Peer review status: This is a non-peer-reviewed preprint submitted to EarthArXiv.

Main Manuscript for

Beyond efficiency: Disentangling structural and behavioral sufficiency in U.S. residential decarbonization pathways

Shuhaib Nawawi[1,2], Parth Vaishnav[1], Xiaoyang Zhong[2,3,4], Morgan R. Edwards[5,6], Alessio Mastrucci[2]

[1] School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, USA

[2] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

[3] Institute of Environment and Ecology, Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen, China

[4] Institute of Environmental Sciences (CML), Leiden University, Leiden, The Netherlands

[5] La Follette School of Public Affairs, University of Wisconsin—Madison, Madison, WI, USA

[6] Nelson Institute Center for Sustainability and the Global Environment, University of Wisconsin—Madison, Madison, WI, USA

*Corresponding author(s): Shuhaib Nawawi

Email: nawawi@iiasa.ac.at

Author Contributions: S.N., A.M., and P.V., conceived and designed the research; S.N. and P.V. advised on all matters related to the building energy model, while A.M. and X.Y. advised on the stock turnover model; S.N. performed analyses, created graphics, and wrote the initial draft; M.E. provided inputs on policy implications and proofread the paper. All authors contributed to editing and finalizing the paper.

Competing Interest Statement: The authors declare no competing interest.

Keywords: residential decarbonization; energy efficiency; structural and behavioral sufficiency

This PDF file includes:

Main Text
Figures 1 to 6

Abstract

Decarbonization strategies in the residential sector have largely focused on lowering the carbon intensity of energy supply and improving end-use efficiency. Sufficiency, defined as avoiding unnecessary energy demand while maintaining well-being, remains largely absent from national energy system analyses, obscuring the relative and combined roles of efficiency and sufficiency in reducing energy demand. Here, we disentangle the effects of structural and behavioral sufficiency on residential energy demand and emissions, and quantify their individual and combined effects alongside efficiency improvements, including electrification. Using an integrated modelling framework that links U.S. housing stock turnover to hourly building energy demand, we find that floorspace expands by 55% from 2020 to 2050 under business-as-usual trends, increasing energy demand by 11%. Relative to this 2050 trajectory, efficiency and structural sufficiency reduce demand by 18% and 31%, and by 45% when combined. Adopting conservative, health-informed thermostat setpoints further reduces energy demand by 31–33%. These results show that accounting for sufficiency changes the scale of residential energy demand reductions achievable under decarbonization pathways, highlighting the importance of how buildings are used alongside what is built in bringing the sector closer to deep decarbonization while maintaining household well-being.

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 maintaining wellbeing, including through smaller dwellings, different housing forms, or changed thermostat practices[6–8]. Previous research indicates that sufficiency-oriented strategies, particularly those affecting floorspace 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 need to explicitly distinguish and jointly evaluate structural and behavioral dimensions of sufficiency, which are typically not resolved in existing analyses.

Despite its mitigation potential, existing analyses do not explicitly resolve the distinct mechanisms through which structural and behavioral sufficiency shape residential energy demand[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 (Table S1) assumes a static building stock, overlooking construction, renovation, and retirement processes that shape demand[15–17].

Here, we explicitly resolve the structural and behavioral mechanisms of sufficiency and evaluate how they shape future U.S. residential energy demand and emissions, alongside energy efficiency and electrification via heat pump adoption. 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. By comparing combinations of efficiency and sufficiency pathways, this analysis shows how building stock evolution and building use shape residential decarbonization, supporting the evaluation and sequencing of residential policy portfolios.

Methods

1. Policy Scenario Framework

Our scenario framework distinguishes two demand-side levers (Fig. 1): structural sufficiency and efficiency shape “what we build,” while setpoint-based behavioral sufficiency governs “how we use buildings.” This framing aligns with IPCC demand-side mitigation categories that emphasize infrastructure, technology, and sociocultural practices[19,20]. Structural sufficiency is represented through per-capita floorspace and housing form, while efficiency is represented through renovation rates and depth and heat pump adoption.

The **Reference** scenario reflects business-as-usual housing trends, including per-capita floorspace growth of 10% per decade[2], constant housing type shares (Supplementary Tables S2–S4), and continuation of recent renovation and heat pump adoption trajectories. The **Efficiency** scenario increases renovation rates from 1.5% to 2% per year, assumes deeper efficiency gains, and accelerates heat pump adoption while holding floorspace growth and housing form constant; these assumptions represent plausible improvements 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 stock toward multi-family dwellings while maintaining Reference efficiency assumptions, representing a structural sufficiency pathway rather than an upper bound on feasible change. The **Combined** scenario integrates the Efficiency and Sufficiency assumptions. All scenarios use identical state-level population projections from Shared Socioeconomic Pathway 2 (SSP2; “Middle of the Road”; Supplementary Figs. S1-S2), isolating the effects of housing stock evolution and energy-service assumptions from population change.

On the “how we use” dimension, scenarios represent contrasting heating and cooling practices through different assumptions about thermostat setpoints. 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 health-informed lower-bound comfort assumptions. Specifically, Sufficient Comfort assumes heating and cooling setpoints of 18 °C and 26 °C, respectively.

We evaluate each combination of “what we build” and “how we use” scenarios and assess sensitivity to alternative climate and power-sector pathways. Climate pathways are represented using **RCP4.5** and **RCP8.5**[24–26]. Power-sector pathways are represented using three electricity decarbonization cases from the 2024 Cambium dataset[27] produced by 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.

2. 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 from 2020 to 2050. STURM is a stock-driven, dynamic stock-turnover model based on material flow analysis that tracks residential floorspace by region, housing type, and efficiency/vintage class. A detailed description of the MESSAGEix-Buildings framework and STURM model structure is provided in Mastrucci et al. (2021).[18]

At each timestep, STURM updates the stock through new construction, renovation, and retirement. New construction meets population-driven housing demand and replaces retired dwellings; renovation transfers floorspace into improved efficiency classes; and retirement removes older stock according to lifetime survival curves.

Future floorspace demand is determined by state-level population projections, household size, housing type shares, and floorspace per capita. Household size and urban–rural shares are initialized using the 2020 Residential Energy Consumption Survey (RECS)[2] and held constant in future years. State-level population projections follow the U.S. version of the Global Change Analysis Model (GCAM-USA)[28] 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.

Scenario-relevant assumptions—including renovation rates and depth, heat pump adoption, floorspace growth, housing type shares, and building survival curves—are specified exogenously to span plausible but distinct “what we build” trajectories (Fig. 1; Supplementary Tables S2–S4). STURM outputs scenario-specific residential floorspace by region, housing type, and efficiency/vintage class. These outputs are coupled with RC-BEM intensities to estimate residential energy demand.

3. Reduced-Complexity Building Energy Model

We use the Reduced-Complexity Building Energy Model (RC-BEM), a surrogate model trained and validated against EnergyPlus simulations, to estimate hourly heating and cooling demand as a function of building characteristics, weather, and indoor temperature states. Model structure, training, and validation are described in Nawawi et al. (2025).[15]

The model is trained using Typical Meteorological Year (TMY3)[29] weather files for customized EnergyPlus simulations of 54 representative U.S. cities spanning 16 climate zones and 24 states. Standard EnergyPlus runs maintain user-defined indoor setpoints with limited temperature variation. We therefore modified thermostat schedules to cycle HVAC systems on and off every six hours, inducing indoor temperature decay and recovery that allows RC-BEM to learn building thermal response under varying weather conditions. Building heterogeneity across locations is represented using ResStock[30], a residential building stock platform developed by NLR, which samples location-specific distributions of floor area, construction vintage, insulation levels, and HVAC system efficiencies. This yields approximately 17,000 unique single-family home prototypes. Appliance-level EnergyPlus outputs, including furnace fuel use, air-conditioner electricity use, and heat-pump electricity use, are converted to hourly heating and cooling demand using HVAC performance assumptions, including annual fuel utilization efficiency for furnaces and coefficient of performance for heat pumps.

