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Beyond efficiency: Sufficiency unlocks deep decarbonization of U.S. residential sector

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This PDF file includes:

Main Text
Figures 1 to 6

Abstract

Residential decarbonization strategies in the United States have focused predominantly on energy efficiency measures such as heat pump adoption and building envelope upgrades, while sufficiency—avoiding unnecessary energy demand while ensuring well-being—remains largely unrepresented in quantitative national scenarios. Here, we assess the effects of structural sufficiency (i.e., moderating dwelling size and promoting compact, multi-family housing forms) and behavioral sufficiency (i.e., adopting more conservative, health-informed thermostat setpoints) alongside energy efficiency and electrification using an integrated modeling framework that captures U.S. housing stock turnover and hourly, climate-responsive building energy demand. Under business-as-usual housing trends, residential floorspace expands by 55% from 2020 to 2050, and final energy demand increases by 11%. Relative to this trajectory in 2050, efficiency improvements and structural sufficiency reduce demand by 18% and 31%, respectively. When combined, they can lower demand by 45%. Adopting sufficient comfort setpoints further reduces final energy demand by 31–33% across housing stock scenarios. Our findings highlight that structural and behavioral sufficiency represent substantial untapped mitigation opportunities and should complement efficiency-focused residential energy policies while maintaining household well-being in a warming climate.

Significance Statement

The Intergovernmental Panel on Climate Change identifies sufficiency—avoiding unnecessary energy demand while maintaining well-being—as a major climate mitigation strategy alongside efficiency and renewable energy. Yet sufficiency remains largely absent from quantitative U.S. residential decarbonization scenarios, which focus primarily on technological efficiency improvements. We evaluate how structural changes in housing (e.g., smaller, denser housing) and behavioral practices (e.g., moderate thermostat settings) affect residential energy demand and emissions using a framework that links housing stock turnover with hourly building energy demand. Our results show that combining housing, behavioral, and technological strategies substantially reduces energy use and peak loads. The framework distinguishing “what we build” from “how we use buildings” provides a transferable approach for evaluating residential mitigation pathways globally.

Main Text

Introduction

The U.S. residential sector accounts for approximately 18% of national energy-related CO_2 emissions[1], with space heating and cooling representing roughly half of household energy use[2]. Addressing residential energy demand for space-conditioning is therefore critical to U.S. decarbonization efforts. Choices about housing infrastructure create long-lived lock-ins[3] by fixing dwelling size and built form, constraining the extent to which efficiency measures can reduce energy demand. Over recent decades, U.S. residential floorspace per capita has increased by roughly 56%, rising from about 600 square feet per person in the 1980s to more than 900 square feet today.[4] Public policies have shaped these trends in meaningful ways. As one notable example, the Servicemen’s Readjustment Act of 1944 (also known as the GI Bill)—provided low-interest mortgages that rapidly accelerated suburban expansion.[2] This contributed to a housing stock dominated by single-family homes, which use approximately 30–60% more energy per dwelling than multi-family units[2,5].

Mitigation strategies within the residential sector have largely focused on improving energy efficiency—reducing energy use per unit of service through measures such as improved building envelopes, more efficient equipment, and electrification of end uses—whereas sufficiency avoids unnecessary energy demand while ensuring wellbeing[6–8]. Previous research indicates that sufficiency-oriented strategies, particularly those affecting floor area and housing type, can reduce building-sector energy demand and associated emissions by roughly 20–45% by mid-century in high-income contexts (including the U.S.), in some cases approaching the magnitude of reductions achievable through efficiency measures[6]. Beyond structural sufficiency, residential energy demand is also shaped by indoor temperature setpoints, underscoring the importance of evaluating sufficiency under alternative behavioral assumptions.

Despite its mitigation potential, sufficiency remains inconsistently represented or omitted in national decarbonization scenarios, limiting the availability of evidence needed to inform policy design[9–11]. This underrepresentation reflects, in part, limitations in modeling frameworks, which often rely on aggregated or archetype-based representations that limit their ability to capture heterogeneity in housing structure and household practices relevant to sufficiency. Most integrated assessment models (IAMs) capture only aggregated residential energy use—typically at annual time scales and without explicit representation of building-level heterogeneity—obscuring variation across buildings and households[12,13]. These models also typically rely on degree-day methods that approximate space-conditioning demand using ambient temperature alone, neglecting important weather factors such as humidity, wind speed, and solar irradiance[14]. Beyond IAMs, much of the building efficiency literature assumes a static building stock, overlooking construction, renovation, and retirement processes that shape demand over time[15–17]. (Supplementary Table S1 gives an overview of the literature on U.S. residential decarbonization.)

Here we evaluate how structural and behavioral sufficiency, alongside energy efficiency and electrification (via heat pump adoption), shape future U.S. residential energy demand and emissions, both individually and in combination. To address limitations of existing modeling approaches, we develop an integrated framework that links a dynamic building stock–turnover model (MESSAGEix-Buildings)[18] with a climate-responsive reduced-form building energy model (RC-BEM)[15]. The integrated framework captures heterogeneity in housing stock evolution—including building types and urban form—while simulating hourly thermal demand under future climate trajectories. We conduct simulations for 2020–2050 under Representative Concentration Pathways (RCPs) 4.5 and 8.5 and quantify changes in residential energy demand and greenhouse gas (GHG) emissions under alternative power-sector decarbonization pathways.

This framework enables a comparative assessment of energy efficiency, electrification, structural sufficiency, and behavioral sufficiency, revealing how the effectiveness of building-sector policies depends on housing stock evolution and indoor temperature set points, and how incorporating sufficiency alongside efficiency is essential for achieving deep emissions reductions in the U.S. residential sector. A high-resolution assessment that captures variation in efficiency and sufficiency across space and over time is essential for evaluating portfolios of residential energy policies targeting technologies, buildings, and behavior. Such an approach also helps identify how these strategies can be sequenced to meet climate policy goals.

Policy Scenario Framework

Our scenario framework distinguishes two demand-side levers (Fig. 1). Structural sufficiency and energy efficiency collectively shape "what we build," while setpoint-based behavioral sufficiency governs "how we use buildings." This framing aligns with the IPCC Sixth Assessment Report, which emphasizes infrastructure, technology, and sociocultural practices as key drivers of low-energy demand futures[19,20].

On the "what we build" dimension, structural sufficiency is represented through changes in per-capita floorspace and housing form, reflected in shifts in the relative shares of single-family and multi-family dwellings. Energy efficiency is represented through assumptions about renovation rates and depth, as well as heating electrification via heat pump adoption.

The **Reference** scenario reflects business-as-usual conditions based on recent U.S. housing trends, characterized by per-capita floorspace growth of 10% per decade[2], constant housing type shares (Supplementary Tables S2–S4), and continuation of recent trajectories in renovation activity and heat pump adoption. The **Efficiency** scenario accelerates renovation rates (from 1.5% to 2% per year), assumes greater renovation depth represented by larger efficiency gains, and substantially increases heat pump adoption, while holding floorspace growth and housing form constant. These assumptions represent ambitious but plausible improvements in retrofit activity and electrification relative to recent U.S. trends, rather than maximum feasible rates. The **Sufficiency** scenario stabilizes per-capita floorspace at 2020 levels and modestly shifts the housing stock toward multi-family dwellings, while maintaining Reference efficiency assumptions. This scenario contrasts with recent U.S. trends of increasing floorspace per person and illustrates a structural sufficiency pathway rather than an upper bound on feasible change. The **Combined** scenario integrates the strategies from Efficiency and Sufficiency scenarios. All scenarios use identical state-level population projections from Shared Socioeconomic Pathway 2 (SSP2; "Middle of the Road"; Supplementary Figs. S1-S2), ensuring that differences across scenarios reflect only assumptions about housing stock evolution and energy service provision.

On the "how we use" dimension, scenarios represent contrasting heating and cooling practices through different assumptions about thermostat setpoints, which define different levels of space-conditioning energy service. The **Baseline Comfort** scenario samples empirically observed, state-specific distributions of heating and cooling thermostat setpoints, reflecting how U.S. households currently condition their homes[2]. The **Sufficient Comfort** scenario applies health-informed indoor temperature setpoints based on World Health Organization guidance[21,22] and a 2022 California heat protection law[23], representing a lower-bound standard that maintains wellbeing while reducing energy demand.

We evaluate each combination of "what we build" and "how we use" scenarios and assess the sensitivity of outcomes to alternative climate and power-sector pathways. Climate pathways are represented using **RCP4.5**, a moderate-warming trajectory consistent with approximately 2.5–3 °C of global warming by 2100, and **RCP8.5**, a high-emissions trajectory projecting approximately 4–5 °C of warming under limited mitigation[24–26]. Power-sector pathways are represented using three electricity decarbonization cases from the 2024 Cambium dataset[27] produced by the National Renewable Energy Laboratory (now the National Laboratory of the Rockies): a **Mid-case** pathway with central cost assumptions, a **Fossil-leaning** pathway with higher renewable costs and lower natural gas prices, and a **Renewable-leaning** pathway with lower renewable costs and higher natural gas prices.

