Decarbonization pathways for the residential sector in the United States

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Abstract

Residential GHG emissions in the United States are driven in part by a housing stock where on-site fossil combustion is common, home sizes are large by international standards, energy efficiency potential is large, and electricity generation in many regions is GHG-intensive. In this analysis we assess decarbonization pathways for the United States residential sector to 2060, through 108 scenarios describing housing stock evolution, new housing characteristics, renovation levels, and clean electricity. The lowest emission pathways involve very rapid decarbonization of electricity supply alongside extensive renovations to existing homes, including improving thermal envelopes and heat pump electrification of heating. Reducing the size and increasing the electrification of new homes provide further emission cuts, and combining all strategies enables reductions of 91% between 2020 and 2050. The potential of individual mitigation strategies shows great regional variation. Reaching zero emissions will require simultaneous deployment of multiple strategies, and greater reduction of embodied emissions.

Reducing GHG emissions rapidly from buildings is central to mitigating global climate change. The United States has one of the highest levels of per-capita residential energy use in the world (1.5 times the OECD average), and the second largest total residential energy use[1]. Recent reductions of residential energy-related emissions in the US have primarily derived from decarbonizing electricity supply, with much smaller reductions from energy efficiency and increased use of electricity for space heating[2]. Although complete electrification of residential energy is feasible, complete decarbonization of electricity supply is challenging[3,4]. Reducing residential energy demand through efficiency and sufficiency can alleviate this challenge. Two approaches to improve building stock energy efficiency are renovating existing buildings, and replacing older stock with new buildings[5–8]. Comparing these approaches requires consideration of emissions 'embodied' in construction, which constitute around 9% of residential emissions in the US[9]. Literature has not converged on which approach is preferable[10], but existing comparisons of renovating and replacing usually focus on individual buildings or neighbourhoods; rarely have they been made for building stocks of an entire country[8].

'Sufficiency' approaches to reducing GHG emissions are a recent addition to climate change mitigation discourse, and target reduced demand for energy and materials, while delivering wellbeing for all[11,12]. For residential buildings, sufficiency can be translated into a global convergence of floor area per person[13,14] to somewhere in the range of 15–40 m^2/cap[15–18]. Current average floor area usage in the US is 60 m^2/cap[19], one of the highest levels globally[20], although there is considerable variation within the US in floor area consumption by house type, geography, and race[19,21].

In this paper we estimate emission pathways from operation, construction, and renovation of residential buildings in the US in 108 scenarios from 2020 to 2060. The primary aim is to assess potential GHG emission reductions from individual and combined strategies applied to existing homes, new homes, and electricity supply; and to illustrate how these potentials vary regionally by climate, housing stock characteristics, electricity grid region, and population growth. The consideration of embodied emissions, engineering-based energy modelling using high-resolution housing characteristics, and representation of detailed renovation measures based on empirical renovation data are novel aspects of this work. Results show that deep renovations of existing homes and rapid decarbonization of electricity supply have the greatest potential for emission reductions. Reducing the size of the largest new homes, and increasing the electrification and multifamily share of new housing can deliver substantial further reductions, but a faster replacement of existing homes does not reduce emissions.

Description of scenarios

108 emissions scenarios (3 x 4 x 3 x 3) are developed, defined by three scenarios describing evolution of the US housing stock[19], four scenarios describing characteristics of new housing, three renovation scenarios, and three electricity supply scenarios[22,23] (Table 1). The scenarios incorporate different approaches to climate change mitigation; sufficiency approaches are represented in High Multifamily

Growth and Reduced floor area scenarios, efficiency improvements occur in Renovation, High Stock Turnover and Increased Electrification scenarios, while energy supply decarbonization is represented in Electricity Supply scenarios. In the higher ambition scenarios, historic trends are altered to levels that are optimistic but still feasible, they do not necessarily achieve the maximum technical potential. For instance, the increase in renovation rates by factor 1.5 reflect the possibility for increased renovation rates, but also practical constraints on how much they can increase. The scenarios are not optimized to achieve a specific emissions reduction target. Further description of the scenarios, modelling approach, and limitations, is provided in the Methods section.

Assessment of climate change mitigation strategies

Annual GHG emissions decline in all scenarios, and the extent of decline is largely explained by the extent of electricity decarbonization and renovation depth (Fig. 1). In 2030, 55 out of 108 scenarios meet a US government target for reducing emissions by 50% compared to 2005[23]; this generally requires at least LREC electricity and Advanced Renovation. Only one scenario reduces emissions by 50% between 2020 and 2030, which is a global reduction required to limit climate change to 1.5°C warming[24]. This scenario has CFE electricity, Extensive Renovation, smaller (RFA) new housing, Increased Electrification and High Multifamily stock growth. In 2050, 36 scenarios reduce emissions by at least 80% relative to 2005, which was the 'mid-century strategy' outlined in the US nationally determined contribution to the Paris 2015 agreement[25]. Meeting this target requires either LREC electricity combined with Extensive Renovation, CFE electricity with Advanced/Extensive Renovation, or CFE electricity with Regular Renovation, lower floorspace (RFA and high-MF) and Increased Electrification of new housing. Due to residual emissions from residential fossil fuels and construction, even the most ambitious scenarios modelled do not meet a 1.5°C-consistent goal of zero emissions in 2050[24]. Cumulative 2020-2060 emissions range from 12.0 - 28.9 $GtCO_{2e}$ (Fig. 2). A current-population-based allocation of the remaining global carbon budget to meet 1.5°C with 50% likelihood[26] gives the US a budget of 21 $GtCO_{2e}$ from all sources from 2020. This would be even smaller under fair effort-sharing allocations[27].