RC-BEM coefficients are estimated using penalized linear regression with lasso regularization. Unlike degree-day approaches that rely primarily on ambient temperature, RC-BEM includes multiple weather and thermal-state input variables: indoor–outdoor temperature differences, wind speed, solar irradiance, infrared radiation, relative humidity, and changes in indoor temperature. Because indoor temperature is an explicit input variable, RC-BEM can represent the thermostat setpoints used in the behavioral sufficiency scenarios.

To account for climate change, we run the trained RC-BEM using Thermodynamic Global Warming (TGW)[31] climate datasets, which preserve local weather variability while incorporating climate change signals from global climate models. The resulting hourly heating and cooling demand profiles are aggregated to annual heating and cooling intensities for each building prototype (kWh m^{-2}) and coupled with STURM-projected floorspace to estimate regional and national residential energy demand.

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

RC-BEM represents single-family residential energy performance using nine construction-vintage efficiency classes (s1–s9), corresponding to building construction decades from pre-1940 stock (s1) through 2010s construction (s9). STURM stock projections include future stock classes not directly simulated in RC-BEM, including newly constructed and renovation-derived classes. To close these gaps, we mapped each missing class to the nearest simulated RC-BEM class and adjusted its energy intensity using RECS-derived median site energy intensity ratios 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% for standard renovations and 60% for low-energy (i.e., deep) renovations.

Because RC-BEM is trained only on single-family prototypes, multi-family homes are represented using adjusted single-family intensity proxies scaled to multi-family floorspace from STURM. When no matching RC-BEM prototype class was available, we used energy intensity values from similar buildings in the same climate zone or, if still unavailable, national-average values.

5. Model Integration and Validation

To integrate the models, we combine STURM residential floor-area projections by state/region, housing type, climate zone, and efficiency/vintage class with RC-BEM heating and cooling intensities (kWh m^{-2}). Total demand is calculated by multiplying intensity by floor area and aggregating across vintages, zones, housing types, and regions. Where prototype pools were incomplete, donor intensities were drawn hierarchically from the same city, climate zone, or national average. Monthly demand was allocated using monthly shares from the best-available donor pool. Integrated outputs include regional and national totals, floor-area-normalized intensities, and monthly demand profiles.

We validate the integrated model against base-year statistics. Modeled housing units total 129.75 million in 2020, closely matching the 2020 U.S. Census estimate of approximately 126.8 million occupied housing units. Modeled 2020 heating and cooling energy use is calibrated to national residential end-use consumption reported by the U.S. Energy Information Administration, with calibration details provided in Supplementary Table S5.

6. Final Energy Demand

We compute final/site energy demand for heating and cooling by processing the integrated model outputs into monthly and annual metrics. RC-BEM outputs useful heating and cooling demand, which we convert to final/site energy using end-use-specific equipment efficiencies. For combustion heating, we assume 90% gas furnace efficiency; for heat-pump heating and electric cooling, we apply year-dependent coefficients of performance (COPs), reflecting federal standards and projected efficiency improvements (e.g., COP = 3.2 in 2020, rising to 4.4 in 2050).

To ensure consistency with historical statistics, modeled 2020 site energy demand 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 S5). The analysis excludes Hawaii and Alaska. 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 differences across scenarios.

7. Primary Energy Demand and Emissions

We translate site energy demand into primary energy using region- and year-specific electricity primary energy factors (PEFs) from the Cambium dataset. For the 2020 historical baseline, we use 2010s average PEFs by Census region: Northeast 2.63, Midwest 2.92, South 2.62, and West 2.37. For 2050, we use business-as-usual projected PEFs: Northeast 2.32, Midwest 2.32, South 2.33, and West 2.17. Non-electric fuels, including natural gas and propane, are assigned a PEF of 1. Monthly primary energy demand is calculated by multiplying each site energy flow by its corresponding PEF and aggregating across fuels, end uses, and regions.

We estimate national residential CO_2e emissions by combining projected site energy demand with fuel- and grid-specific emission factors, reporting results as direct and indirect emissions corresponding to Scope 1 and Scope 2. Direct emissions from on-site combustion of natural gas, fuel oil, and propane are calculated by multiplying state-level fossil fuel demand from the integrated STURM–RC-BEM outputs by EPA emission factors for CO_2, CH_4, and N_2O, with non-CO_2 gases converted to CO_2e using 100-year global warming potentials. Indirect emissions are calculated by multiplying state-level residential electricity demand by grid emission rates from EPA's eGRID[32] dataset for 2020 and Cambium[27] pathways for 2025–2050: HighRECost_LowNGPrice, MidCase, and LowRECost_HighNGPrice.

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%), exceeding reductions from efficiency alone. 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 informs power-system implications, although grid operations are not explicitly modeled.

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). Sufficient Comfort reduces final energy demand in every state, 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 larger, more energy-intensive heating loads in colder climates. 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[33,34], 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 and conclusions

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 framework links housing infrastructure decisions to future residential energy demand and emissions, enabling evaluation of sufficiency-based interventions within broader 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[2,35]. 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 approaches but does not fully achieve deep decarbonization benchmarks, indicating that housing and demand-side transformations alone are insufficient and require additional measures such as faster electrification and deeper electricity-sector decarbonization.

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 limits representation of household-level life-cycle processes and market dynamics. 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 should incorporate endogenous household and market decision-making, extend coverage to all household energy uses, and represent socioeconomic heterogeneity.

Coupling adaptive comfort behavior with physical energy demand would better capture real-world feedbacks and support policy design that reflects heterogeneous thermal comfort needs and barriers to energy sufficiency.

Translating modeled pathways into practice depends on governance and planning frameworks. State-level building codes can limit municipal ambition[36], while zoning restrictions can constrain denser urban form[37,38]. Financial incentives for retrofits and electrification can help, although recent U.S. political developments threaten long-term decarbonization[39,40]. Advancing structural sufficiency therefore requires zoning, building-code, and housing-policy reforms that enable smaller dwellings and compact, multi-family development[41,42].

Ambitious housing transformation is essential for aligning U.S. climate mitigation goals with equitable thermal comfort. Upgrading buildings can reduce demand and flatten seasonal peaks while easing grid strain and electrification barriers in underserved households. Because many U.S. households struggle to meet energy needs, supportive policies may increase energy use.[43] Policymakers should therefore prioritize safe, efficient, and equitable housing while integrating sufficiency into codes, incentives, and planning frameworks.

Acknowledgments

This research was supported by Friends of IIASA Wes and Ankie Foell Fund, the University of Michigan (U-M) Graham Sustainability Institute, and U-M Science, Technology, and Public Policy program. Portions of this work were carried out during the Young Scientists Summer Program at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria.

Data Availability Statement

The data supporting the findings of this study are included within the article and Supplementary Information. Additional processed outputs needed to reproduce the figures are available from the corresponding author upon request.

