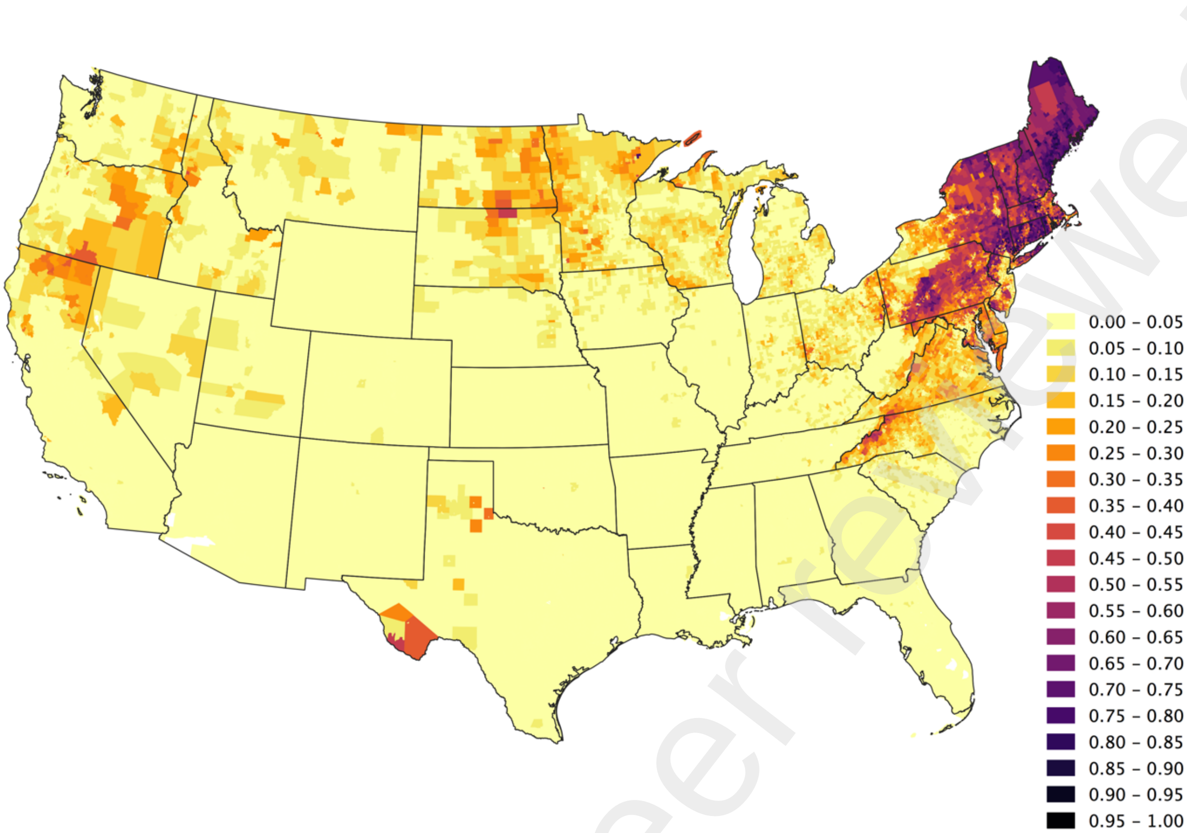

Figure S19 | Fraction of Households Using Fuel Oil or Kerosene for Space Heating. Census tracts with white fill have no residential or commercial building square footage in the source data.