Within each electricity supply and renovation scenario set, housing stock evolution and the characteristics of new housing provide further variations in emissions. Annual emissions are lower by 33-54 $MtCO_{2e}$/yr in 2050 if building new homes with reduced floor area (RFA) and increased electrification (IE) compared to baseline new housing characteristics, while cumulative 2020-2060 emissions see reductions of 1.1-1.8 $GtCO_{2e}$ (Fig. 2). With MC electricity, RFA has greater potential for emission reductions than IE, but if electricity supply decarbonizes completely by 2035, these two strategies have approximately the same cumulative potential (Fig. 2c). These strategies are complementary, so the largest emission reductions occur when they are combined. Due to higher embodied emissions[19] and the size difference between old and new single-family housing (Extended

Data Fig. 1), High Stock Turnover results in increased emissions (Fig. 2), despite improvements in efficiency which accompany faster growth of new housing. Therefore, renovating has far greater emission reductions potential than replacing existing homes. Like RFA, High-Multifamily stock growth reduces both embodied emissions, and future energy-related emissions. High multifamily stock growth reduces cumulative 2020-2060 emissions by 0.30-0.81 $GtCO_{2e}$ compared to baseline stock growth (Fig. 2).

While extensive renovation and rapid electricity decarbonization have high potential, there are limitations to relying on either strategy individually, as illustrated by Fig. 3a-b and Fig 4a-b. With Extensive Renovation and gradual (MC) decarbonization of electricity (Fig. 3a), emissions from fossil combustion decline markedly, but emissions from electricity remain substantial. Conversely, with faster (LREC) electricity decarbonization but Regular Renovation of existing homes (Fig. 3b), emissions from fuel use remain large, and are locked in for decades (beyond 2060) through installation of fossil-based replacement heating equipment. The most impressive emission reductions result from the combination of rapid (CFE) decarbonization of electricity and extensive renovation, with further reductions possible from construction of new homes which are smaller, electrified, and more multifamily (Extended Data Fig. 2). With the most optimistic combination of renovation, new housing, and stock scenarios, the additional emission reductions from completely decarbonizing electricity by 2035 (CFE) compared to LREC are immense, 2050 annual emissions reduce from 227 to 83 $MtCO_{2e}$/yr (Fig. 3c vs Fig. 3d) and cumulative 2020-2060 emissions reduce from 17.7 to 12.0 $GtCO_{2e}$ (Fig. 2). After electricity emissions reach zero in 2035, subsequent reductions in CFE scenarios are more gradual, and annual emissions decline slowly from 2045 onwards (Fig. 1, Fig. 3d). In CFE-ER scenarios, the majority of emissions from 2050 onwards are from construction (Fig. 3d). Embodied emissions projections assume improvements in material production and construction activities leading to ~23% reductions in average embodied emission intensities ($kgCO_{2e}/m^2$) by 2060[19]. Greater reductions in embodied emissions could result from building without basements or garages, substituting wood for concrete structural elements, using low-carbon cementitious materials, greater electrification of construction transport and energy use, and avoiding insulation with high-GWP blowing agents[19,28–30].

Our lowest emission scenario shows combined energy and embodied emissions of 0.25 ton CO_{2e}/cap by 2050, down from 2.74 ton CO_{2e}/cap in 2020. This is lower than 2050 per-capita US residential emissions in the lowest emission scenario from Goldstein et al.[31] (0.62 ton $CO2_{2e}$/cap, energy emissions only), but higher than 0.15 ton CO_{2e}/cap from the lowest emission scenario by Pauliuk et al.[17] (embodied emissions and energy emissions from heating, cooling, and hot water only) or 0.17 ton CO_2e/cap from IEA's sustainable development scenario[32] (energy emissions only).

Geographical variation in strategy potential

Tremendous geographical variation exists in the effectiveness of strategies, depending on local housing stock characteristics, GHG intensity of electricity, population projections, and climate. Fig. 4 compares percentage reductions in cumulative 2020-2060 emissions by state from Extensive Renovation, LREC electricity, IE-RFA new housing and High-Multifamily stock growth. CFE electricity is excluded from this comparison, as LREC represents a less challenging yet optimistic electricity supply scenario to compare against non-electricity strategies.

Extensive renovation has greatest influence in regions with cold/mixed climates, low GHG-intensity electricity, low shares of electric heating, higher shares of old housing, and lower population growth. New England (northeast US) and New York state demonstrate the greatest potential, with 31-35% reduction of cumulative emissions (Fig. 4a). LREC electricity supply has the greatest influence in regions with high 2020 electricity GHG intensity, greater reductions in electricity GHG intensity (Extended Data Fig. 3-4), and high shares of electric heating. In relative terms the greatest reductions occur in Missouri, Kansas, Tennessee, and Kentucky (30-34%, Fig. 4b). Combining ER and LREC provides high reductions in regions which benefit from each strategy individually, and especially large reductions in regions with colder climates, low electric heat share and older homes, but relatively GHG-intensive electricity in 2020 (Sup. Fig 32b). One illustrative example is Wisconsin, where reductions from ER and LREC individually are 7% and 20% respectively, but the combined reduction from ER-LREC is 38%.

Constructing new homes with IE and RFA has greatest influence in areas with less GHG-intensive electricity, high population growth, and lower shares of electric heating, while emission reductions from High-Multifamily stock growth are greatest in regions with high population growth and large differences in electrification between single- and multifamily homes. For both IE-RFA and High-Multifamily, relative emission reductions are greatest in California. Absolute emission reductions from each strategy are largest in populous states like Texas, New York and California (Supp. Fig 30). The most effective strategy can be identified in each county, and is most often ER or LREC (Extended Data Fig. 5a). Excluding electricity supply scenarios shows that IE-RFA and High-Multifamily can be preferable to Extensive Renovation in fast-growing counties in states including Texas, Florida, and Georgia (Extended Data Fig. 5b).