AI Statement

During the preparation of this work, the authors used ChatGPT to improve the clarity and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

References

1. Total Energy Monthly Data - U.S. Energy Information Administration (EIA). https://www.eia.gov/totalenergy/data/monthly/.
2. Residential Energy Consumption Survey (RECS) - Energy Information Administration. https://www.eia.gov/consumption/residential/.
3. Ürge-Vorsatz, D. *et al.* Locking in positive climate responses in cities. *Nat. Clim. Change* **8**, 174–177 (2018).
4. Moura, M. C. P., Smith, S. J. & Belzer, D. B. 120 Years of U.S. Residential Housing Stock and Floor Space. *PLOS ONE* **10**, e0134135 (2015).
5. Reyna, J. *et al.* U.S. Building Stock Characterization Study: A National Typology for Decarbonizing U.S. Buildings. *Renew. Energy* (2022).
6. Chapter 9: Buildings. https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-9/.
7. COP26: Sufficiency Should be First. *Buildings and Cities* https://www.buildingsandcities.org/insights/commentaries/cop26-sufficiency.html (2021).
8. Hu, S. *et al.* A systematic review of building energy sufficiency towards energy and climate targets. *Renew. Sustain. Energy Rev.* **181**, 113316 (2023).
9. Berrill, P., Wilson, E. J. H., Reyna, J. L., Fontanini, A. D. & Hertwich, E. G. Decarbonization pathways for the residential sector in the United States. *Nat. Clim. Change* **12**, 712–718 (2022).
10. van Heerden, R. *et al.* Demand-side policies can significantly reduce emissions from energy use in buildings and transport. *Nat. Energy* **10**, 293–294 (2025).
11. Levesque, A., Pietzcker, R. C. & Luderer, G. Halving energy demand from buildings: The impact of low consumption practices. *Technol. Forecast. Soc. Change* **146**, 253–266 (2019).
12. Mastrucci, A. *et al.* Modeling Low Energy Demand Futures for Buildings: Current State and Research Needs. *Annu. Rev. Environ. Resour.* **48**, 761–792 (2023).
13. Zhang, Y. *et al.* Long-term decarbonization impacts on residential energy security across income groups and US states. *Environ. Res. Lett.* **20**, 054040 (2025).

14. van Ruijven, B. J., De Cian, E. & Sue Wing, I. Amplification of future energy demand growth due to climate change. *Nat. Commun.* **10**, 2762 (2019).

15. Nawawi, S., Yi, M., Craig, M., Deetjen, T. & Vaishnav, P. Cross-sectoral trade-offs in a changing climate: Surrogate models to balance home energy bills, occupant comfort, and power system externalities. *iScience* **28**, 112728 (2025).

16. White, P. R., Rhodes, J. D., Wilson, E. J. H. & Webber, M. E. Quantifying the impact of residential space heating electrification on the Texas electric grid. *Appl. Energy* **298**, 117113 (2021).

17. Waite, M. & Modi, V. Electricity Load Implications of Space Heating Decarbonization Pathways. *Joule* **4**, 376–394 (2020).

18. Mastrucci, A., van Ruijven, B., Byers, E., Poblete-Cazenave, M. & Pachauri, S. Global scenarios of residential heating and cooling energy demand and CO2 emissions. *Clim. Change* **168**, 14 (2021).

19. Chapter 5: Demand, services and social aspects of mitigation. https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-5/.

20. Creutzig, F. *et al.* Demand-side solutions to climate change mitigation consistent with high levels of well-being. *Nat. Clim. Change* **12**, 36–46 (2022).

21. High indoor temperatures. in *WHO Housing and Health Guidelines* (World Health Organization, 2018).

22. Low indoor temperatures and insulation. in *WHO Housing and Health Guidelines* (World Health Organization, 2018).

23. California AB209 | 2021-2022 | Regular Session. *LegiScan* https://legiscan.com/CA/text/AB209/id/2606026.

24. van Vuuren, D. P. *et al.* The representative concentration pathways: an overview. *Clim. Change* **109**, 5 (2011).

25. Thomson, A. M. *et al.* RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Clim. Change* **109**, 77 (2011).

26. Riahi, K., Grübler, A. & Nakicenovic, N. Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol. Forecast. Soc. Change* **74**, 887–935 (2007).

27. Gagnon, P. *et al. Cambium 2024 Scenario Descriptions and Documentation*. https://www.osti.gov/biblio/2558937 (2025) doi:10.2172/2558937.

28. GCAM v8.2 Documentation: GCAM-USA. https://jgcri.github.io/gcam-doc/gcam-usa.html.

29. TMY3 Weather Data for ComStock and ResStock | NLR Data Catalog. https://data.nrel.gov/submissions/156.

30. Wilson, E. J., Christensen, C. B., Horowitz, S. G., Robertson, J. J. & Maguire, J. B. *Energy Efficiency Potential in the U.S. Single-Family Housing Stock*. https://www.osti.gov/biblio/1414819 (2017) doi:10.2172/1414819.

31. Jones, A. D. *et al.* Continental United States climate projections based on thermodynamic modification of historical weather. *Sci. Data* **10**, 664 (2023).

32. US EPA, O. Emissions & Generation Resource Integrated Database (eGRID). https://www.epa.gov/egrid (2020).

33. Sachs, J. *et al.* pathways to deep decarbonization - 2014 report. https://www.osti.gov/etdeweb/biblio/22328772 (2014).

34. DDPP - Pathways to deep decarbonization in the United States. *DDP initiative* https://ddpinitiative.org/publication/ddpp-united-states/.

35. Bureau, U. C. CHARS - Historical Characteristics Tables. https://www.census.gov/construction/chars/historical/tables.html.

36. MCL - Act 230 of 1972 - Michigan Legislature. https://www.legislature.mi.gov/Laws/MCL?objectName=MCL-ACT-230-OF-1972.

37. Glaeser, E. & Gyourko, J. The Economic Implications of Housing Supply. *J. Econ. Perspect.* **32**, 3–30 (2018).

38. Full article: Supply Skepticism: Housing Supply and Affordability. https://www.tandfonline.com/doi/full/10.1080/10511482.2018.1476899?scroll=top&needAccess=true#abstract.

39. Rep. Yarmuth, J. A. [D-K.-3. Text - H.R.5376 - 117th Congress (2021-2022): Inflation Reduction Act of 2022. https://www.congress.gov/bill/117th-congress/house-bill/5376/text (2022).

40. Orders, E. Unleashing American Energy. *The White House* https://www.whitehouse.gov/presidential-actions/2025/01/unleashing-american-energy/ (2025).

41. California SB9 | 2021-2022 | Regular Session. *LegiScan* https://legiscan.com/CA/text/SB9/id/2433375.

42. California Code, GOV 65915. https://leginfo.legislature.ca.gov/faces/codes_displaySection.xhtml?lawCode=GOV&sectionNum=65915.

43. Cong, S., Nock, D., Qiu, Y. L. & Xing, B. Unveiling hidden energy poverty using the energy equity gap. *Nat. Commun.* **13**, 2456 (2022).