Results

1. Residential energy demand can be decoupled from floorspace growth

Under the Reference scenario, floorspace expands by 55%, from 27,200 Mm^2 in 2020 to 42,100 Mm^2 in 2050 (Fig. 2A). This expansion is accompanied by an 11% increase in final residential energy demand, from 4.9 EJ to 5.5 EJ by mid-century (Fig. 2B). Nearly all of this increase is driven by space heating, which grows from 4.0 EJ to 4.6 EJ, while cooling demand changes little because efficiency gains offset higher cooling loads from larger dwellings and a warmer climate.

In the Efficiency scenario, floorspace growth mirrors the Reference case; however, final energy demand declines to approximately 4.5 EJ by 2050 (−18% relative to the 2050 Reference value). This reduction is concentrated in space heating: deeper renovations and higher renovation rates reduce useful thermal demand, while heat pump adoption delivers the same heating service with substantially lower final energy requirements than combustion-based systems.

In contrast, the structural sufficiency scenario limits total floorspace growth to 17% by 2050, reducing final energy demand to approximately 3.8 EJ (−31%). This outcome exceeds the reduction achieved through efficiency improvements alone, highlighting the central role of floorspace in shaping residential energy demand. When efficiency improvements are combined with structural sufficiency, final energy demand declines further to approximately 3.0 EJ (−45%) by mid-century, representing the largest absolute reduction across all scenarios.

Across all scenarios, differences between the RCP4.5 and RCP8.5 climate trajectories result in less than a 2% change in total final energy demand in 2050, indicating that mid-century demand outcomes are robust to climate uncertainty (Supplementary Fig. S3).

2. Residential peak loads decline under warming and housing transformations

Resolving hourly residential energy demand reveals how reductions in total energy use affect peak demand and daily load profiles that are not visible in annual metrics alone (Fig. 3 shows representative winter and summer days). This temporal detail is relevant for understanding interactions with power systems, including renewable integration and peak capacity requirements, although these dynamics are not explicitly modeled here.

In January, residential load exhibits a pronounced diurnal structure with morning and evening heating peaks. In the 2050 Reference scenario, peak hourly load is highest in the Midwest, reaching 224 GW, compared with overnight minima of 110 GW. In the West, lower loads relative to 2020 primarily reflect reduced heating demand under warmer 2050 climate conditions in the weather inputs. Under the Combined scenario, peak winter load declines substantially relative to the 2050 Reference case across regions, by roughly 35–40%, with reductions approaching ~80–90 GW in colder regions, while the timing of daily peaks remains largely unchanged.

In July, residential load shifts to afternoon cooling peaks and is much lower in absolute magnitude than in winter, with peak hourly loads reaching ~45 GW in the South and West, compared with winter peaks exceeding 200 GW in cold-climate regions. Under the Combined scenario, peak summer load reductions are more modest at approximately 25%, corresponding to absolute reductions of ~4–11 GW depending on region, with the largest reductions occurring in the South. In this region, improvements in building efficiency and cooling technologies offset warmer climate conditions, resulting in lower cooling loads despite rising temperatures. The timing of afternoon cooling peaks remains unchanged.

Together, these results demonstrate a strong seasonal asymmetry. Winter loads in 2050 are generally lower than in 2020 due to warmer climate conditions reducing heating demand, whereas summer loads are similar or slightly higher as cooling demand increases. Further reductions in the Combined scenario arise from housing and technology changes that lower overall demand levels without substantially altering the diurnal structure of residential load.

3. Behavioral sufficiency yields substantial additional reductions in energy demand

Thermostat setpoints directly determine the level of space-heating and cooling services delivered and therefore represent a key behavioral driver of residential energy demand. According to 2020 Residential Energy Consumption Survey (RECS) data, prevailing thermostat practices in the U.S. result in energy use well beyond levels required to meet health-based comfort guidance. The national median setpoints are 21.1°C and 22.2°C for heating and cooling, respectively (Fig. 4A); fewer than 10% of homes use heating setpoints below 18 °C or cooling setpoints above 26 °C. These distributions define the Baseline Comfort assumption in our model.

By 2050, adopting Sufficient Comfort, which assumes household heating and cooling setpoints aligned with health-based temperature thresholds, reduces final residential energy demand by 31 – 33% (1.6 – 1.8 EJ) relative to Baseline Comfort across housing stock scenarios (Fig. 4B). The magnitude of this reduction is comparable to that achieved through structural sufficiency alone under Baseline Comfort.

4. Housing improvements narrow geographic variation in sufficient-comfort savings

We disaggregate state-level energy savings from adopting Sufficient Comfort setpoints to assess geographic variation and distributional impacts (Fig. 5). Across all U.S. states, adopting Sufficient Comfort reduces final energy demand, with absolute savings dominated by population size. Under the Reference scenario, the median state reduces energy use by 33 PJ/year (IQR: 16–66), with the largest contributions from highly populous states such as California and Texas (Fig. 5A). In the Combined scenario, absolute savings fall to a median of 21 PJ/year (IQR: 11–44) due to lower baseline demand, while the interquartile range narrows relative to the Reference case.

Expressed on a per-capita basis, energy savings from Sufficient Comfort are largest in colder regions of the U.S., particularly across the Midwest and northern states (Fig. 5B). Under the Reference scenario, per-person savings reach up to 6.1 GJ/person-yr, with a national median of 4.6 GJ/person-yr (IQR: 4.0–5.2). These patterns reflect the dominance of space-heating demand in colder climates, where heating loads are both larger and more energy-intensive than cooling, making energy use more responsive to heating setpoints. In the Combined scenario, both the magnitude and the spread of per-capita savings are reduced, lowering the national median to 2.9 GJ/person-yr (2.7–3.2) and substantially narrowing geographic variation across states.

5. Deep residential decarbonization hinges on both housing and grid transformations

National primary energy demand in 2050 exhibits strong seasonal variation, with January representing the maximum month across all housing stock scenarios (Fig. 6A). Structural sufficiency and efficiency reduce demand across all months, with the largest absolute reductions occurring in winter. Under Baseline Comfort, structural sufficiency lowers the January peak by 24% relative to the Reference case, while combining efficiency and structural sufficiency reduces the peak by 32% (from 1,281 to 878 PJ). Adopting Sufficient Comfort further reduces the January peak by 24% in both the Reference and Combined scenarios (to 974 and 667 PJ, respectively).

These reductions in primary energy demand correspond to substantial declines in residential GHG emissions across housing stock and grid scenarios (Fig. 6B). Emissions fall rapidly through 2030 as space-heating electrification expands and the electricity sector decarbonizes, declining from 328 $MtCO_2e$ in 2020 to 250 $MtCO_2e$ (−24%) in the Reference scenario and 211 $MtCO_2e$ (−36%) in the Combined scenario under Baseline Comfort.

After 2030, emissions trajectories increasingly reflect electricity-sector assumptions. By 2050, emissions range from 203–231 $MtCO_2e$ in the Reference scenario to 108–133 $MtCO_2e$ in the Combined scenario, depending on grid pathway. Fossil-leaning grids yield persistently higher emissions, while renewable-leaning pathways produce lower outcomes, introducing a 22–33 $MtCO_2e$ (10–25%) spread within each housing stock scenario. Even the Combined scenario approaches but does not fully achieve the deep decarbonization benchmark[28,29], suggesting that additional mitigation measures, including faster electrification or carbon removal, may be required to reach comparable targets. Shifting from Baseline to Sufficient Comfort further reduces 2050 emissions by 23–33%, bringing outcomes closer to the deep decarbonization benchmark but not fully achieving it.

Discussion

This study presents an integrated U.S. assessment of residential decarbonization pathways, jointly examining structural sufficiency and energy efficiency in the built environment ("what we build") alongside behavioral sufficiency in household operation ("how we use"). By linking a state-level housing stock turnover model with a climate-responsive building energy model, we capture geographic and climatic variation that national assessments often obscure while resolving residential energy demand at hourly temporal scales. This integrated framework connects long-lived housing infrastructure decisions with future residential energy demand and emissions trajectories, allowing us to evaluate the role of sufficiency-based interventions within a broader portfolio of mitigation strategies.

Our results underscore the long-term consequences of today's housing decisions for avoiding infrastructural lock-in. Our Reference scenario mirrors historic patterns: since the 1970s, average single-family home size has grown by over 20% while household size has declined, resulting in roughly a 40% increase in floorspace per person[2,30]. Although growth was most rapid in earlier decades and has slowed in recent years, the long-term trajectory still reflects increasing floorspace per capita. If these patterns persist, the resulting structural lock-in could erode efficiency gains and make achieving climate policy goals, including net-zero emissions by mid-century, more difficult. Even the most ambitious combination modeled here, integrating efficiency, structural sufficiency, sufficient comfort, and a low-carbon grid, comes close to but does not fully achieve deep decarbonization benchmarks. This remaining gap suggests that housing and demand-side transformations alone may be insufficient, highlighting the potential need for additional measures such as faster electrification, deeper electricity-sector decarbonization, or carbon removal.