Technical, economic and policy challenges to mitigation

Technical challenges for renewable-driven electricity decarbonization include diurnal and seasonal balancing of supply and demand, and maintaining grid stability with high penetration of inverter-based (wind and solar) technologies[4]. The MC / LREC scenarios[22] project factor 4.8 / 6 increases in combined wind and solar generating capacity between 2020 and 2050, requiring average annual combined wind and solar increases of 26 / 35 GW respectively, with growth in solar including increases in residential rooftop PV. This is comparable to current growth rates. Between 2019 and 2020, combined wind and solar capacity grew by 30GW[33], up from 5GW in 2014. A continuation of growth rates since 2014 would see annual increases of 102 GW by 2030. The closest description of an electricity system comparable to the CFE scenario is the 2050 100% renewable electricity scenario from Cole et al.[3]. To reach 100% renewable supply by 2035 would require average annual increases in combined wind and solar capacity of 119 GW from 2020. Assuming no land requirements for offshore wind and distributed rooftop PV, land use for wind and solar would grow from 41,800 km^2 in 2020 to 92,000 / 152,800 km^2 by 2050, in MC / LREC respectively, or 179,300 km^2 for 100% renewable electricity by 2035. Electricity grids approaching 100% renewable generation may exhibit non-linear increases in incremental system costs above 95% renewable generation[3]. Increased transmission connection between Eastern and Western Interconnections in the US can reduce costs of electricity supply, and enable lowest-cost generation mixes with high (85%) renewable penetration[34]. Increased transmission and electricity storage capacity can also help to smooth regional and temporal imbalances in electricity demand and supply, and will be important in energy systems with increased end-use electrification and high penetration of variable renewable generation[35]. For seasonal supply-demand imbalances, alternative storage solutions such as power-to-hydrogen may be required[4].

Extensive renovation of existing homes requires increased insulation and reduced infiltration, and replacement of space and water heating equipment with high efficiency heat pumps and electric water heaters. Supplementary Information Section 3 details the changes in equipment and envelope characteristics in renovation scenarios, as well as costs and emission reductions from specific renovation measures. With extensive renovation, envelope upgrades improve 7 million housing units per year by 2040, while 6-7 million heat pumps will be installed in existing homes from 2035 onwards (Extended Data Fig. 6). Including installations in new homes, annual demand for heat pump units could grow to 9 million in 2050. Such growth in heat pump supply appears possible considering current growth trajectories (Supp. Fig 12), and industry capacity for producing AC units, which have similar manufacturing requirements[36]. Fossil-fuel to heat pump replacements offer substantial GHG reductions especially in cold climates; these replacements are economical when replacing fuel oil or propane, but can lead to higher costs when replacing natural gas equipment (Supp. Fig 17). This is one potential economic barrier to residential decarbonization, and focused policy support may be required for gas to heat pump renovations. Envelope renovations offer high GHG reductions, particularly in cold regions and in homes without much insulation, and are usually economic (Supp. Fig 19). Combined heating system and envelope renovations offer the largest emission reductions, particularly for fossil to heat pump replacements in cold climates (Supp. Fig 20). Energy reductions from envelope and heating renovations are largest in older (<1960) single-family homes in cold climates (Supp. Table 6-7). Our economic assessment of renovation strategies considers only renovations occurring through 2025, and are subject to considerable uncertainty surrounding future equipment and energy costs and discount rates.

Residential renovations in the US are supported by a patchwork of utility, federal, and local initiatives, including utility efficiency programs, low-income weatherization programs, and tax credits. Federal standards set minimum efficiency levels for replacement equipment, but the levels have historically been set separately for electric and fossil equipment, and thus have not encouraged adoption of more efficient electric equipment over fossil alternatives[37]. Very few state or utility efficiency programs reward energy or emissions savings from fuel switching[38], while numerous states discourage or prohibit fuel-switching[39]. The Better Energy, Emissions, and Equity initiative[40] launched in May 2021 aims to accelerate the adoption of heat pump water heaters and improve the performance of cold climate heat pumps. The proposed Build Back Better Act also includes rebates for qualifying electrification projects, which could boost heat pump replacements. Heat pump electrification of space heating can be more cost-effective when purchasing new or replacement air conditioners, so that heating and cooling equipment costs are combined[36]. This is not considered in our economic assessment of renovations, but could substantially improve the economics of natural gas to heat pump renovations. Although housing tenure is outside of our model framework, split incentives between landlords and tenants are another potential barrier to residential renovations[41]. To address this, efficiency programs can target rental homes with incentives, alternative financing solutions (e.g. on-bill financing) and building performance standards to ensure accelerated renovations of rental housing, particularly in communities with lower access to clean efficient energy[21].

Challenges surrounding building fewer large homes or more multifamily homes mostly relate to policy and societal norms. Policy options include introducing size limits, removing zoning and other local restrictions on denser housing[42,43], and restructuring Federal tax policies which make multifamily investments costlier than single-family[44]. RFA and high multifamily stock growth could stabilize floor area per capita at current levels[19], but will not induce substantial reductions (Extended Data Fig. 7). Thus, reducing floor area consumption to sufficiency levels (40 m^2/cap or lower) cannot be done by focusing on new housing alone[19]; doing so would require strategies for existing homes, such as household sharing[45], or converting existing single-family homes into multiple housing units. In our lowest emission scenarios, where construction becomes the majority emission source by mid-century, such measures targeting existing homes would reduce the need for new construction, and make zero emissions targets much more attainable. Otherwise, the elimination of embodied emissions will rely on material efficiency[17] and greater advances in low-carbon material selection and production[28,29].

Conclusion

In this paper we assess decarbonization pathways for residential buildings in the US in 108 scenarios to 2060, incorporating embodied and energy-related emissions. Our analysis delivers new insights into how much emissions can be reduced from different mitigation measures, in various segments of the housing stock. The pathways with lowest emissions require rapid decarbonization of electricity alongside extensive electrification-focused renovations of existing homes. Most of the energy related emissions in 2060 will be from homes that exist today. However, increasing the turnover of housing stock will not reduce residential emissions, due to higher embodied emissions, and because efficiency benefits are partially offset by larger new homes. Accelerated and deep renovation of existing homes is therefore a crucial component of residential decarbonization. Envelope and heating renovations are particularly impactful in regions with cold climates, low shares of electric heating, and large shares of old homes. In new homes, substantial emission reductions arise from avoiding construction of excessively large houses, or increasing the electrification of heating, especially when combined with rapid grid decarbonization. The characteristics of new homes are most influential in regions with strong population growth. Regions with high shares of electric heating and high GHG intensity of electricity benefit most from rapid electricity decarbonization. Our least-emission scenario still projects 12 Gt of cumulative CO_{2e} emissions between 2020 and 2060, which is 57% of the US's entire carbon budget for meeting 1.5°C with 50% likelihood. Targeting 1.5°C would therefore require solutions beyond the most ambitious scenarios presented here, including more comprehensive reductions of embodied emissions, through reduced floor area growth and innovations in material production.