Figures and Tables

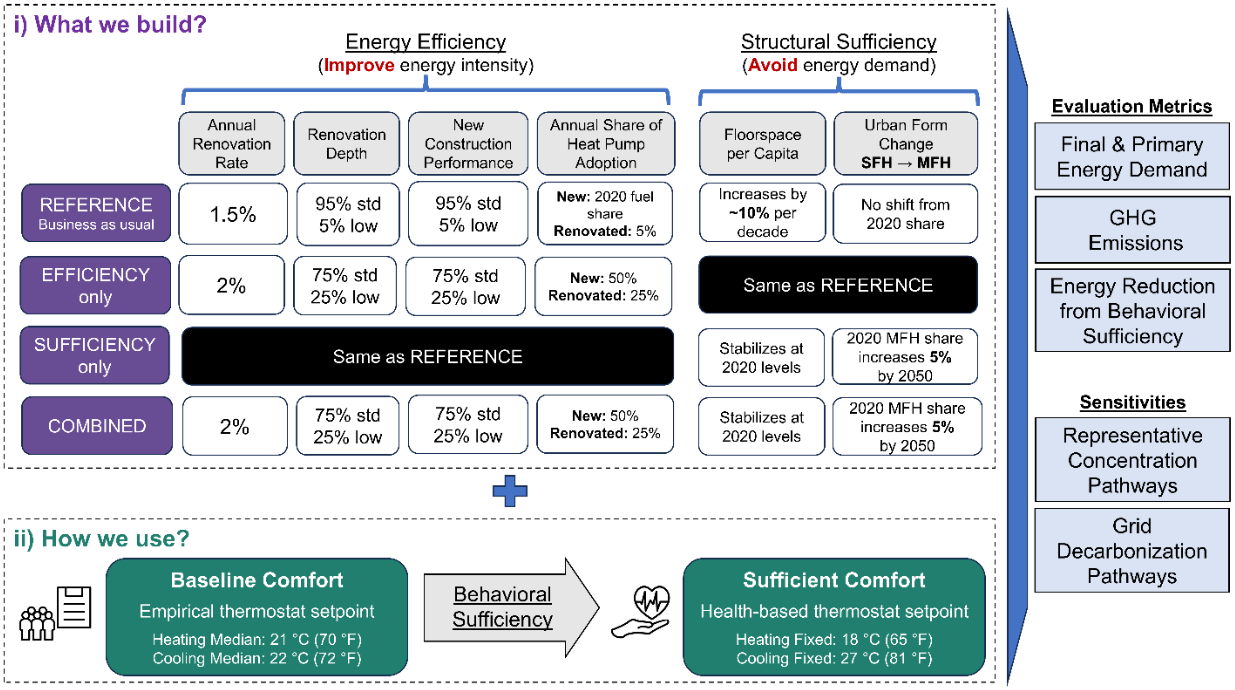

Figure 1. Scenario framework for the U.S. residential sector.
Scenarios distinguish between what we build—represented by Reference, Efficiency, Sufficiency, and Combined housing stock pathways—and how we use, represented by thermostat setpoint assumptions spanning Baseline Comfort and Sufficient Comfort.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

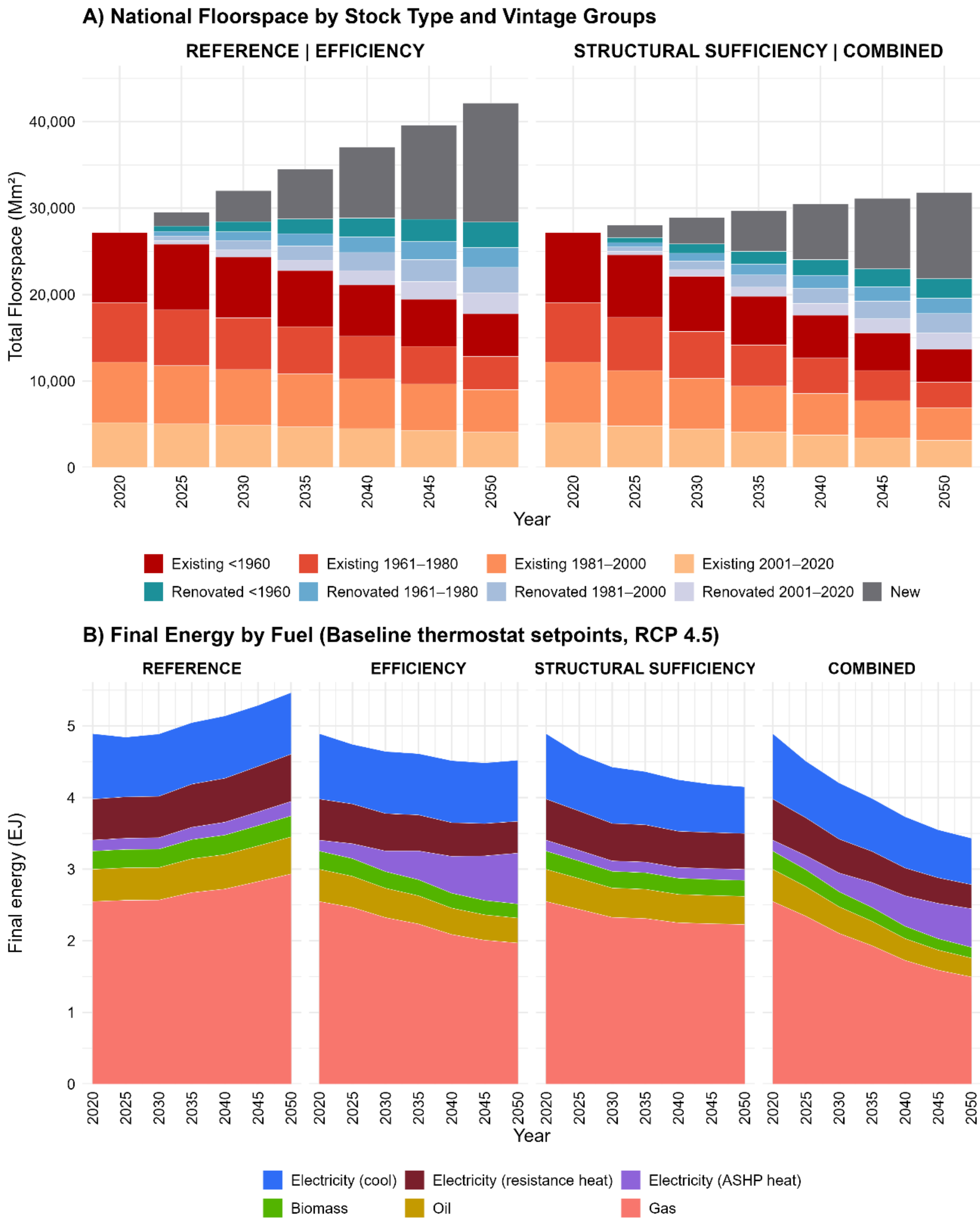

Figure 2. U.S. residential floorspace and final energy across housing stock pathways. (A) National residential floorspace through 2050 by building cohort (existing, renovated, and new construction). (B) Final energy demand by fuel under the same pathways, assuming Baseline Comfort thermostat setpoints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