While our modeling framework advances understanding of the role of sufficiency in building energy policy, it also has limitations. First, our model parameters for new construction, renovation, and retirement are specified exogenously. This prevents life-cycle processes at the household level—such as decisions to renovate versus rebuild or the timing of retirements—from emerging endogenously, and limits insight into how affordability or market dynamics shape stock turnover. Second, we restrict attention to space heating and cooling. While these loads dominate climate-sensitive demand, omitting other end uses understates the residential sector's total footprint and constrains comparability with whole-sector assessments. Third, household income distributions and affordability constraints are not represented, precluding explicit analysis of equity, energy insecurity, or heterogeneous adoption pathways. Fourth, occupant behavior is represented through fixed thermostat setpoint regimes rather than dynamic responses to energy prices, technologies, or extreme events, meaning behavioral conclusions should be interpreted as bounding cases rather than forecasts.

Future work can address these gaps by embedding endogenous household and market decision-making into our integrated stock turnover and building energy modelling framework, extending coverage to all household energy demand and incorporating socioeconomic heterogeneity. Coupling behavioral models of adaptive comfort management with physical energy demand would further capture real-world feedbacks. Together, these steps would enable a more comprehensive, policy-relevant assessment of how residential transformation interacts with equity, affordability, and resilience in the U.S. energy transition. These types of insights will be important for designing responsive policies, including targeted incentive and investment programs that reflect different thermal comfort needs of households (especially vulnerable groups) and address systemic barriers to achieving energy sufficiency.

Translating modeled pathways into practice depends heavily on local context and governance structures. In some states, building codes are set at the state level, which can limit municipal ambition, as in 24 states where local governments are barred from exceeding state standards[31]. Elsewhere, cities have greater autonomy but face zoning restrictions that constrain denser urban form[32,33]. Financial incentives for retrofits and electrification can help overcome these barriers, and recent political efforts to weaken or reverse them in the U.S. threaten long-term decarbonization efforts[34,35]. Because housing form and dwelling size are shaped by long-term planning and regulatory decisions that constrain individual consumer choice, advancing structural sufficiency requires reform through zoning, building codes, and coordinated housing supply policies. Examples include zoning reforms that allow greater housing density or smaller dwelling units in traditionally single-family neighborhoods[36], along with incentive programs[37] that encourage multi-family development and compact urban form.

Ambitious housing transformation is essential for aligning U.S. climate change mitigation goals with equitable access to thermal comfort in a changing climate. Upgrading building infrastructure can reduce energy demand and flatten seasonal energy peaks, simultaneously easing strain on the grid and addressing infrastructure barriers to electrification in underserved households.[38,39] While there are opportunities for sufficiency to reduce energy demand in aggregate, many U.S. households report difficulty meeting their energy needs—and supportive policies for households may increase their energy use.[40] As these challenges evolve, policymakers must prioritize designs and practices that ensure safe, efficient, and comfortable housing for all—moving beyond energy demand to measure success by equity and well-being. Integrating sufficiency-oriented practices into codes, incentives, and planning frameworks is key for achieving deep decarbonization with fairness and adaptability across communities.

Materials and Methods

1. Stock Turnover Model

We use the Stock TURnover Model (STURM), a module of the MESSAGEix-Buildings framework, to project the evolution of the U.S. residential building stock. STURM tracks annual new construction, renovation, and demolition, capturing changes in floorspace, vintage composition, and energy efficiency at regional and national levels. Key parameters—new construction, renovation, and retirement rates—are set exogenously, using parametric variations chosen to span plausible but distinct trajectories (“what we build” in Fig. 1 for scenario-specific assumptions).

Household size and urban–rural shares are initialized using the 2020 Residential Energy Consumption Survey (RECS) and assumed to be constant for all future years. State-level population projections follow the U.S. version for the Global Change Analysis Model (GCAM-USA) under SSP2, which assumes moderate population growth, urbanization, and income with no extreme challenges to mitigation or adaptation. Simulations are conducted at five-year intervals from 2020 through 2050.

2. Reduced-Complexity Building Energy Model

We use the Reduced-Complexity Building Energy Model (RC-BEM) to estimate hourly heating and cooling demand in U.S. single-family homes under different climates and comfort conditions.[15] A detailed description of the RC-BEM model structure and validation is provided in Nawawi et al. RC-BEM is trained on EnergyPlus simulations generated for 54 representative U.S. cities, spanning 16 climate zones and 24 states. To capture building heterogeneity, we use ResStock, a building stock analysis platform developed by the U.S. National Renewable Energy Laboratory (NREL), which synthesizes realistic building prototypes by sampling across distributions of floor area, construction vintage, insulation levels, and HVAC system efficiencies. This procedure yields a sampling pool of ~17,000 unique single-family homes, which forms the basis for scaling results to the national level through integration with STURM building stock projections.

EnergyPlus outputs are converted to heating and cooling demand by accounting for HVAC performance (i.e., annual fuel utilization efficiency for furnaces and coefficient of performance for heat pumps). RC-BEM is trained using simulations driven by Typical Meteorological Year (TMY3) weather files. For the scenario analyses, however, the model is applied to Thermodynamic Global Warming (TGW)[41] climate datasets, which preserve local weather variability while incorporating climate change signals from global models. Indoor temperature states are included as independent predictors in the RC-BEM, and the EnergyPlus training dataset spans a wide range of indoor temperature conditions, allowing the model to represent the alternative setpoints used in the behavioral sufficiency scenarios. Multivariate regression with lasso regularization is applied to prevent overfitting. Once trained, RC-BEM produces hourly demand profiles for each prototype across years (2020–2050) and climate scenarios (RCP4.5, RCP8.5). These hourly profiles are subsequently aggregated to annual totals and scaled to the national level using STURM-projected floor areas.

3. Proxies for Missing Efficiency Classes and Multi-family Homes

RC-BEM represents residential energy performance using nine efficiency classes (s1–s9), which correspond to building construction decades, from pre-1940 stock (s1) through 2010s construction (s9). STURM stock projections include additional classes not directly simulated in RC-BEM (such as new construction or renovation-derived classes). To close these gaps, we applied parametric proxy rules derived from RECS median site energy intensity values by construction decade. For example, s1 is represented by s2 adjusted to be 10.4% more energy intensive, and s9 is represented by s8 adjusted to be 7.1% less intensive.[2] Renovation-derived classes are proxied from their parent vintage, with efficiency improvements of 30% (standard) or 60% (low).

Multi-family homes, which are not directly simulated in RC-BEM, are represented using single-family intensity proxies scaled to multi-family floorspace from STURM. When no direct pool was available, we used energy intensity values from similar buildings in the same climate zone, or, if still unavailable, from national averages. This ensures complete coverage of all residential floorspace in STURM.

4. Model Integration and Validation

To integrate the stock turnover and building energy models, we combine STURM stock projections with RC-BEM intensity estimates in a post-processing framework. For each scenario, STURM provides floor area by region, climate zone, and building vintage, which is matched with RC-BEM heating and cooling intensities (kWh/m²). Total demand is obtained by multiplying intensity by floor area and then aggregating across vintages, zones, and regions.

Where prototype pools were incomplete, we applied a hierarchical fallback procedure: donor intensities were drawn first from the same city, then from the climate zone, and finally from the national average. Monthly demand was distributed using donor shares from the best-available pool. The integrated energy outputs include regional and national totals, per-square-meter intensities, and monthly demand profiles.

Base-year validation compares modeled housing stock and energy demand against observed statistics. Modeled housing units (129.75 million) closely match 2020 U.S. Census housing counts (~126.8 million occupied units). Simulated heating and cooling energy use is calibrated to national residential end-use consumption reported by the U.S. Energy Information Administration (Supplementary Table S5).

5. Final Energy Demand

We compute site energy demand for heating and cooling by processing the integrated outputs into monthly and annual metrics. Model outputs of "useful" (delivered) energy from RC-BEM are converted to final energy using end-use-specific efficiencies. For heating, we assume 90% efficiency for gas furnaces. For cooling, we apply a year-dependent coefficient of performance (COP), reflecting federal standards and projected improvements (e.g., COP = 3.2 in 2020, rising to 4.4 in 2050).

To ensure consistency with historical statistics, modeled site demand in 2020 is calibrated to the Residential Energy Consumption Survey (RECS 2020). National totals reported in RECS Table CE3.1 are 4,026 trillion Btu (4.25 EJ) for space heating and 866 trillion Btu (0.91 EJ) for space cooling (Supplementary Table S4). Note that we did not include Hawaii and Alaska in our analyses. Calibration factors are computed as the ratio of observed to modeled demand by Census region and end use and applied across all scenario years. This adjustment anchors the model to empirical benchmarks while preserving relative scenario differences.

6. Primary Energy Demand and Emissions

We translate site energy demand into primary energy by applying region- and year-specific primary energy factors (PEFs) for electricity, derived from NREL's Cambium dataset. For 2020 (historical baseline), we use averages from the 2010s: Northeast 2.63, Midwest 2.92, South 2.62, and West 2.37. For 2050, we use business-as-usual projections: Northeast 2.32, Midwest 2.32, South 2.33, and West 2.17. Non-electric fuels (e.g., natural gas, propane) are assigned a PEF of 1, treating site energy as equal to primary energy.

Each site energy flow is multiplied by its PEF, yielding monthly primary energy demand in exajoules (EJ). Aggregation across fuels and end uses produces regional and national totals. We also compute peak-to-average ratios of monthly demand to characterize temporal demand profiles.

We estimated national CO_2e emissions from the residential sector by combining projected site energy demand with fuel- and grid-specific emission factors. Results are reported as the sum of direct and indirect emissions.