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Author Contributions

P.B. and E.G.H. conceived the study. P.B. designed the scenarios with input regarding practical energy simulation considerations from J.L.R., A.D.F. and E.J.H.W. P.B. ran the energy simulations with assistance from A.D.F. P.B. performed the post-processing and graphical representation of the results. The writing of the manuscript was led by P.B. with substantive input from E.J.H.W. and E.G.H.

Competing Interests Statement

The authors declare no competing interests.

Tables

Table 1 Description of the dimensions which combine to generate the 108 scenarios

Housing Stock Evolution	Description
1. Baseline Stock Growth	Stock turnover based on historical rates by house type and region.
2. High Stock Turnover	Housing stock turnover rates increase by factor of 1.5
3. High Multifamily Growth (c.f. Supp. Fig. 2, 3, 25)	Multifamily population share grows by 0.25 percentage points per year in counties with 20-year population growth > 5%.
New Housing Characteristics	Description
A. Baseline	Future floor area distributions by metro region and house type unchanged from 2010s. Slow/moderate growth of electrification of end uses differentiated by Census Division
B. Reduced Floor Area (RFA) (c.f. Supp. Fig. 23, 24)	No new housing unit is larger than 279 m^2. Increased shares of new housing built in the 185–278 m^2 size range. Average size of new single-family reduces 25% from 258 to 192 m^2.
C. Increased Electrification (IE) (c.f. Supp. Fig. 22)	Faster increase of all-electric new homes, considering spread of electricity and gas prices by Census Division. All new homes all-electric by 2030 in every Census Region except Northeast, which reaches all-electric new construction by 2040
D. IE & RFA	Combination of new housing characteristic scenarios B and C
Renovation of Existing Stock	Description
Regular Renovation (RR) (Supplementary Information Section 3)	Renovation continues at historic rates, moderate efficiency improvements and slow electrification of space/water heating
Advanced Renovation (AR)	Renovation rates increase by factor of 1.5 relative to historic levels (leading to earlier retirements of existing equipment), with high efficiency improvements and moderate increase in electric share of space/water heating equipment replacements
Extensive Renovation (ER)	Similar to AR except higher share of heat pumps in space/water heating renovations. 100% electric heat pump replacements of fossil heating equipment from 2025
Electricity Supply Scenarios	Description
Mid-Case Electricity (MC) (c.f. Supp. Fig. 27)	Reference scenario from NREL Standard Scenarios[22], grouped by Cambium Generation and Emissions Assessment Region[46]. National average GHG intensity of 169 $kgCO_2/kWh$ by 2050
Low Renewable Energy Cost Electricity (LREC)	NREL Standard Scenario with lowest GHG intensity, reaching national average of 82 $kgCO_2/kWh$ by 2050
Carbon Free Electricity by 2035 (CFE)	Government target for carbon-free electricity generation by 2035[23]. Trajectory assumed to map LREC until 2025, reach half of 2025 intensity by 2030, and reach 0 $kgCO_2/kWh$ by 2035

The four scenario dimensions which combine to generate the scenario space appear in bold

References

1. IEA. *World Energy Balances 2020*. https://www.iea.org/data-and-statistics/data-product/world-energy-balances (2020).

2. Berrill, P., Gillingham, K. T. & Hertwich, E. G. Drivers of change in U.S. residential energy consumption and greenhouse gas emission, 1990-2015. *Environ. Res. Lett.* **16**, 03045 (2021).

3. Cole, W. J. *et al.* Quantifying the challenge of reaching a 100% renewable energy power system for the United States. *Joule* **5**, 1732–1748 (2021).

4. Denholm, P. *et al.* The challenges of achieving a 100% renewable electricity system in the United States. *Joule* **5**, 1331–1352 (2021).

5. Power, A. Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social and economic viability? *Energy Policy* **36**, 4487–4501 (2008).

6. Dubois, M. & Allacker, K. Energy savings from housing: Ineffective renovation subsidies vs efficient demolition and reconstruction incentives. *Energy Policy* **86**, 697–704 (2015).

7. Ding, G. & Ying, X. Embodied and operating energy assessment of existing buildings – Demolish or rebuild. *Energy* **182**, 623–631 (2019).

8. Cabrera Serrenho, A., Drewniok, M., Dunant, C. & Allwood, J. M. Testing the greenhouse gas emissions reduction potential of alternative strategies for the english housing stock. *Resour. Conserv. Recycl.* **144**, 267–275 (2019).

9. Berrill, P., Miller, T. R., Kondo, Y. & Hertwich, E. G. Capital in the American carbon, energy, and material footprint. *J. Ind. Ecol.* **24**, 589–600 (2020).

10. Schwartz, Y., Raslan, R. & Mumovic, D. The life cycle carbon footprint of refurbished and new buildings – A systematic review of case studies. *Renew. Sustain. Energy Rev.* **81**, 231–241 (2018).

11. Saheb, Y. COP26: Sufficiency Should be First. *Buildings & Cities* (2021).

12. Samadi, S. *et al.* Sufficiency in energy scenario studies: Taking the potential benefits of lifestyle changes into account. *Technol. Forecast. Soc. Change* **124**, 126–134 (2017).

13. Lorek, S. & Spangenberg, J. H. Energy sufficiency through social innovation in housing. *Energy Policy* **126**, 287–294 (2019).

14. Thomas, S. *et al.* Energy sufficiency policy for residential electricity use and per-capita dwelling size. *Energy Effic.* **12**, 1123–1149 (2019).

15. Cohen, M. J. New Conceptions of Sufficient Home Size in High-Income Countries: Are We Approaching a Sustainable Consumption Transition? *Housing, Theory Soc.* **38**, 173–203 (2021).

16. Grubler, A. *et al.* A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat. Energy* **3**, 515 (2018).

17. Pauliuk, S. *et al.* Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. *Nat. Commun.* **12**, 5097 (2021).

18. Millward-Hopkins, J., Steinberger, J. K., Rao, N. D. & Oswald, Y. Providing decent living with minimum energy: A global scenario. *Glob. Environ. Chang.* **65**, 102168 (2020).