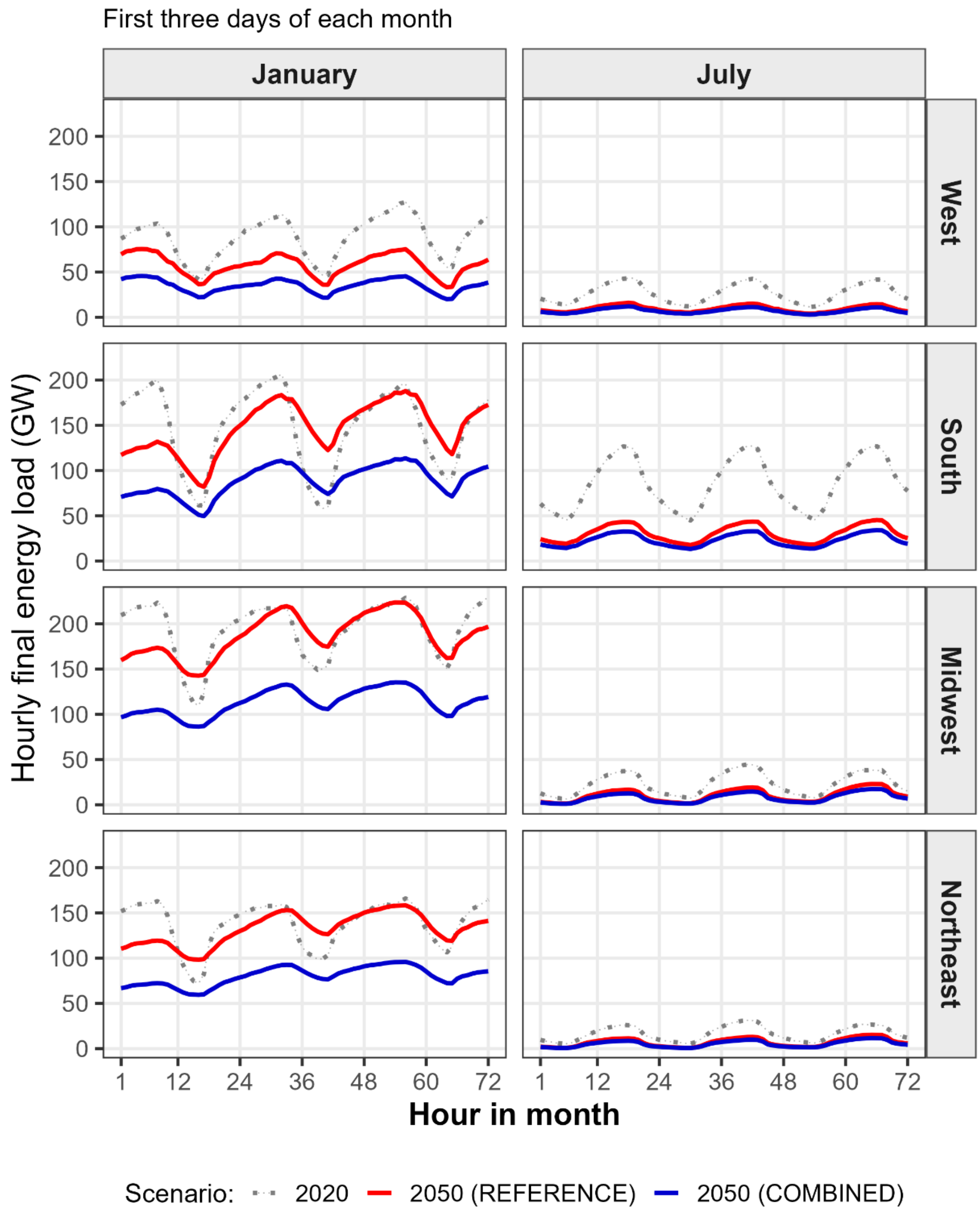

Figure 3. Hourly residential energy load by Census regions.
Hourly final energy load during the first three days of January and July, shown as illustrative winter and summer periods across U.S. Census regions, comparing 2020 baseline conditions with 2050 Reference and Combined scenarios. Results assume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

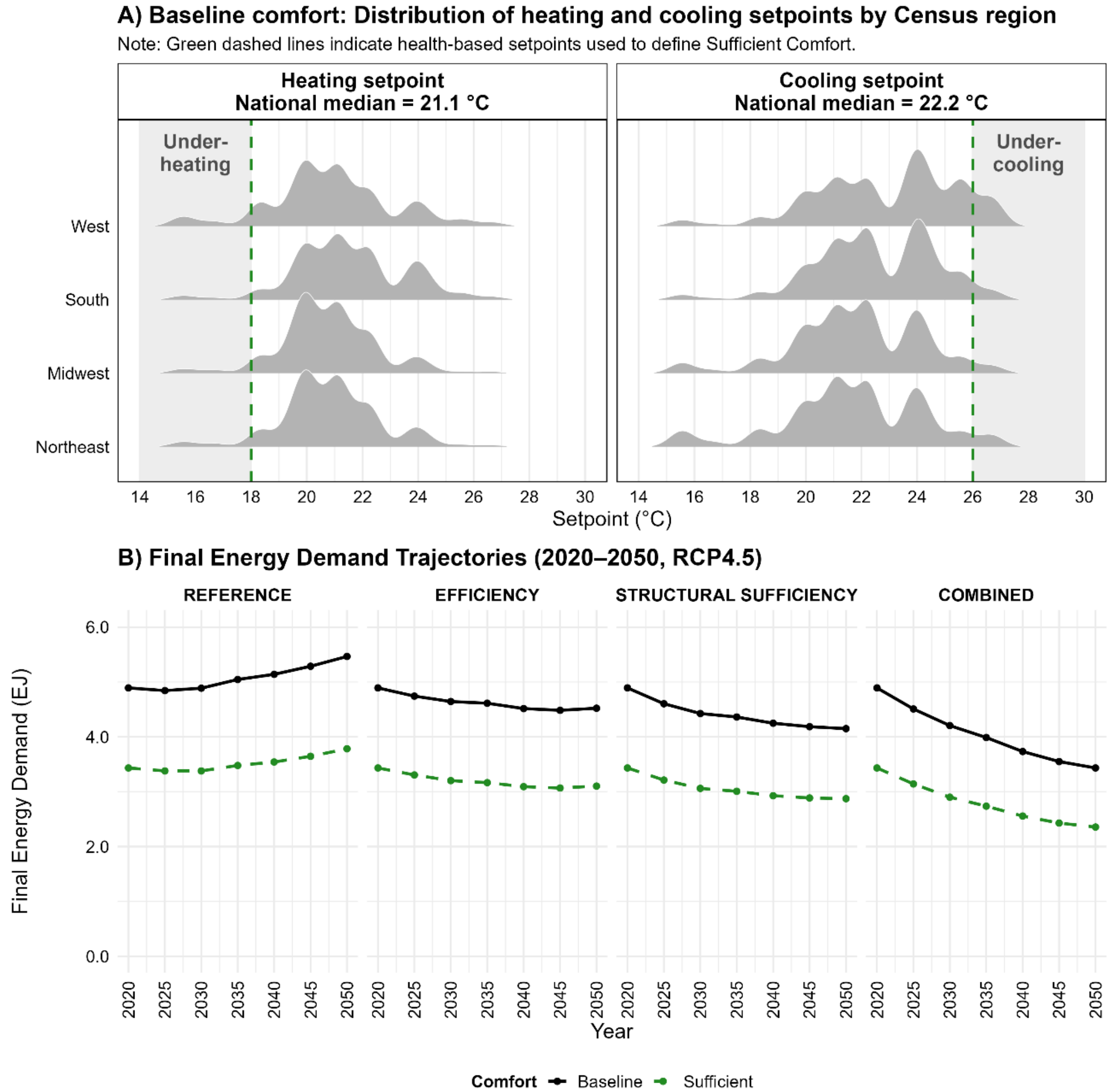

Figure 4. Impact of thermostat setpoints on U.S. residential final energy demand. (A) Distribution of heating and cooling thermostat setpoints by U.S. Census region under Baseline Comfort; dashed lines indicate health-based thermostat setpoints used to define Sufficient Comfort. (B) National final energy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