Direct emissions arise from on-site combustion of fossil fuels (e.g., natural gas, fuel oil, propane). State-level residential demand for these fuels was taken from the STURM–ResStock framework for each scenario (Reference, Efficiency, Structural Sufficiency, and Combined) and comfort assumption (Baseline vs. Sufficient). We applied EPA's emission factors for CO_2, CH_4, and N_2O (converted to CO_2e using 100-year global warming potentials) to compute fuel-specific emissions, which were then aggregated nationally.

Indirect emissions reflect the carbon intensity of electricity supplied to households. For 2020, we used historical average emission rates from EPA's eGRID dataset. For 2025–2050, we applied average emission rates from NREL's Cambium dataset, which provides scenario-specific projections under alternative renewable cost and natural gas price assumptions. Three grid pathways were used: HighRECost_LowNGPrice, MidCase, and LowRECost_HighNGPrice. Residential electricity demand by state, scenario, and behavior was multiplied by the corresponding Cambium emission rates and aggregated nationally.

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Figures and Tables

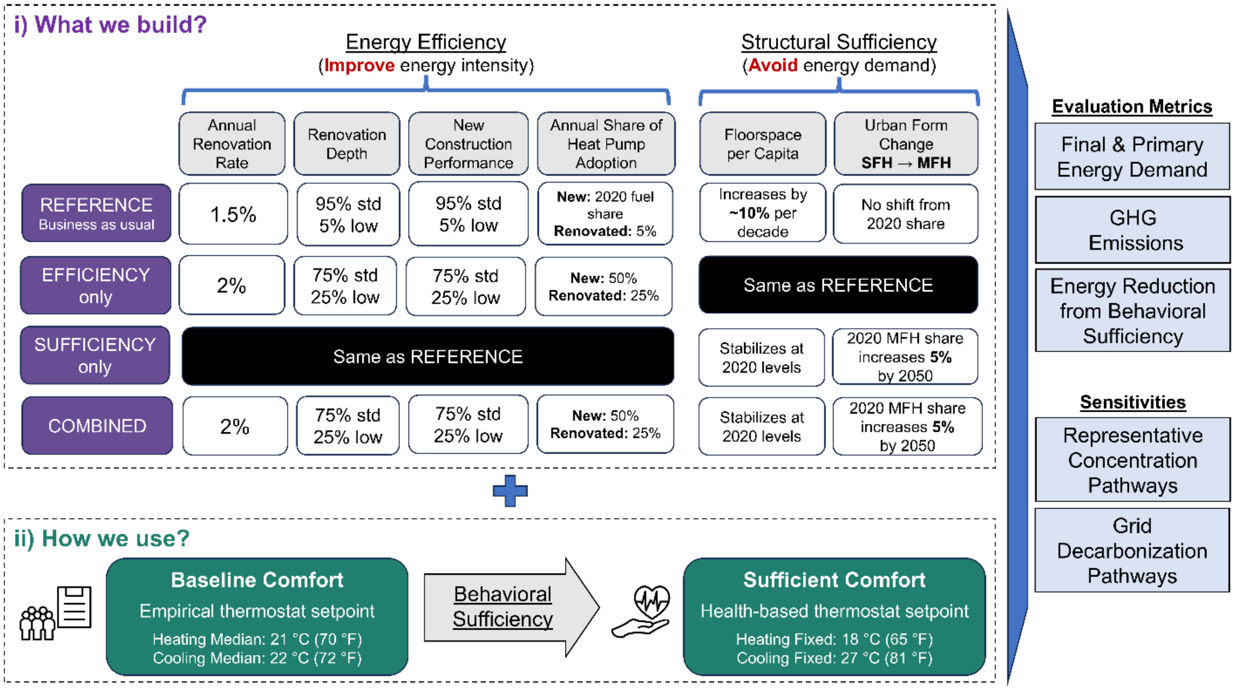

Figure 1. Scenario framework for the U.S. residential sector.
Scenarios distinguish between what we build—represented by Reference, Efficiency, Sufficiency, and Combined housing stock pathways—and how we use, represented by thermostat setpoint assumptions spanning Baseline Comfort and Sufficient Comfort. Outcomes are evaluated for residential energy demand and greenhouse gas (GHG) emissions, with sensitivities to Representative Concentration Pathways (RCPs) and electricity-sector decarbonization pathways.

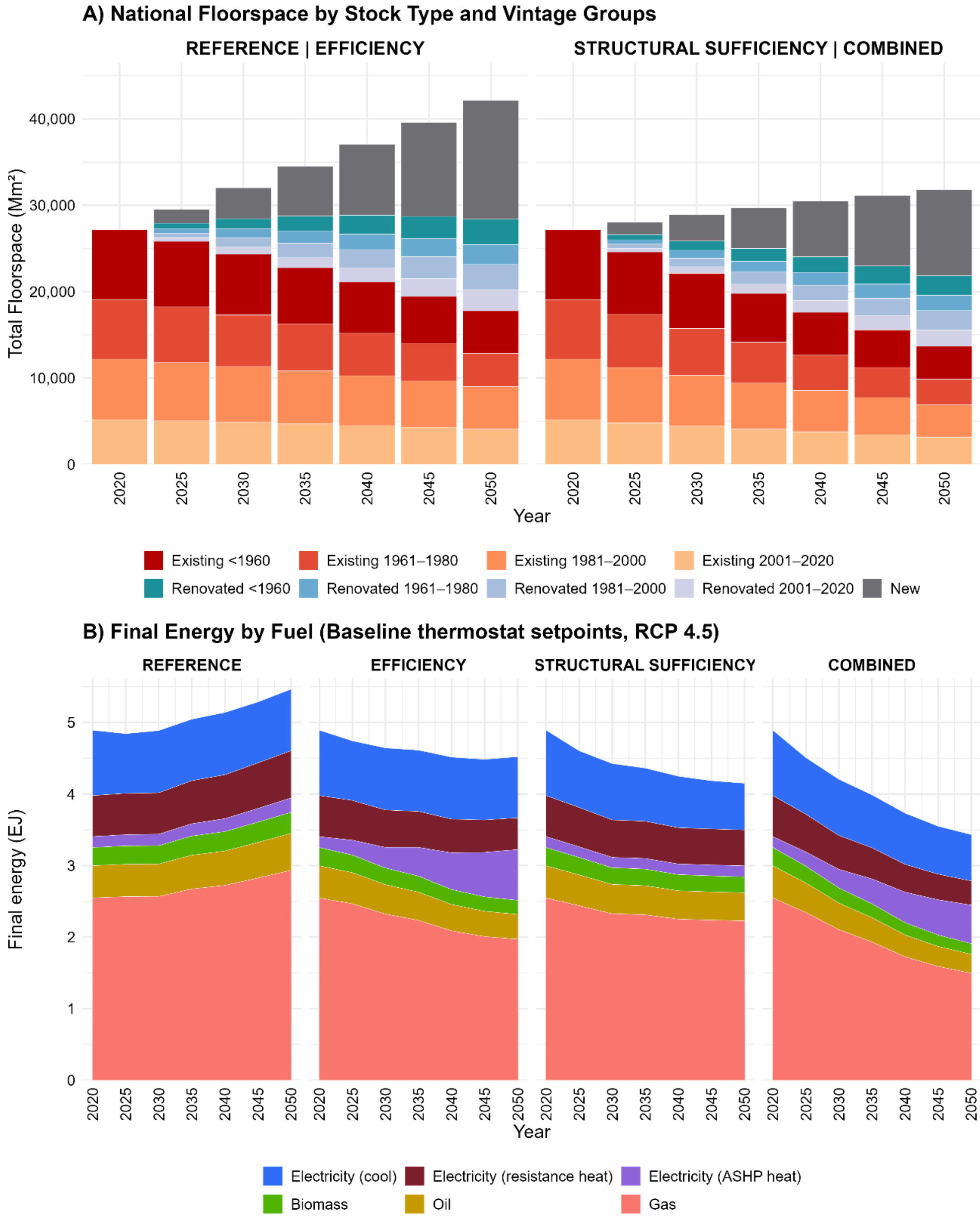

Figure 2. U.S. residential floorspace and final energy across housing stock pathways. (A) National residential floorspace through 2050 by building cohort (existing, renovated, and new construction). (B) Final energy demand by fuel under the same pathways, assuming Baseline Comfort thermostat setpoints and RCP4.5.