19. Berrill, P. & Hertwich, E. Material flows and GHG emissions from housing stock evolution in US counties, 2020-2060. *Build. Cities* **2**, 599–617 (2021).

20. Ellsworth-Krebs, K. Implications of declining household sizes and expectations of home comfort for domestic energy demand. *Nat. Energy* **5**, 1–6 (2019).

21. Goldstein, B., Reames, T. G. & Newell, J. P. Racial inequity in household energy efficiency and carbon emissions in the United States: An emissions paradox. *Energy Res. Soc. Sci.* **84**, 102365 (2022).

22. Cole, W., Corcoran, S., Gates, N., Mai, T. & Das, P. *2020 Standard Scenarios Report : A U . S . Electricity Sector Outlook*. https://www.nrel.gov/docs/fy21osti/77442.pdf (2020).

23. The White House. FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies. *Statements and Releases* https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/ (2021).

24. Otto, I. M. *et al.* Social tipping dynamics for stabilizing Earth's climate by 2050. *Proc. Natl. Acad. Sci. U. S. A.* (2020) doi:10.1073/pnas.1900577117.

25. The White House. United States Mid-Century Strategy for Deep Decarbonization. 111 https://unfccc.int/files/focus/long-term_strategies/application/pdf/us_mid_century_strategy.pdf (2016).

26. IPCC. IPCC, 2021: Summary for Policymakers. in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press., 2021). doi:10.1260/095830507781076194.

27. van den Berg, N. J. *et al.* Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Clim. Change* **162**, 1805–1822 (2020).

28. Churkina, G. *et al.* Buildings as a global carbon sink. *Nat. Sustain.* 1–8 (2020) doi:10.1038/s41893-019-0462-4.

29. Pamenter, S. & Myers, R. J. Decarbonizing the cementitious materials cycle: A whole-systems review of measures to decarbonize the cement supply chain in the UK and European contexts. *J. Ind. Ecol.* **25**, 359–376 (2021).

30. Arceo, A., Tham, M., Guven, G., Maclean, H. L. & Saxe, S. Capturing variability in material intensity of single-family dwellings : A case study of Toronto , Canada. *Resour. Conserv. Recycl.* **175**, 105885 (2021).

31. Goldstein, B., Gounaridis, D. & Newell, J. P. The carbon footprint of household energy use in the United States. *Proc. Natl. Acad. Sci.* **54**, 201922205 (2020).

32. IEA. *World Energy Outlook 2020*. https://www.iea.org/reports/world-energy-outlook-2020 (2020).

33. EIA. *Electric Power Annual 2020 (Table 4.2B)*. https://www.eia.gov/electricity/annual/ (2021).

34. Acevedo, A. L. F. *et al.* Design and Valuation of High-Capacity HVDC Macrogrid Transmission for the Continental US. *IEEE Trans. Power Syst.* **36**, 2750–2760 (2021).

35. Murphy, C. *et al. Electrification Futures Study : Scenarios of Power System Evolution and Infrastructure Development for the United States*. https://www.nrel.gov/docs/fy21osti/72330.pdf (2021).

36. Pantano, S., Malinowski, M., Gard-Murray, A. & Adams, N. *3H 'Hybrid Heat Homes'*. https://www.clasp.ngo/research/all/3h-hybrid-heat-homes-an-incentive-program-to-electrify-space-heating-and-reduce-energy-bills-in-american-homes/ (2021).

37. Deason, J., Wei, M., Leventis, G., Smith, S. & Schwartz, L. *Electrification of buildings and industry in the United States Drivers , barriers , prospects , and policy approaches*. https://www.osti.gov/biblio/1430688 (2018) doi:10.2172/1430688.

38. Billimoria, S. & Henchen, M. *Regulatory solutions for Building Decarbonization: Tools for commissions and other government agencies*. rmi.org/insight/regulatory-solutions- for-building-decarbonization (2020).

39. ACEEE. *State Policies and Rules to Enable Beneficial Electrification in Buildings through Fuel Switching*. https://www.aceee.org/sites/default/files/pdfs/fuel_switching_policy_brief_4-29-20.pdf (2020).

40. U.S. Department of Energy. Energy, Emissions and Equity (E3) Initiative. *Office of Energy Efficiency & Renewable Energy* https://www.energy.gov/eere/buildings/energy-emissions-and-equity-e3-initiative (2021).

41. Melvin, J. The split incentives energy efficiency problem: Evidence of underinvestment by landlords. *Energy Policy* **115**, 342–352 (2018).

42. Gyourko, J., Hartley, J. & Krimmel, J. The Local Residential Land Use Regulatory Environment Across U.S. Housing Markets: Evidence from a New Wharton Index. *NBER Work. Pap.* **26573**, (2019).

43. Gray, M. N. & Millsap, A. A. Subdividing the Unzoned City: An Analysis of the Causes and Effects of Houston's 1998 Subdivision Reform. *J. Plan. Educ. Res.* (2020) doi:10.1177/0739456X20935156.

44. Berrill, P., Gillingham, K. T. & Hertwich, E. G. Linking Housing Policy, Housing Typology, and Residential Energy Demand in the United States. *Environ. Sci. Technol.* **55**, 2224–2233 (2021).

45. Ivanova, D. & Büchs, M. Household sharing for carbon and energy reductions: the case of EU countries. *Energies* (2020).