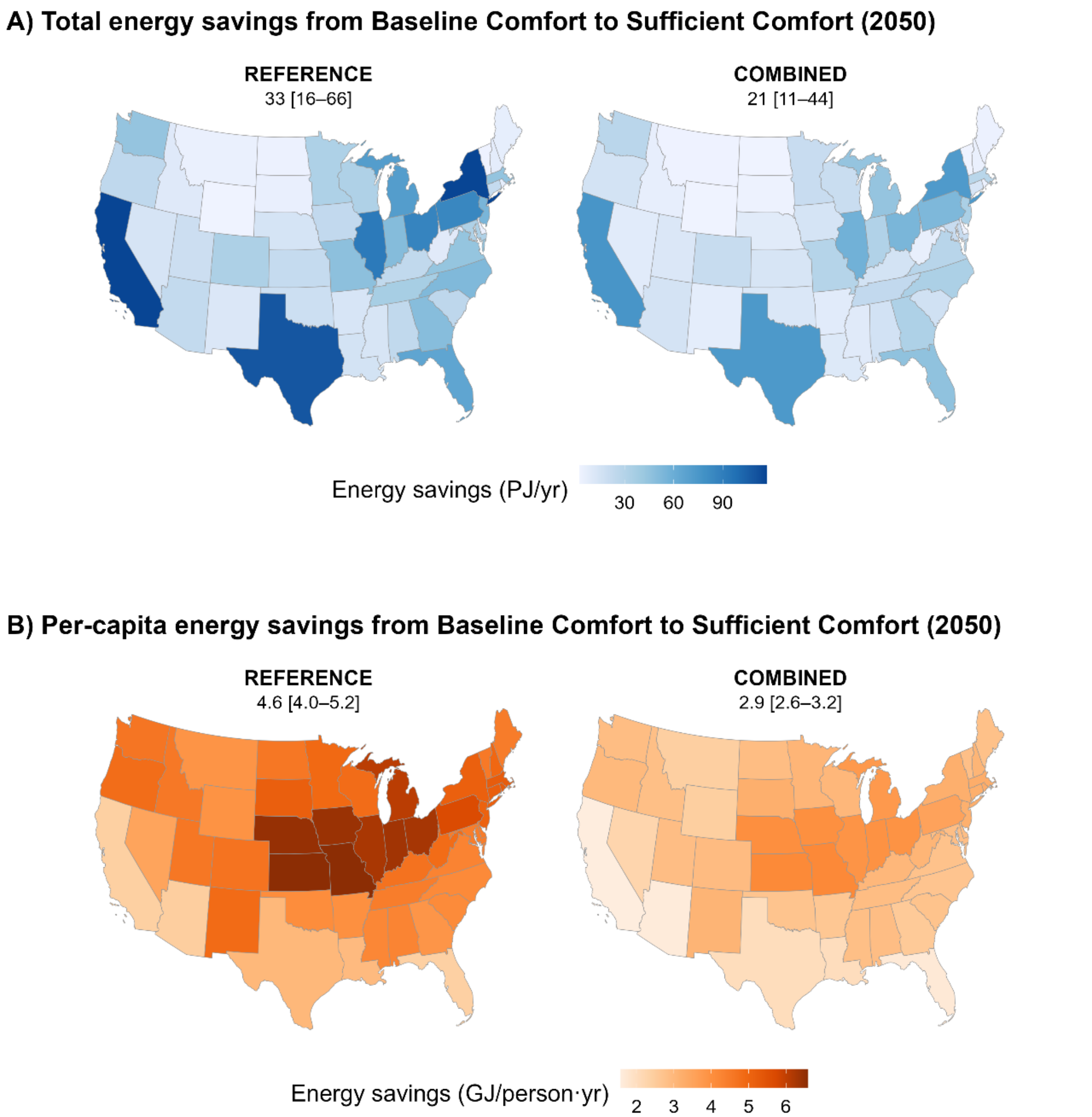

Figure 5. State-level final energy savings from Baseline to Sufficient Comfort in 2050. (A) Absolute annual residential final energy savings by state under the Reference and Combined housing stock pathways. (B) Corresponding per-capita energy savings. Color indicates savings magnitude relative to Baseline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