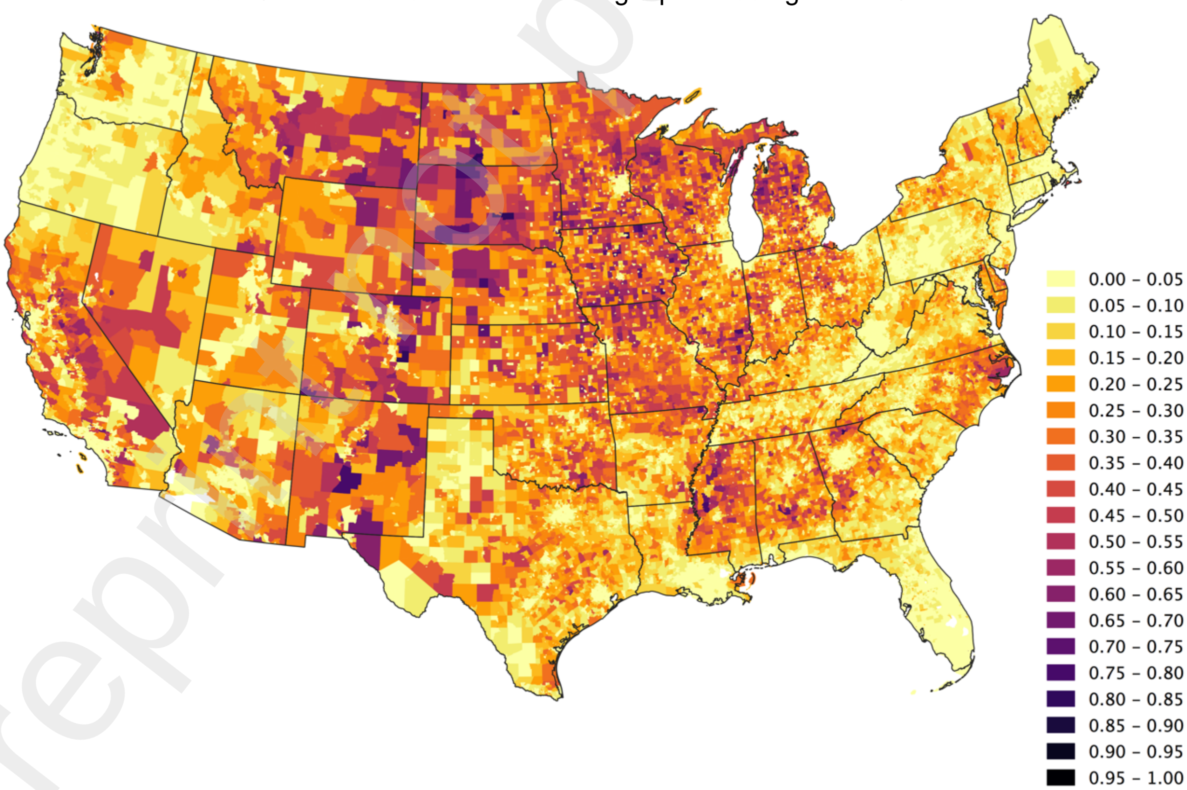

Figure S20 | Fraction of Households Using Propane for Space Heating. Census tracts with white fill have no residential or commercial building square footage in the source data.