46. Gagnon, P. *et al. Cambium Documentation : Version 2021*. https://www.nrel.gov/docs/fy22osti/81611.pdf (2021).

Figures with Legends/Captions

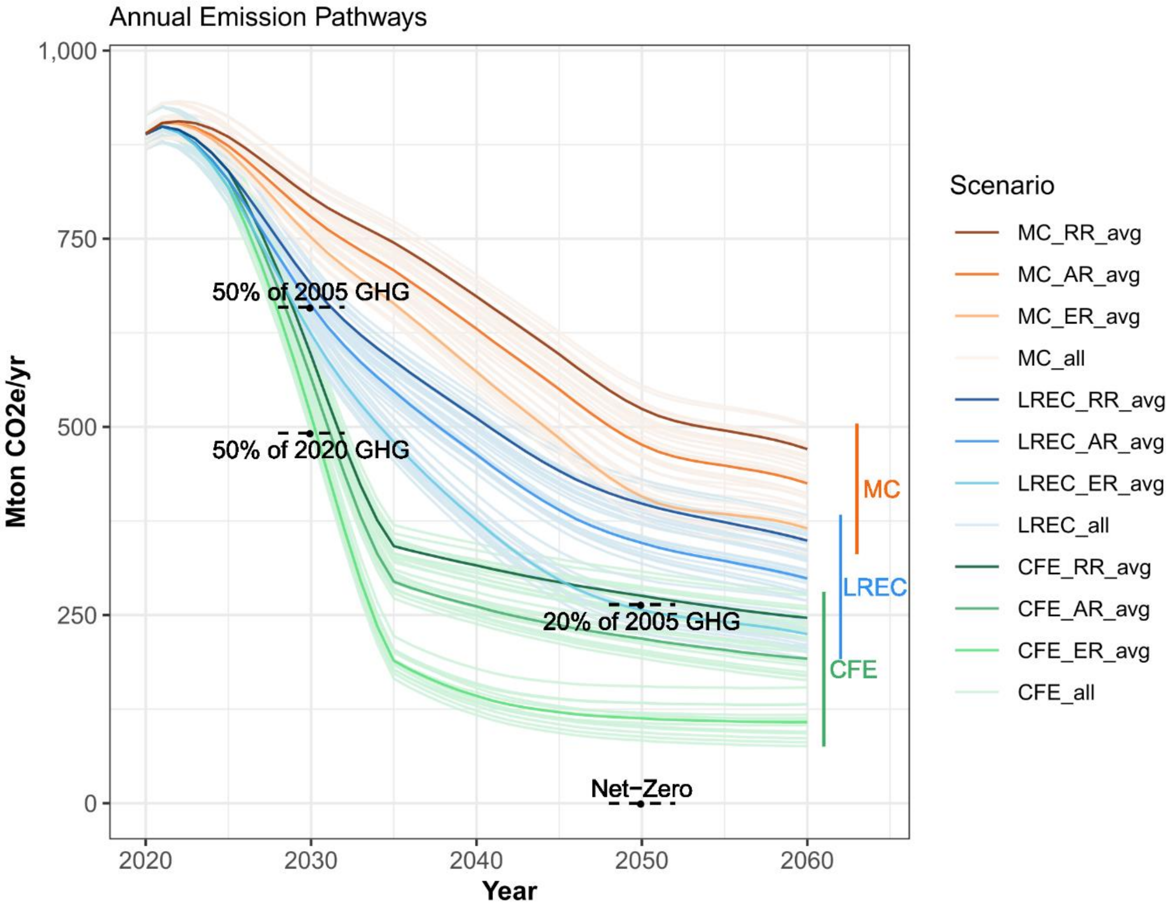


Fig. 1 Annual emission pathways for 108 scenarios. Emission pathways are summarized by the mean pathway in each electricity supply and renovation scenario combination, which appear in nine heavier lines. The light background lines represent each individual scenario, with the color representing the electricity supply scenario. MC = Mid-Case Electricity, LREC = Low-Cost Renewable Electricity; CFE = Carbon Free Electricity by 2035. RR = Regular Renovation, AR = Advanced Renovation, ER = Extensive Renovation.