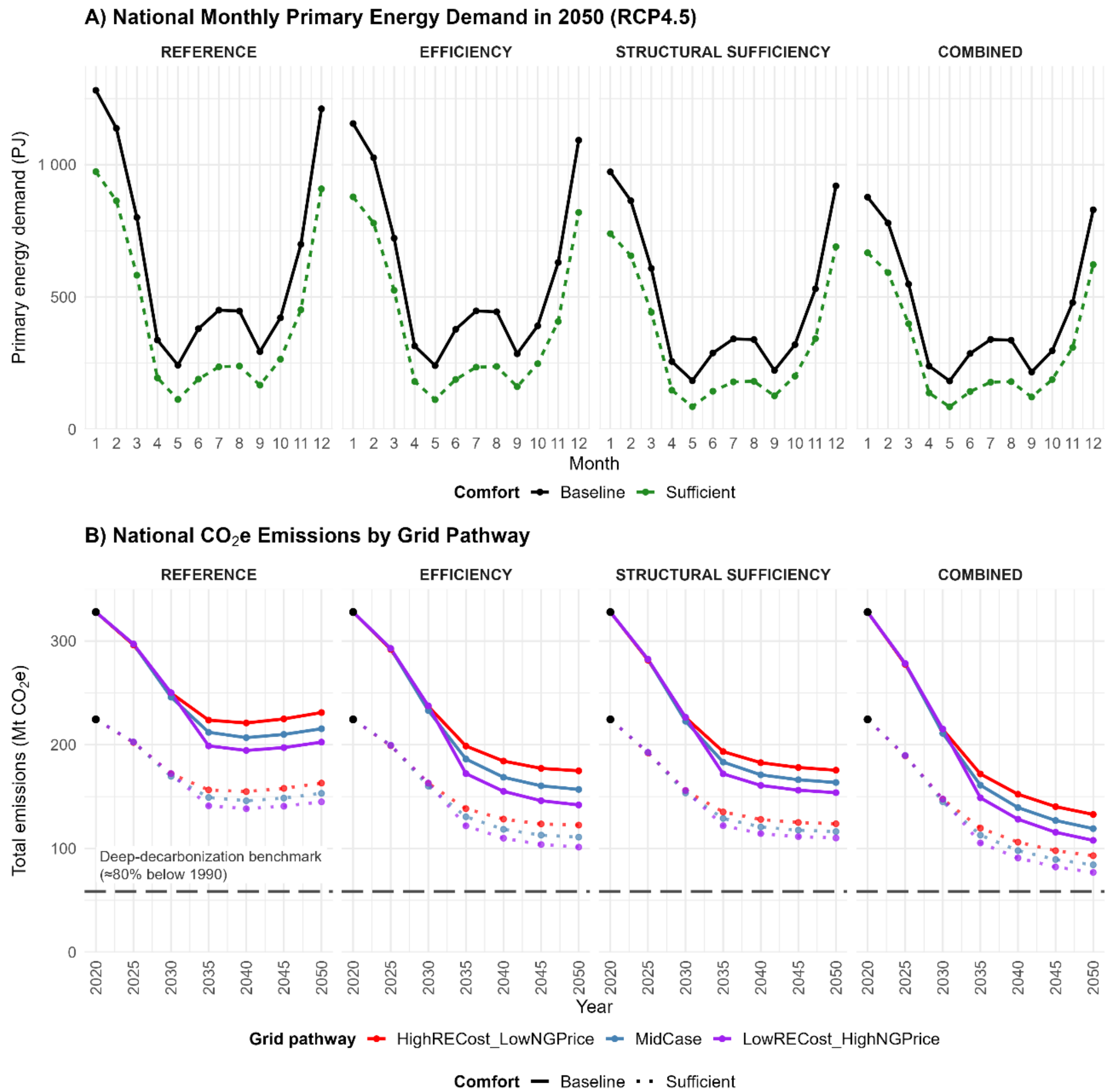

Figure 6. National primary energy demand and emissions
(A) Monthly national primary energy demand in 2050 under Baseline and Sufficient Comfort across housing stock pathways, assuming RCP4.5. (B) Annual residential CO_2e emissions (Scope 1 + 2) under alternative housing stock pathways (facets) and electricity-sector 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.

Peer review status: This is a non-peer-reviewed preprint submitted to EarthArXiv.

Supporting Information for

Beyond efficiency: Disentangling structural and behavioral sufficiency in U.S. residential decarbonization pathways

Shuhaib Nawawi[1,2], Parth Vaishnav[1], Xiaoyang Zhong[2,3,4], Morgan R. Edwards[5,6,] Alessio Mastrucci[2]
[1] School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, USA
[2] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
[3] Institute of Environment and Ecology, Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen, China
[4] Institute of Environmental Sciences (CML), Leiden University, Leiden, The Netherlands
[5] La Follette School of Public Affairs, University of Wisconsin—Madison, Madison, WI, USA
[6] Nelson Institute Center for Sustainability and the Global Environment, University of Wisconsin—Madison, Madison, WI, USA

*Corresponding author(s): Shuhaib Nawawi

Email: nawawi@iiasa.ac.at

This PDF file includes:

Figures S1 to S3
Tables S1 to S5
SI References

Figures

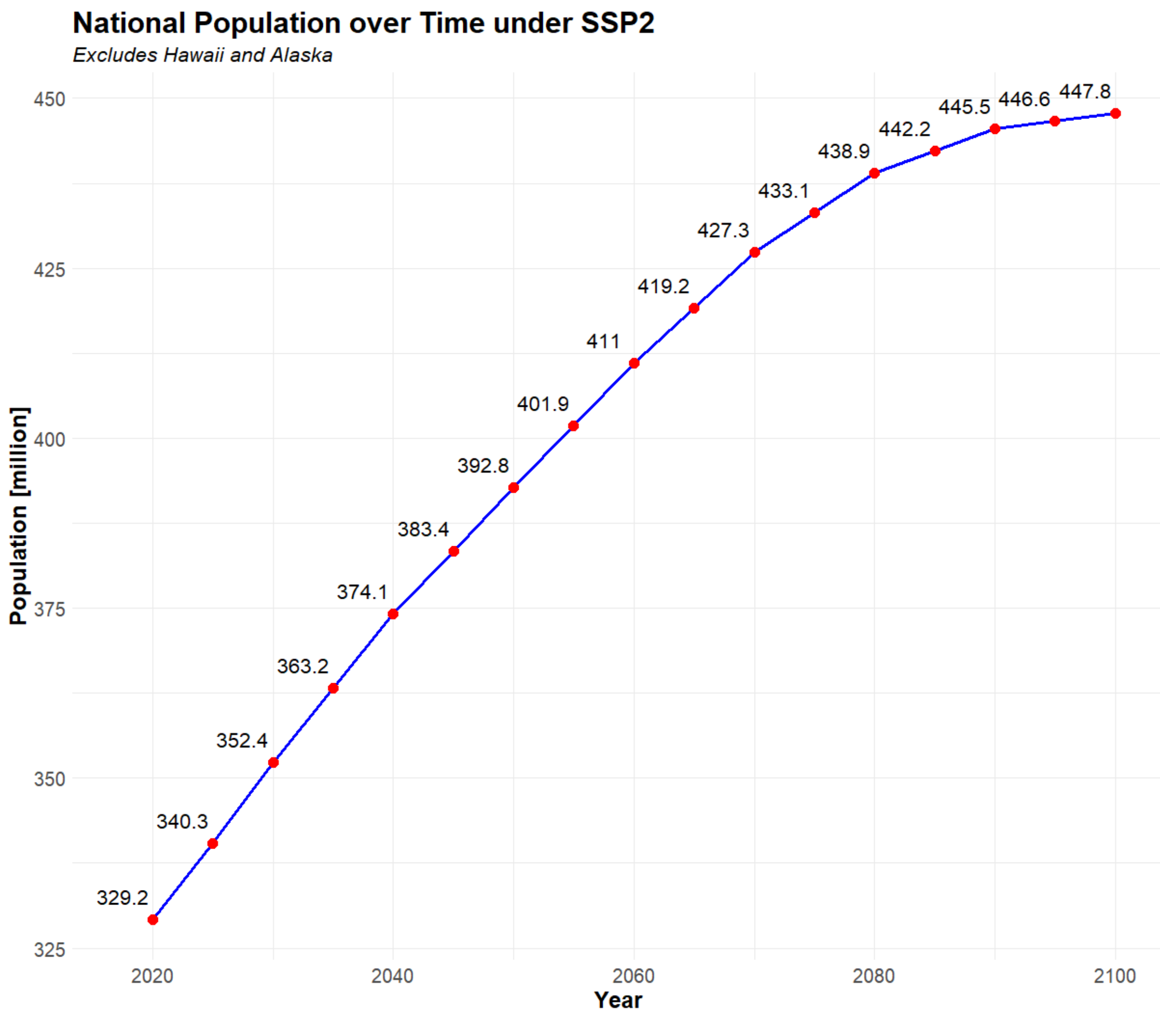

Fig. S1. National population trajectory under SSP2.
U.S. population projections from 2020 to 2100 under Shared Socioeconomic Pathway 2 ("Middle of the Road"), excluding Hawaii and Alaska. This population trajectory is applied uniformly across all policy scenarios. Source: GCAM-USA **[1], [2]**