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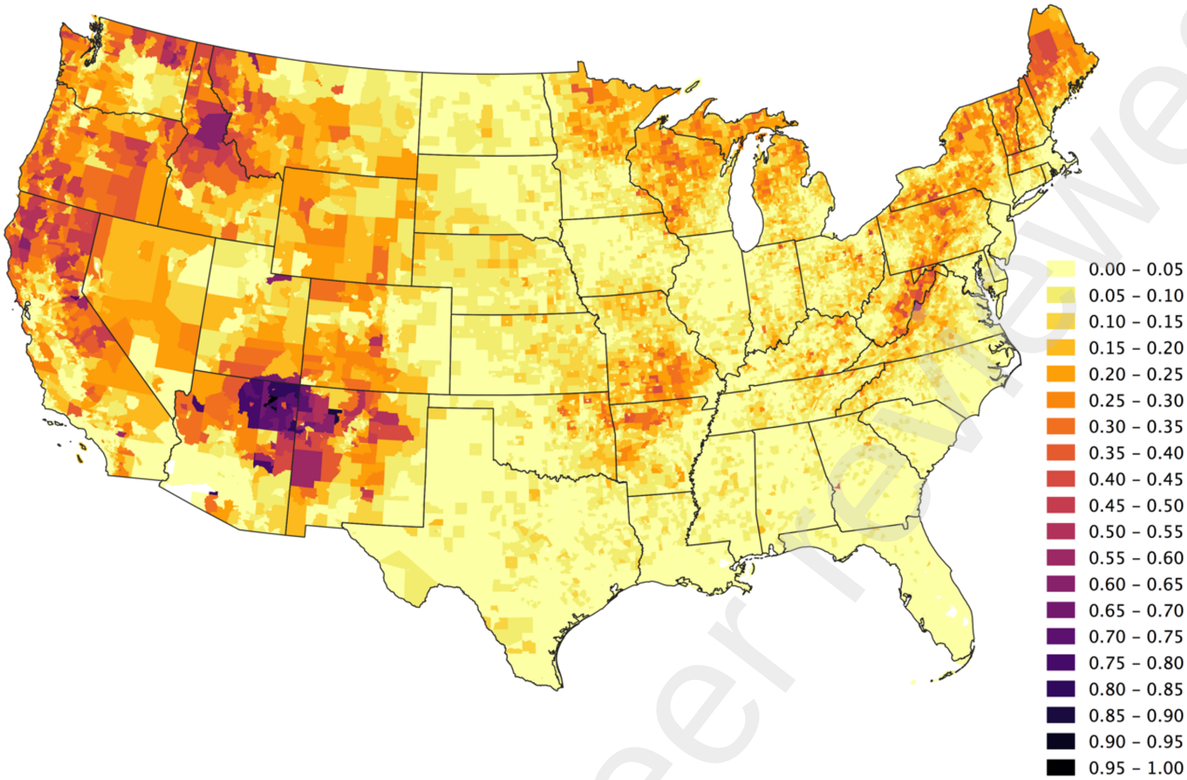

Figure S21 | Fraction of Households Using Other Fuels for Space Heating. Census tracts with white fill have no residential or commercial building square footage in the source data.