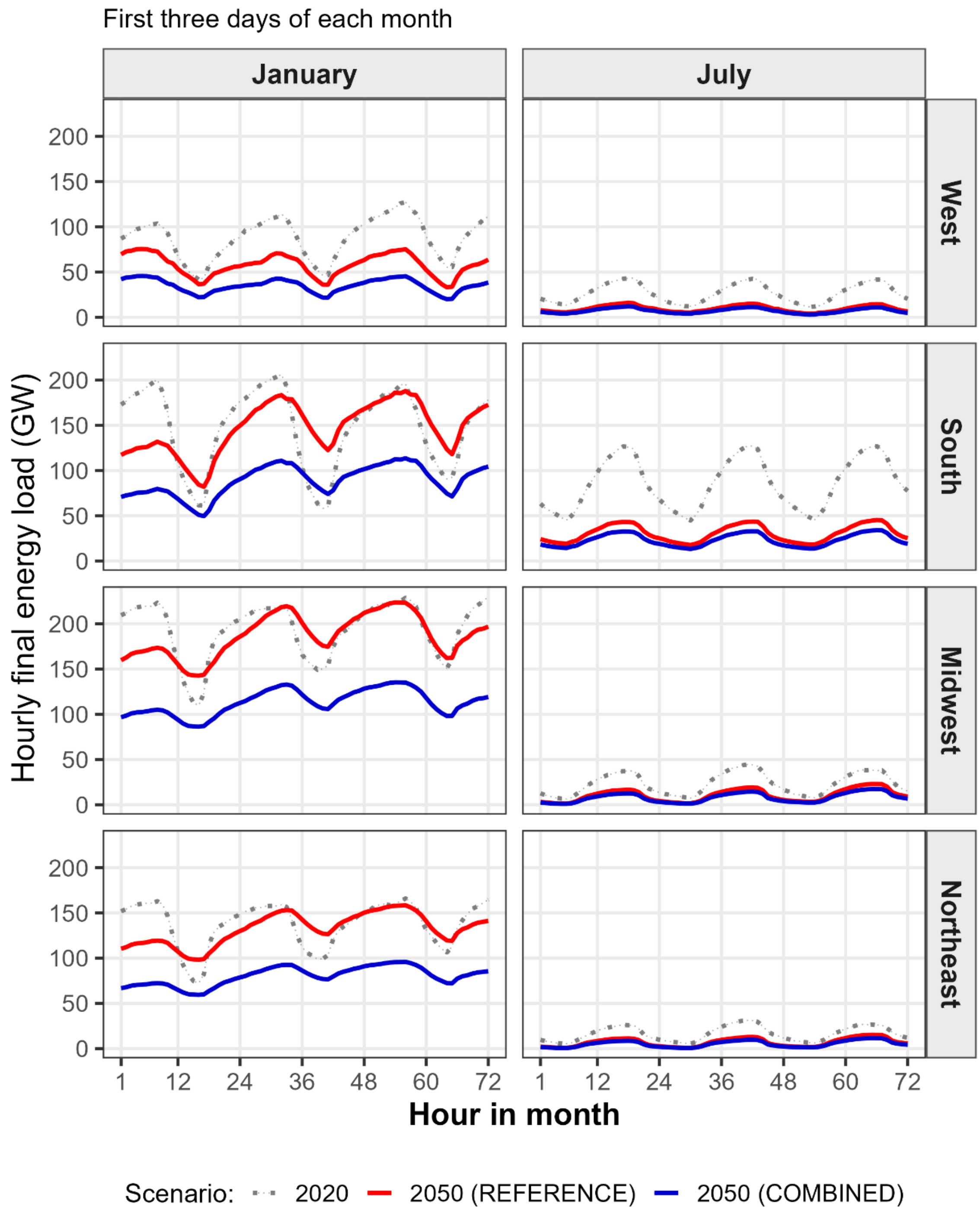

Figure 3. Hourly residential energy load by Census regions.
Hourly final energy load during the first three days of January and July, shown as illustrative winter and summer periods across U.S. Census regions, comparing 2020 baseline conditions with 2050 Reference and Combined scenarios. Results assume Baseline Comfort thermostat setpoints and RCP4.5 climate conditions.

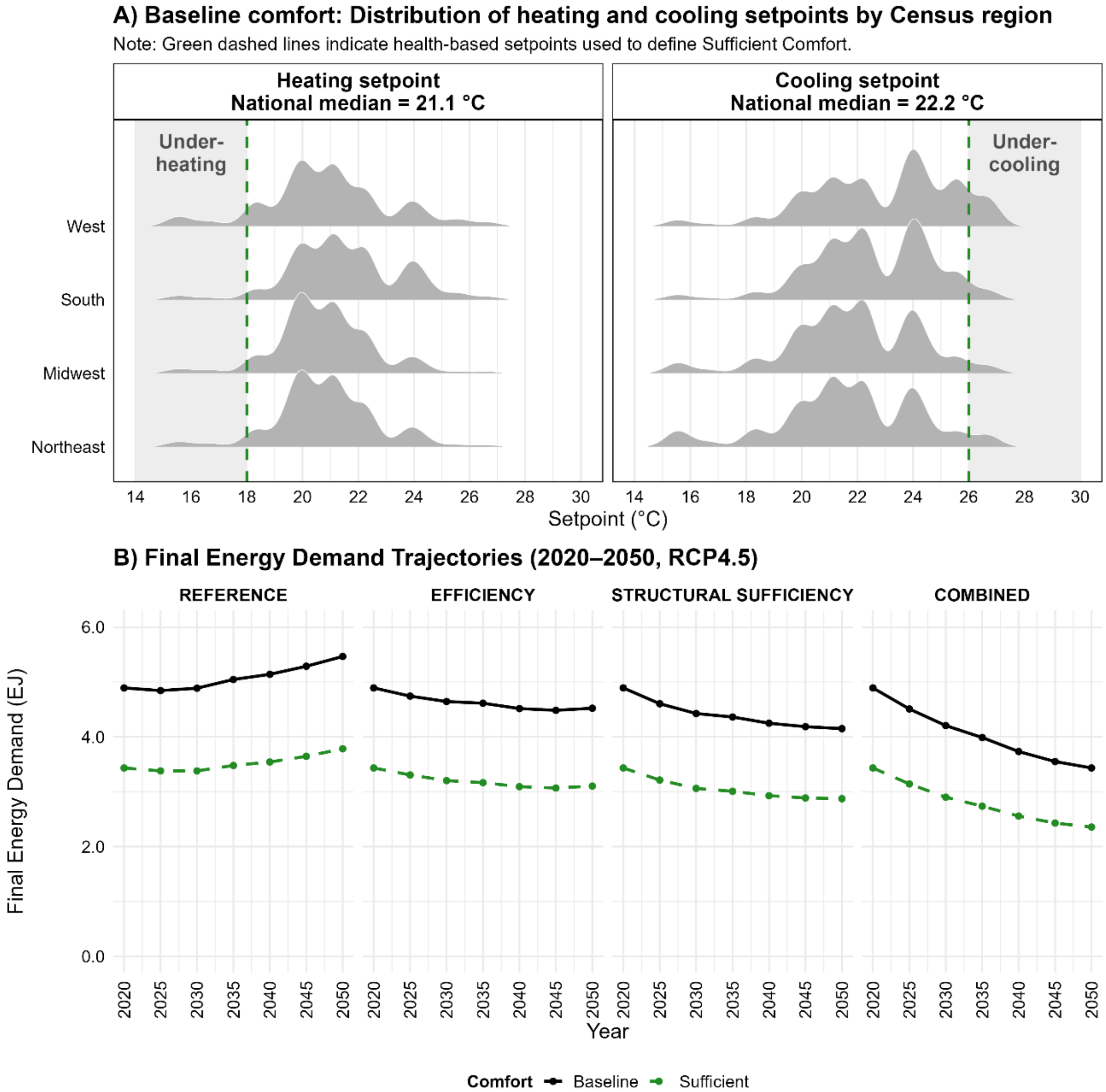

Figure 4. Impact of thermostat setpoints on U.S. residential final energy demand. (A) Distribution of heating and cooling thermostat setpoints by U.S. Census region under Baseline Comfort; dashed lines indicate health-based thermostat setpoints used to define Sufficient Comfort. (B) National final energy demand trajectories from 2020 to 2050 under Baseline Comfort and Sufficient Comfort across housing stock pathways, assuming RCP4.5.