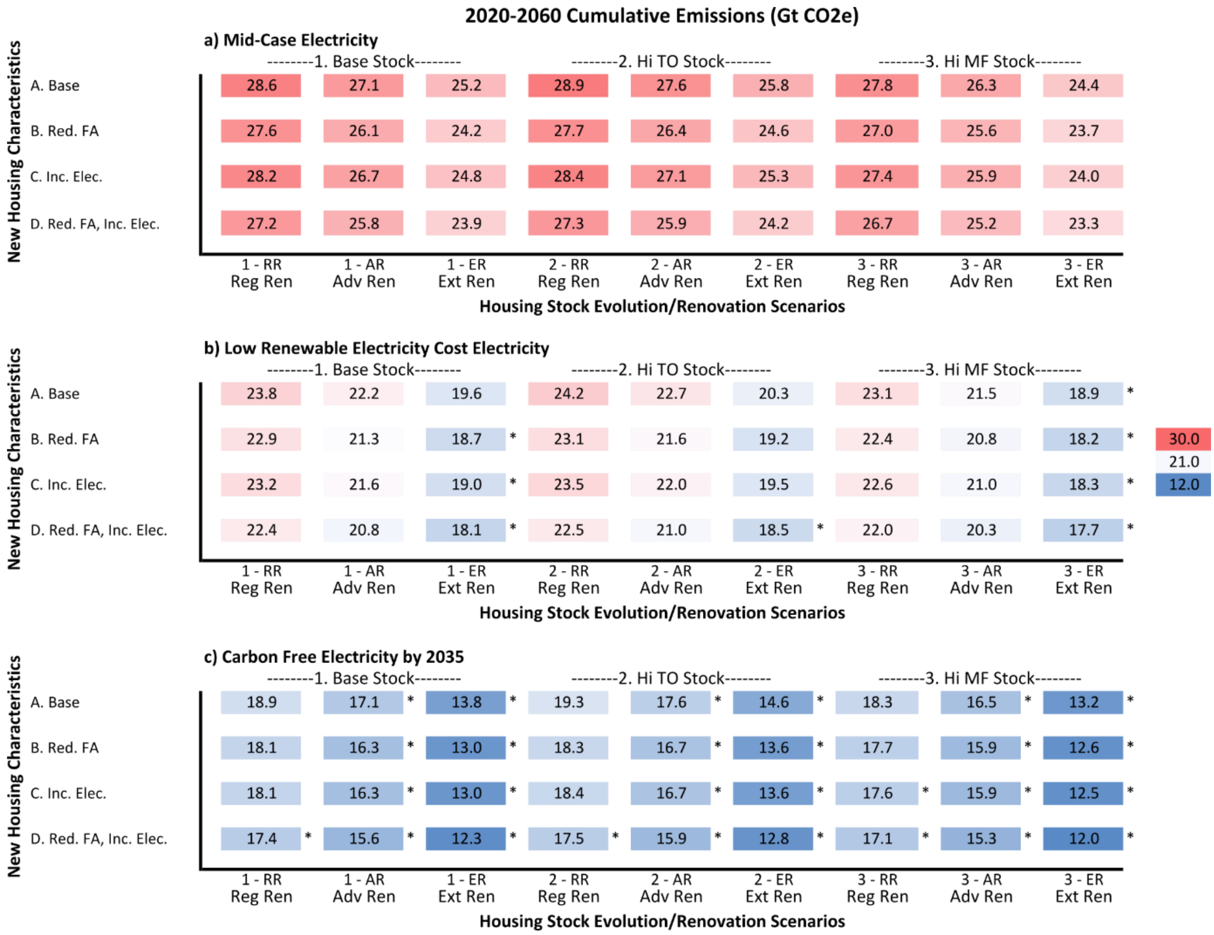


Fig. 2 Cumulative 2020-2060 emissions for 108 scenarios. Three panels show cumulative emissions for each electricity supply scenario: **a** Mid-Case, **b** Low Renewable Electricity Cost, **c** Carbon Free Electricity by 2035. Panel rows show variation by new housing characteristics, columns show variation by housing stock evolution and renovation scenarios. * identifies scenarios which meet the 2050 target of 20% of 2005 emissions or lower.

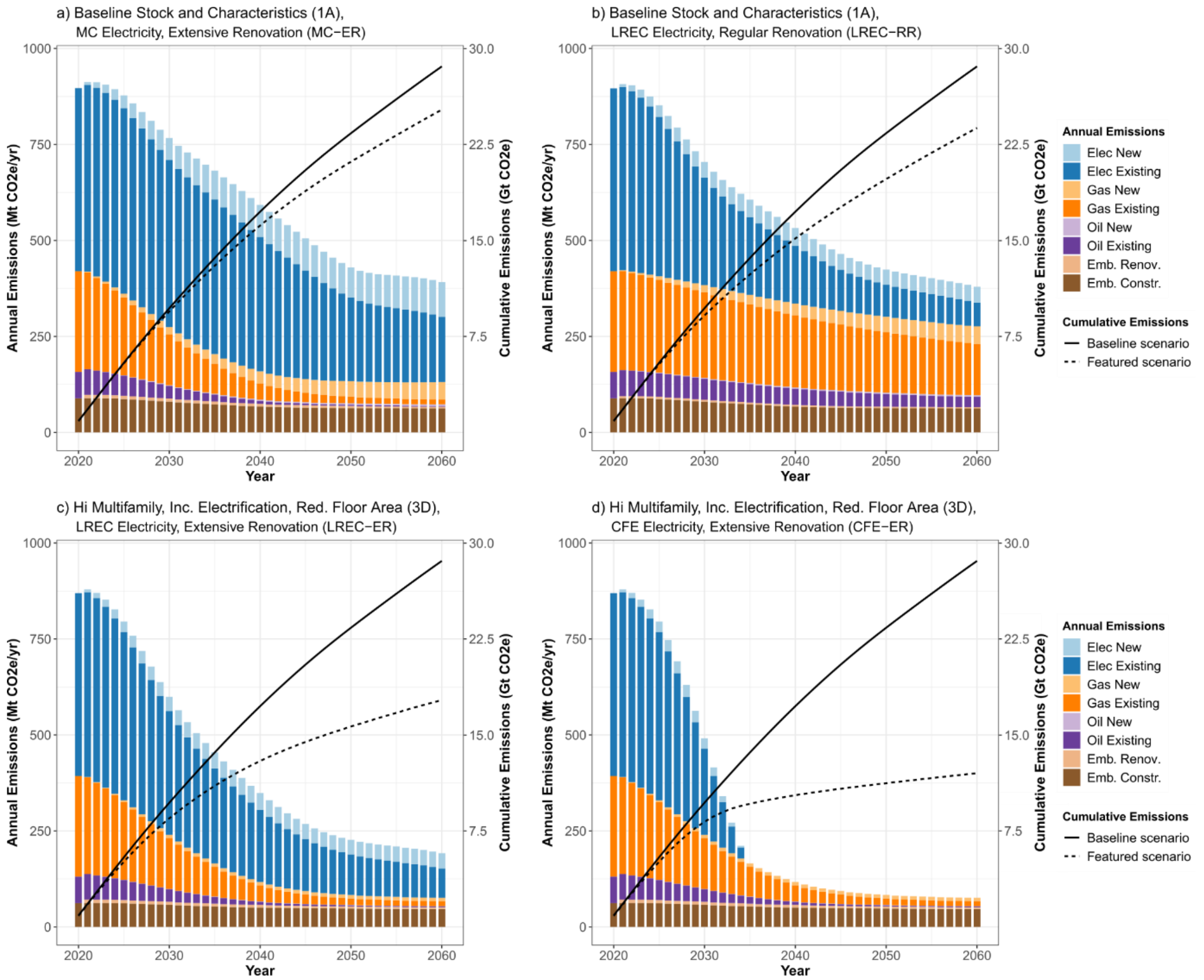


Fig. 3 Annual and cumulative emissions by source for four selected scenarios. a Baseline stock evolution and new housing characteristics, Mid-Case electricity supply and Extensive Renovation. **b** Baseline stock evolution and new housing characteristics, Low Renewable Electricity Cost electricity supply and Regular Renovation. **c** High Multifamily stock evolution, and Increased Electrification and Reduced Floor Area new housing characteristics, Low Renewable Electricity Cost electricity supply and Extensive Renovation. **d** High Multifamily stock evolution, and Increased Electrification and Reduced Floor Area new housing characteristics, Carbon Free Electricity by 2035 electricity supply and Extensive Renovation. Cumulative emissions (secondary y-axis) for each scenario (dotted line) are shown with respect to the Baseline scenario (solid line). Energy emissions are disaggregated by energy carrier and the portion of the stock (New = built after 2020, Existing = built before 2020), 'Oil' includes fuel oil and propane/LPG. Embodied (Emb.) emissions are split into new construction (Constr.) and renovation (Renov.).