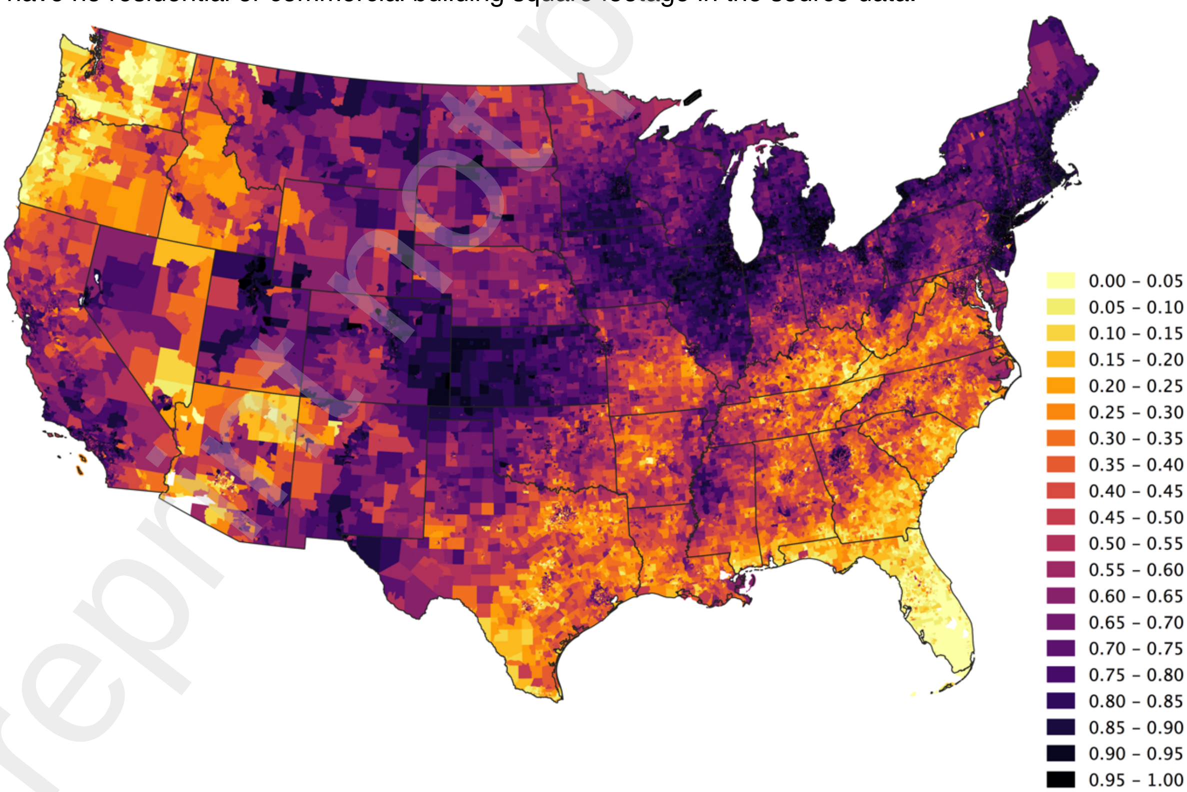

Figure S22 | Fraction of Residential Building Floor Area Currently Heated by Fossil Fuels. Census tracts with white fill have no residential or commercial building square footage in the source data.

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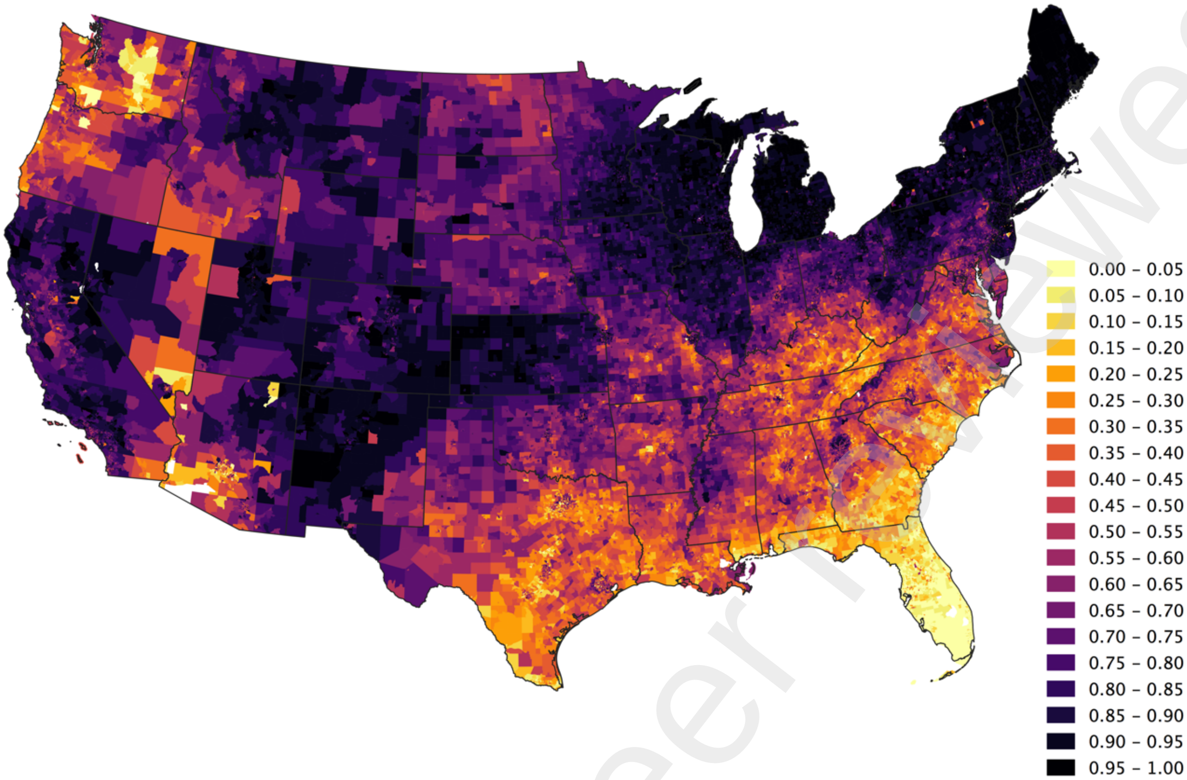

Figure S23 | Fraction of Commercial Building Floor Area Currently Heated by Fossil Fuels. Census tracts with white fill have no residential or commercial building square footage in the source data.

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