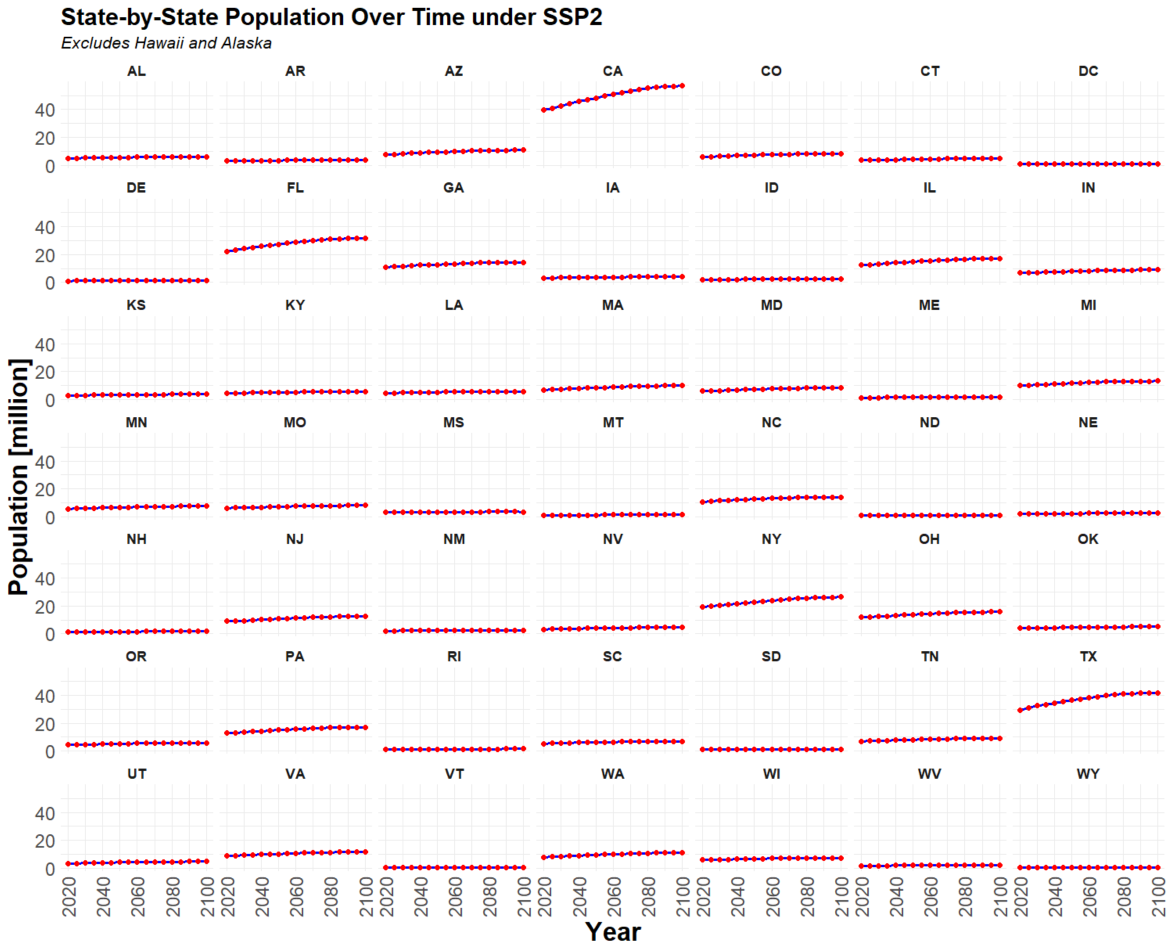

Fig. S2. State-level population trajectories under SSP2.

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]**

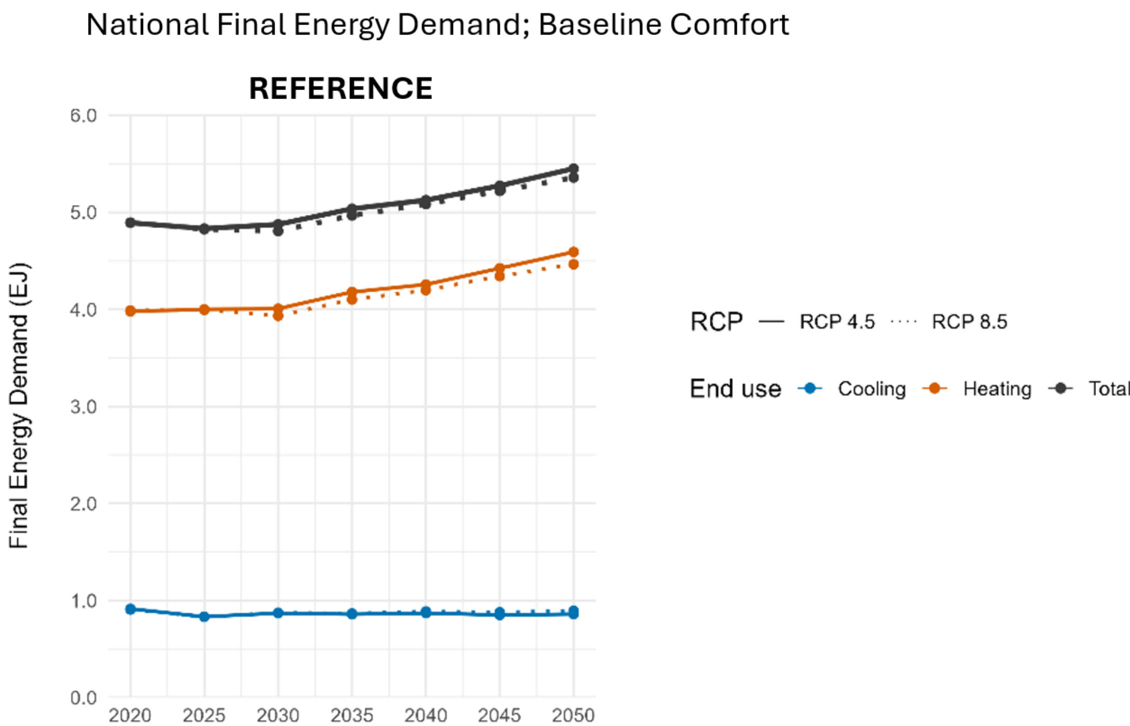

Fig. S3. Sensitivity of national final residential energy demand to climate pathways. Final residential energy demand for heating, cooling, and total use under RCP4.5 and RCP8.5 using Baseline Comfort assumptions. The Reference scenario is shown as a representative case to illustrate that differences 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

[1] *JGCRI/gcam-core*. (Feb. 03, 2026). R. Joint Global Change Research Institute. Accessed: Feb. 04, 2026. [Online]. Available: https://github.com/JGCRI/gcam-core

[2] “GCAM v8.2 Documentation: GCAM-USA.” Accessed: Feb. 04, 2026. [Online]. Available: https://jgcri.github.io/gcam-doc/gcam-usa.html

[3] R. van Heerden *et al.*, “Demand-side policies can significantly reduce emissions from energy use in buildings and transport,” *Nat. Energy*, vol. 10, no. 3, pp. 293–294, Mar. 2025, doi: 10.1038/s41560-025-01721-z.

[4] Y. Zhang *et al.*, “Long-term decarbonization impacts on residential energy security across income groups and US states,” *Environ. Res. Lett.*, vol. 20, no. 5, p. 054040, Apr. 2025, doi: 10.1088/1748-9326/adca4c.

[5] E. J. H. Wilson, P. Munankarmi, B. D. Less, J. L. Reyna, and S. Rothgeb, “Heat pumps for all? Distributions of the costs and benefits of residential air-source heat pumps in the United States,” *Joule*, vol. 8, no. 4, pp. 1000–1035, Apr. 2024, doi: 10.1016/j.joule.2024.01.022.

[6] P. Berrill, E. J. H. Wilson, J. L. Reyna, A. D. Fontanini, and E. G. Hertwich, “Decarbonization pathways for the residential sector in the United States,” *Nat. Clim. Change*, vol. 12, no. 8, Art. no. 8, Aug. 2022, doi: 10.1038/s41558-022-01429-y.

[7] “Residential Energy Consumption Survey (RECS) - Energy Information Administration.” Accessed: Aug. 20, 2024. [Online]. Available: https://www.eia.gov/consumption/residential/