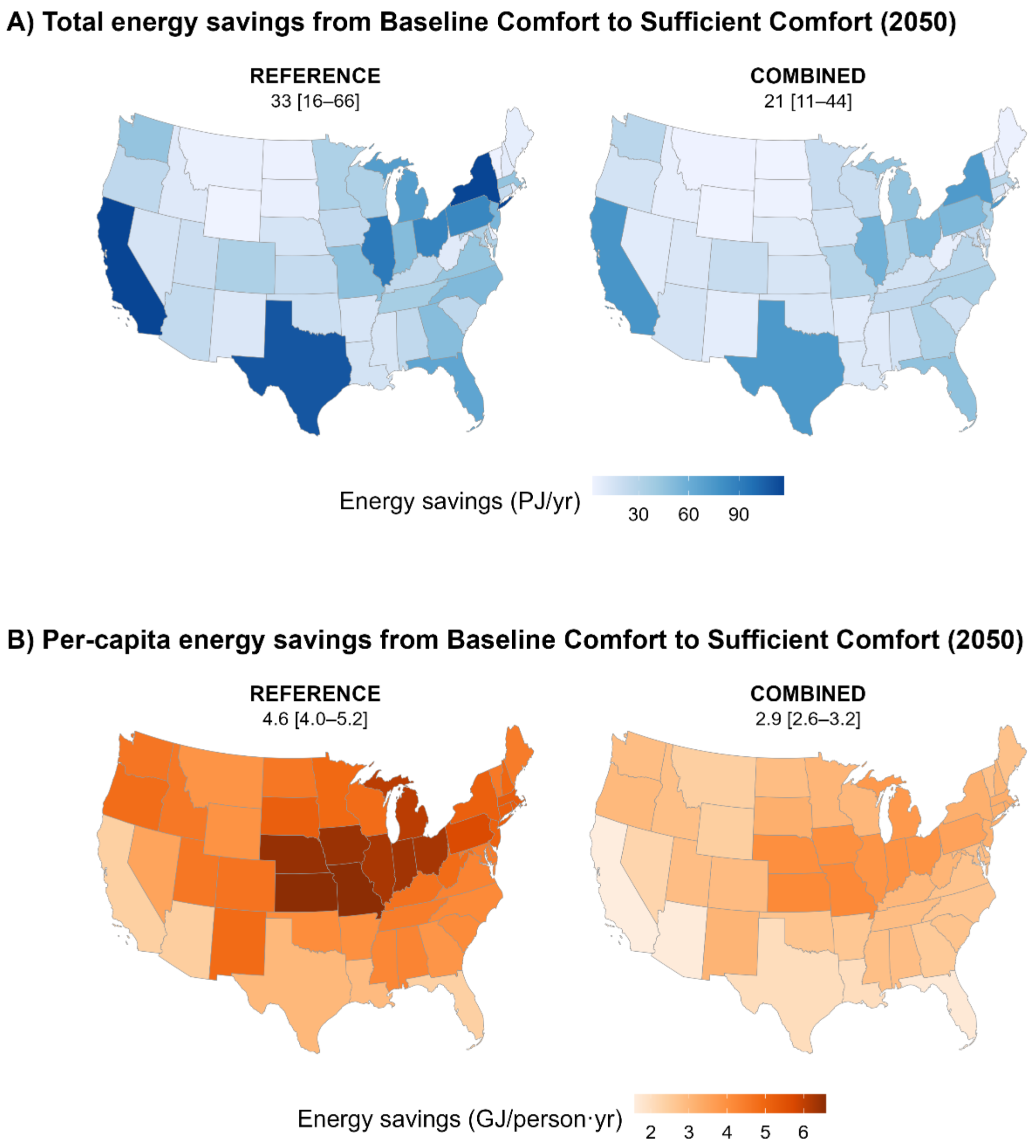

Figure 5. State-level final energy savings from Baseline to Sufficient Comfort in 2050. (A) Absolute annual residential final energy savings by state under the Reference and Combined housing stock pathways. (B) Corresponding per-capita energy savings. Color indicates savings magnitude relative to Baseline comfort; national values above each map indicate the median [IQR] across states.

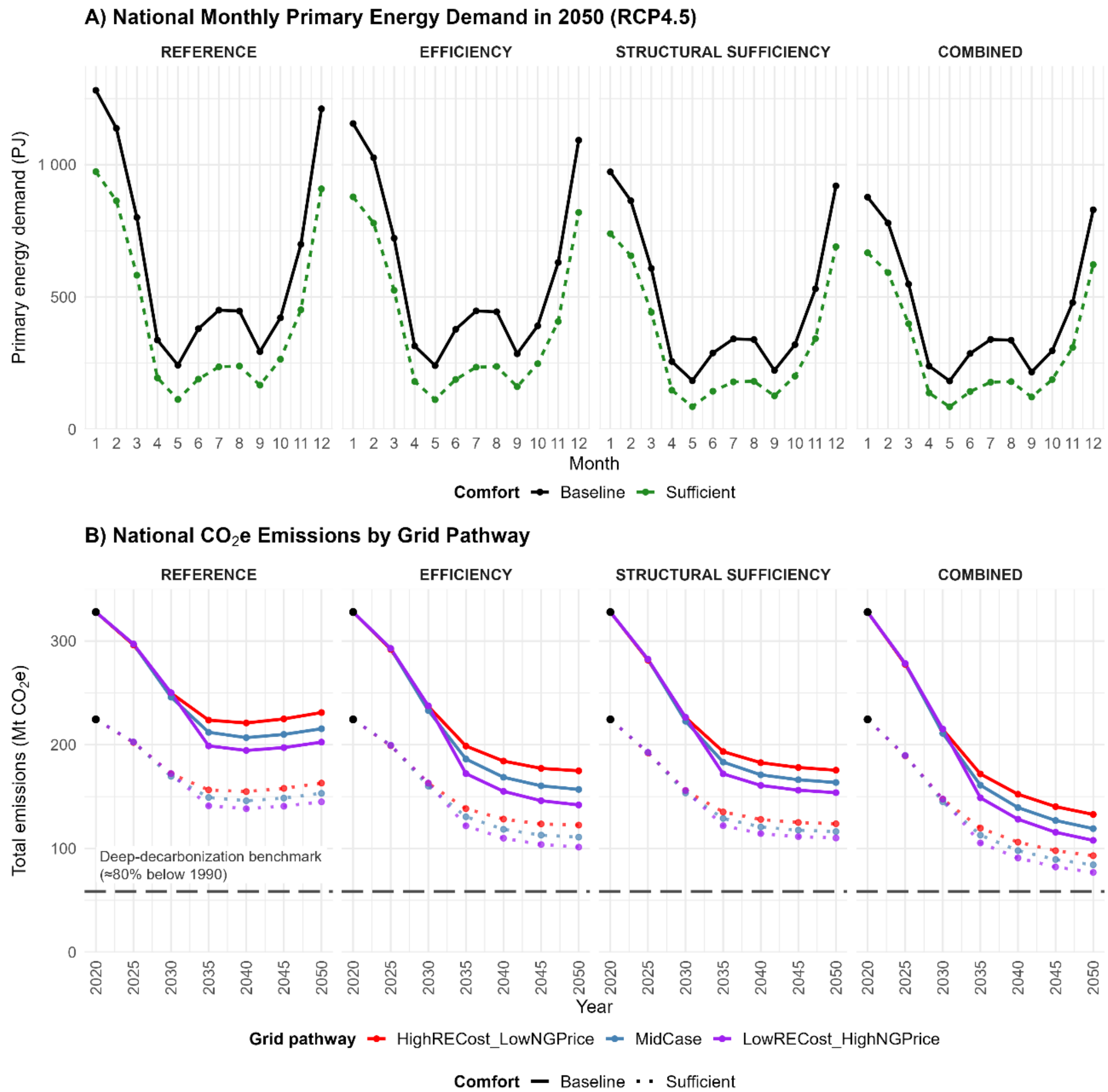

Figure 6. National primary energy demand and emissions
(A) Monthly national primary energy demand in 2050 under Baseline and Sufficient Comfort across housing stock pathways, assuming RCP4.5. (B) Annual residential CO_2e emissions (Scope 1 + 2) under alternative housing stock pathways (facets) and electricity-sector decarbonization pathways (colors), comparing Baseline and Sufficient Comfort thermostat setpoints (line types), assuming RCP4.5. The dashed gray line indicates an illustrative deep-decarbonization benchmark corresponding to an ≈80% reduction in emissions relative to 1990 levels, consistent with Deep Decarbonization Pathways Project targets.

Supporting Information for
Beyond efficiency: Sufficiency unlocks deep decarbonization of U.S. residential sector

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This PDF file includes:

Figures S1 to S3
Tables S1 to S5
SI References

Figures

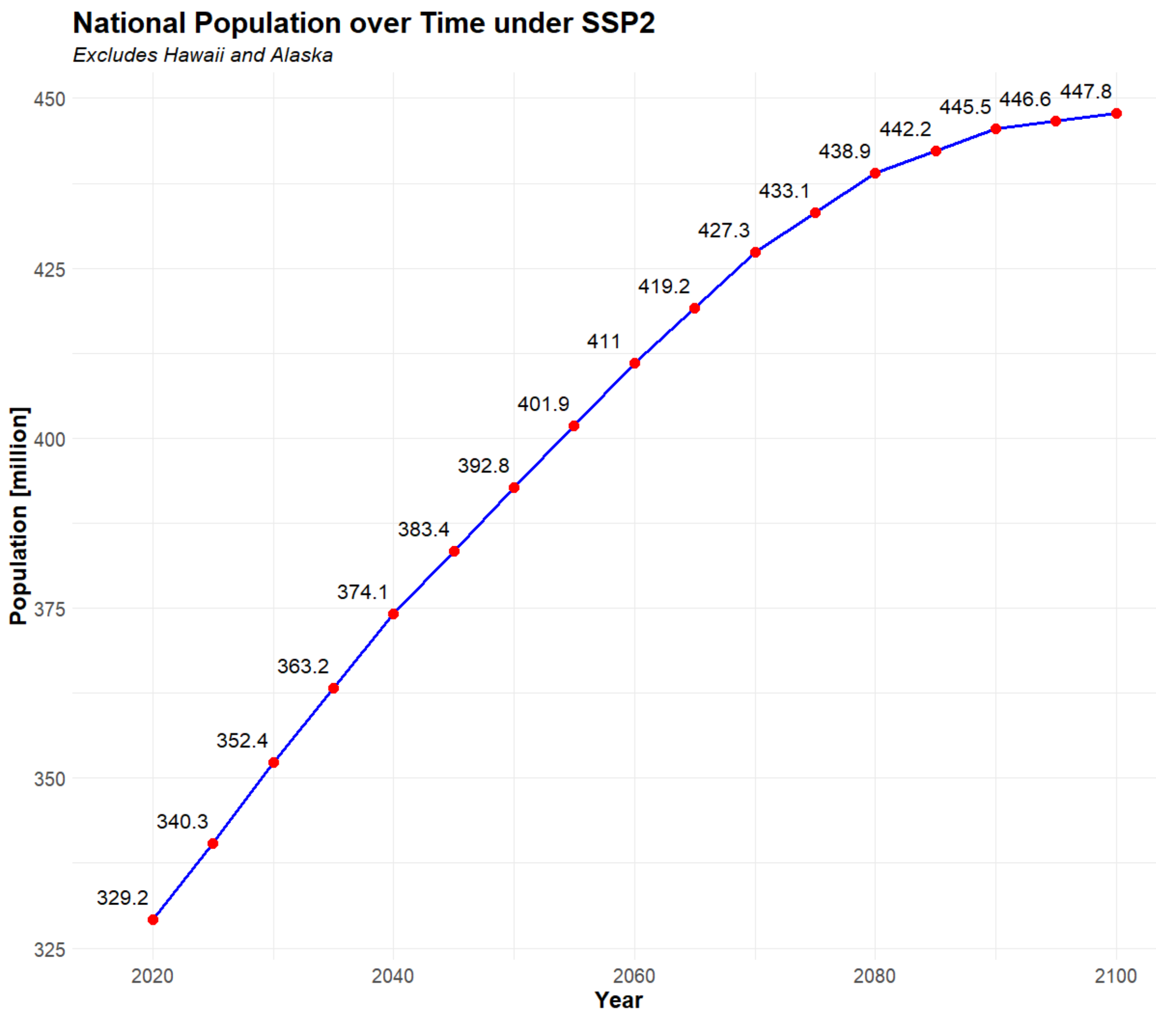

Fig. S1. National population trajectory under SSP2.

U.S. population projections from 2020 to 2100 under Shared Socioeconomic Pathway 2 ("Middle of the Road"), excluding Hawaii and Alaska. This population trajectory is applied uniformly across all policy scenarios. Source: GCAM-USA **[1], [2]**

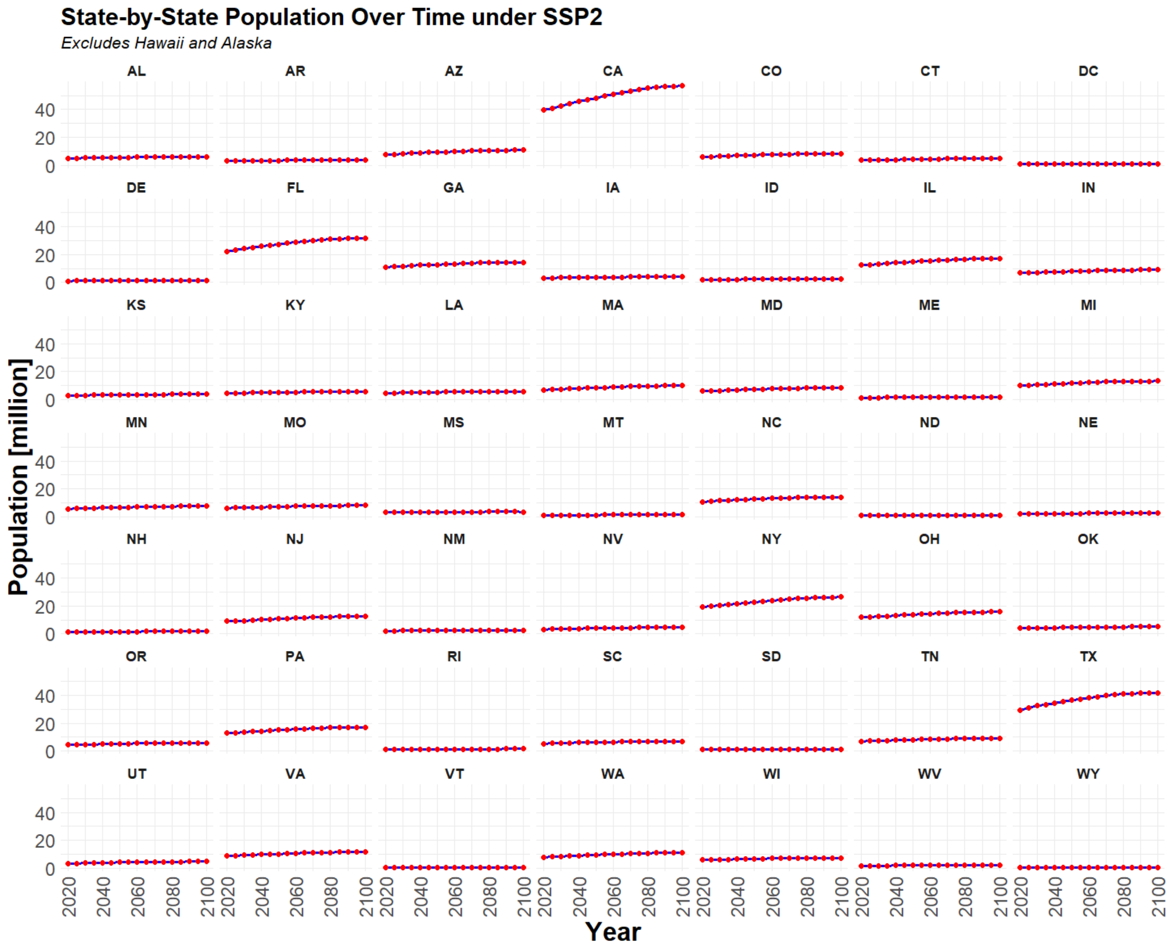

Fig. S2. State-level population trajectories under SSP2.

State-by-state population projections from 2020 to 2100 under Shared Socioeconomic Pathway 2, excluding Hawaii and Alaska. State-level population trajectories are held constant across all policy scenarios to isolate the effects of housing structure, energy efficiency, and comfort assumptions on residential energy demand and emissions. Source: GCAM-USA **[1], [2]**

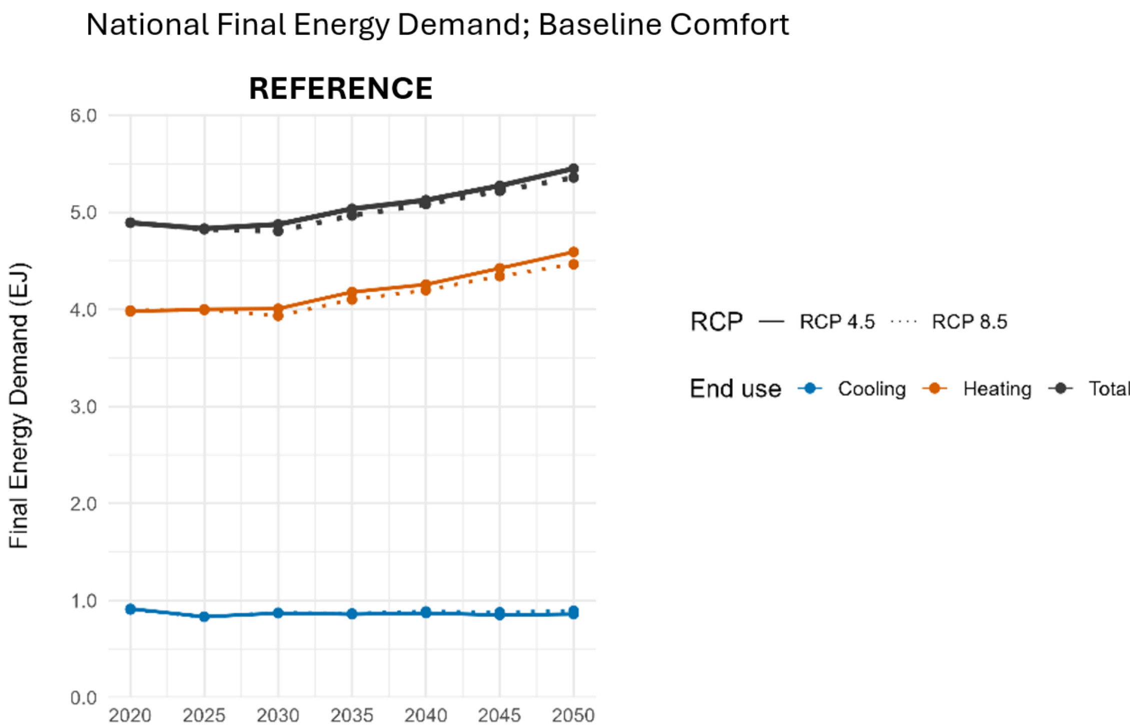

Fig. S3. Sensitivity of national final residential energy demand to climate pathways.
Final residential energy demand for heating, cooling, and total use under RCP4.5 and RCP8.5 using Baseline Comfort assumptions. The Reference scenario is shown as a representative case to illustrate that differences in climate pathways produce relatively small changes in mid-century energy demand compared with differences across policy scenarios.

Tables

Table S1. Comparison of key literatures focusing on U.S. nationwide residential decarbonization.

	Energy Efficiency	***Structural Sufficiency***	***Behavioral Sufficiency***	***Stock Turnover***	***Climate Change***	***Grid Decarbonization***
van Heerden et al (2025) ***[3]***	Yes	Yes	Yes **Note:** Thermostat adjustments are classified as efficiency improvements	Yes	No	Yes
Zhang et al (2025) ***[4]***	Yes	No	No	No	Yes **Note:** Via Cooling/Heating Degree Days approach	Yes
Wilson et al (2024) ***[5]***	Yes	No	No	No	No **Note:** All simulations use TMY3 data	Yes
Berrill et al. (2022) ***[6]***	Yes	Yes	No	Yes	No **Note:** All simulations use TMY3 data	Yes
This paper	**Yes**	**Yes**	**Yes**	**Yes**	**Yes** **Note:** Consider hourly future weather conditions	**Yes**

Table S2. Shares of rural residential building archetypes in 2020 by state. **[7]**

STATE	MFH_LARGE	MFH_SMALL	SFH_ATTACHED	SFH_DETACHED
AL	5.2%	5.6%	1.2%	88%
AR	5.8%	6.1%	1.2%	87%
AZ	5.0%	4.2%	2.6%	88%
CA	5.1%	4.2%	2.9%	88%
CO	6.8%	3.9%	5.3%	84%
CT	5.4%	8.1%	4.2%	82%
DC	0.0%	0.0%	0.0%	0.0%
DE	0.0%	0.0%	0.0%	0.0%
FL	7.4%	5.6%	3.9%	83%
GA	5.0%	5.4%	1.8%	88%
IA	6.0%	3.6%	2.4%	88%
ID	4.7%	4.3%	3.1%	88%
IL	4.0%	4.1%	1.7%	90%
IN	4.5%	3.3%	1.8%	90%
KS	4.8%	4.0%	3.0%	88%
KY	6.2%	6.2%	2.1%	86%
LA	4.7%	6.0%	1.6%	88%
MA	6.7%	7.3%	4.3%	82%
MD	6.9%	3.7%	5.7%	84%
ME	4.7%	5.6%	1.6%	88%
MI	4.9%	2.8%	2.2%	90%
MN	7.7%	2.6%	3.4%	86%
MO	3.6%	5.3%	2.1%	89%
MS	6.6%	5.4%	1.2%	87%
MT	5.5%	4.9%	4.6%	85%
NC	4.5%	4.8%	1.9%	89%
ND	14%	4.2%	6.3%	75%
NE	5.4%	3.9%	2.8%	88%
NH	8.6%	6.8%	5.1%	79%
NJ	0.0%	0.0%	0.0%	0.0%
NM	4.5%	4.3%	2.8%	88%
NV	5.9%	5.3%	3.7%	85%
NY	5.1%	6.9%	2.2%	86%
OH	4.4%	4.4%	2.4%	89%
OK	4.3%	3.6%	1.5%	91%
OR	5.6%	5.1%	3.2%	86%
PA	3.7%	3.9%	6.5%	86%
RI	0.0%	0.0%	0.0%	0.0%
SC	5.9%	5.1%	2.1%	87%
SD	9.2%	3.4%	3.7%	84%
TN	5.0%	5.5%	1.5%	88%

TX	4.9%	4.9%	1.6%	89%
UT	5.8%	4.6%	5.2%	84%
VA	5.7%	3.0%	3.6%	88%
VT	5.1%	7.3%	1.9%	86%
WA	6.3%	3.9%	2.6%	87%
WI	6.0%	4.0%	3.3%	87%
WV	5.1%	3.2%	2.8%	89%
WY	6.0%	4.3%	6.2%	83%

Table S3. Shares of suburban residential building archetypes in 2020 by state. **[7]**

STATE	MFH_LARGE	MFH_SMALL	SFH_ATTACHED	SFH_DETACHED
AL	12%	3.8%	2.3%	82%
AR	12%	5.8%	2.9%	79%
AZ	11%	3.5%	5.9%	79%
CA	14%	5.3%	8.2%	73%
CO	13%	3.1%	8.3%	76%
CT	10%	7.6%	6.7%	76%
DC	0.0%	0.0%	0.0%	0.0%
DE	11%	2.90%	17%	69%
FL	20%	5.5%	7.8%	67%
GA	14%	4.2%	5.6%	77%
IA	13%	3.3%	8.3%	76%
ID	6.9%	4.9%	4.4%	84%
IL	11%	4.7%	9.0%	75%
IN	9.6%	3.9%	5.0%	82%
KS	12%	3.70%	7.50%	77%
KY	12%	6.90%	4.10%	77%
LA	9.7%	5.7%	2.6%	82%
MA	12%	11%	6.80%	71%
MD	17%	1.9%	20%	61%
ME	7.7%	7.7%	4.7%	80%
MI	9.7%	3.1%	6.3%	81%
MN	14%	2.0%	12%	72%
MO	8.8%	4.3%	5.0%	82%
MS	11%	4.5%	1.9%	83%
MT	9.3%	7.3%	8.1%	75%
NC	13%	4.0%	6.3%	76%
ND	32%	4.0%	11%	53%
NE	15%	2.8%	6.1%	76%
NH	10%	5%	8.40%	76%
NJ	12%	8.3%	11%	68%
NM	9.3%	5.0%	5.2%	80%
NV	18%	6.5%	5.5%	70%
NY	8.8%	7.0%	5.1%	79%
OH	10%	4.7%	6.0%	79%
OK	12%	3.8%	2.8%	82%
OR	15%	5.0%	6.2%	74%
PA	7.3%	4.1%	16%	72%
RI	10%	10%	4.4%	75%
SC	11%	4.4%	4.2%	80%
SD	21%	3.1%	8.8%	67%

TN	13%	4.9%	4.7%	77%
TX	18%	4.1%	3.1%	75%
UT	10%	4.2%	7.6%	78%
VA	14%	2.8%	17%	67%
VT	12%	8.2%	9.8%	70%
WA	14%	4.0%	4.9%	77%
WI	14%	5.9%	6.1%	74%
WV	8.70%	4.9%	3.1%	83%
WY	0.0%	0.0%	0.0%	0.0%

Table S4. Shares of urban residential building archetypes in 2020 by state. **[7]**

STATE	MFH_LARGE	MFH_SMALL	SFH_ATTACHED	SFH_DETACHED
AL	18%	8.1%	2.5%	72%
AR	0.0%	0.0%	0.0%	0.0%
AZ	23%	5.8%	5.9%	65%
CA	33%	8.1%	9.9%	49%
CO	23%	4.0%	12%	61%
CT	28%	30%	7.6%	34%
DC	43%	7.8%	33%	16%
DE	0.0%	0.0%	0.0%	0.0%
FL	30%	7.0%	6.9%	56%
GA	44%	5.3%	6.9%	44%
IA	17%	2.6%	4.4%	75%
ID	0.0%	0.0%	0.0%	0.0%
IL	33%	23%	5.4%	39%
IN	22%	7.0%	11%	60%
KS	11%	5.9%	4.1%	79%
KY	19%	7.0%	6.6%	67%
LA	16%	15%	8.9%	60%
MA	34%	27%	9.3%	30%
MD	18%	7.0%	57%	17%
ME	0.0%	0.0%	0.0%	0.0%
MI	12%	4.2%	6.7%	77%
MN	31%	7.6%	4.4%	57%
MO	21%	14%	4.0%	61%
MS	17%	7.3%	2.9%	73%
MT	0.0%	0.0%	0.0%	0.0%
NC	34%	7.0%	7.1%	52%
ND	0.0%	0.0%	0.0%	0.0%
NE	17%	3.9%	5.6%	74%
NH	25%	16%	7.6%	51%
NJ	37%	35%	13%	15%
NM	13%	6.4%	4.8%	76%
NV	32%	12%	5.4%	50%
NY	45%	21%	13%	22%
OH	15%	12%	7.8%	65%
OK	25%	6.1%	4.8%	64%
OR	15%	6.5%	4.4%	74%
PA	14%	8.7%	63%	15%
RI	20%	34%	5.2%	41%
SC	0.0%	0.0%	0.0%	0.0%
SD	0.0%	0.0%	0.0%	0.0%

TN	21%	6.9%	6.0%	67%
TX	27%	6.0%	4.2%	63%
UT	26%	11%	11%	52%
VA	27%	6.3%	14%	52%
VT	0.0%	0.0%	0.0%	0.0%
WA	32%	5.0%	6.4%	57%
WI	13%	21%	7.1%	59%
WV	0.0%	0.0%	0.0%	0.0%
WY	0.0%	0.0%	0.0%	0.0%

Table S5. 2020 site end-use consumption [trillion BTU] in the U.S. used for model calibration. **[7]**

	SPACE HEATING	AIR CONDITIONING
ALL HOMES	**4,026**	**866**
CENSUS REGION AND DIVISION		
NORTHEAST	1,030	93
NEW ENGLAND	293	19
MIDDLE ATLANTIC	737	74
MIDWEST	1,484	131
EAST NORTH CENTRAL	1,054	84
WEST NORTH CENTRAL	430	47
SOUTH	906	497
SOUTH ATLANTIC	459	248
EAST SOUTH CENTRAL	184	66
WEST SOUTH CENTRAL	263	183
WEST	605	145
MOUNTAIN	284	80
MOUNTAIN NORTH	208	18
MOUNTAIN SOUTH	75	62
PACIFIC	322	65

Note: Vacant housing units, seasonal units, second homes, military houses, and group quarters are excluded.

SI References

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