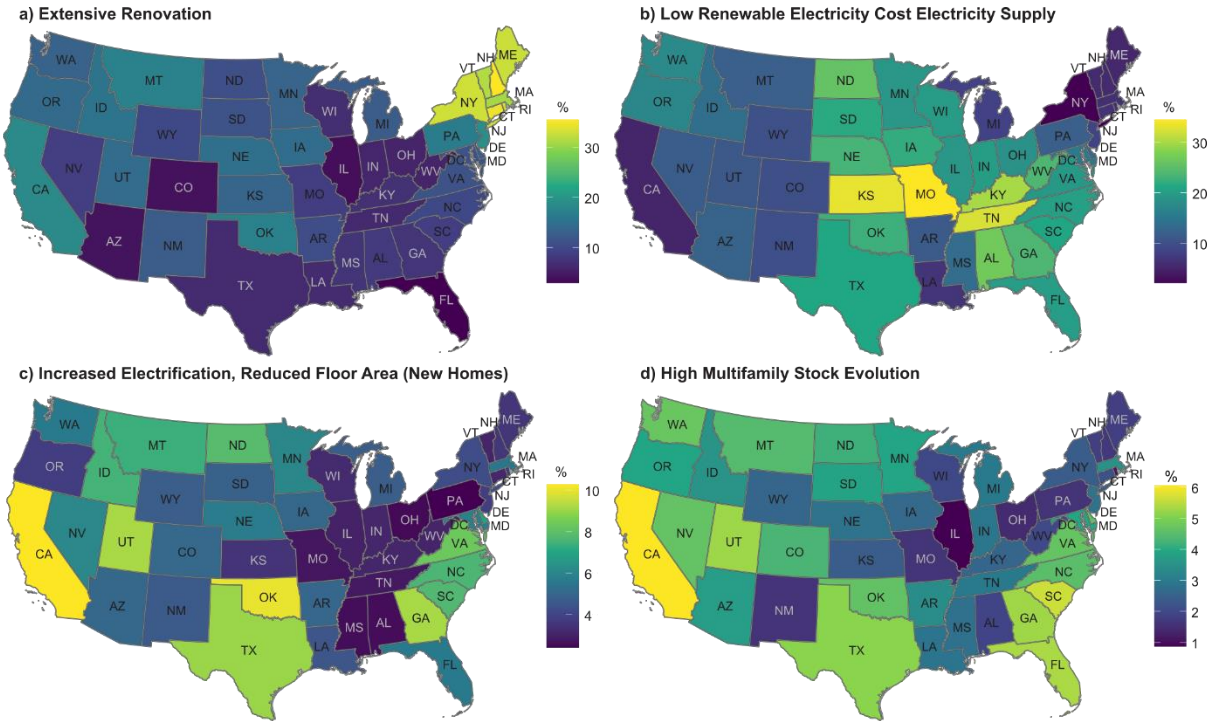
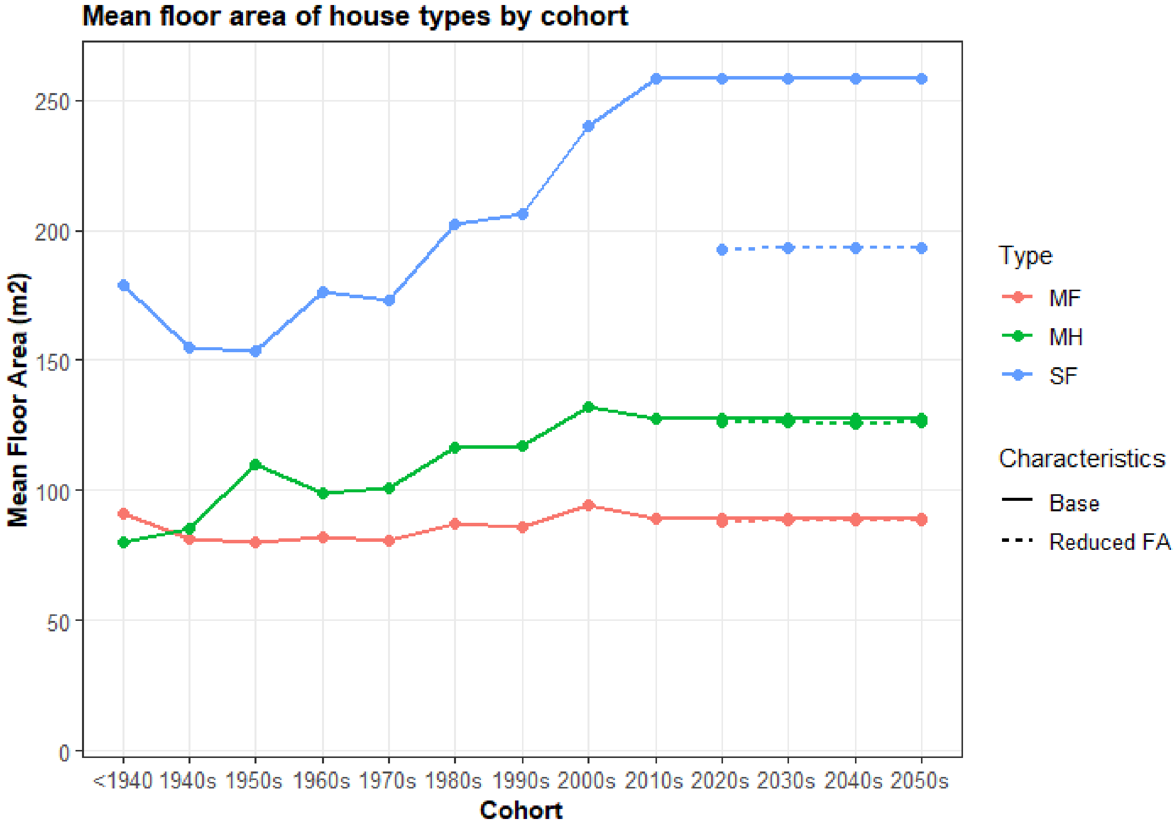
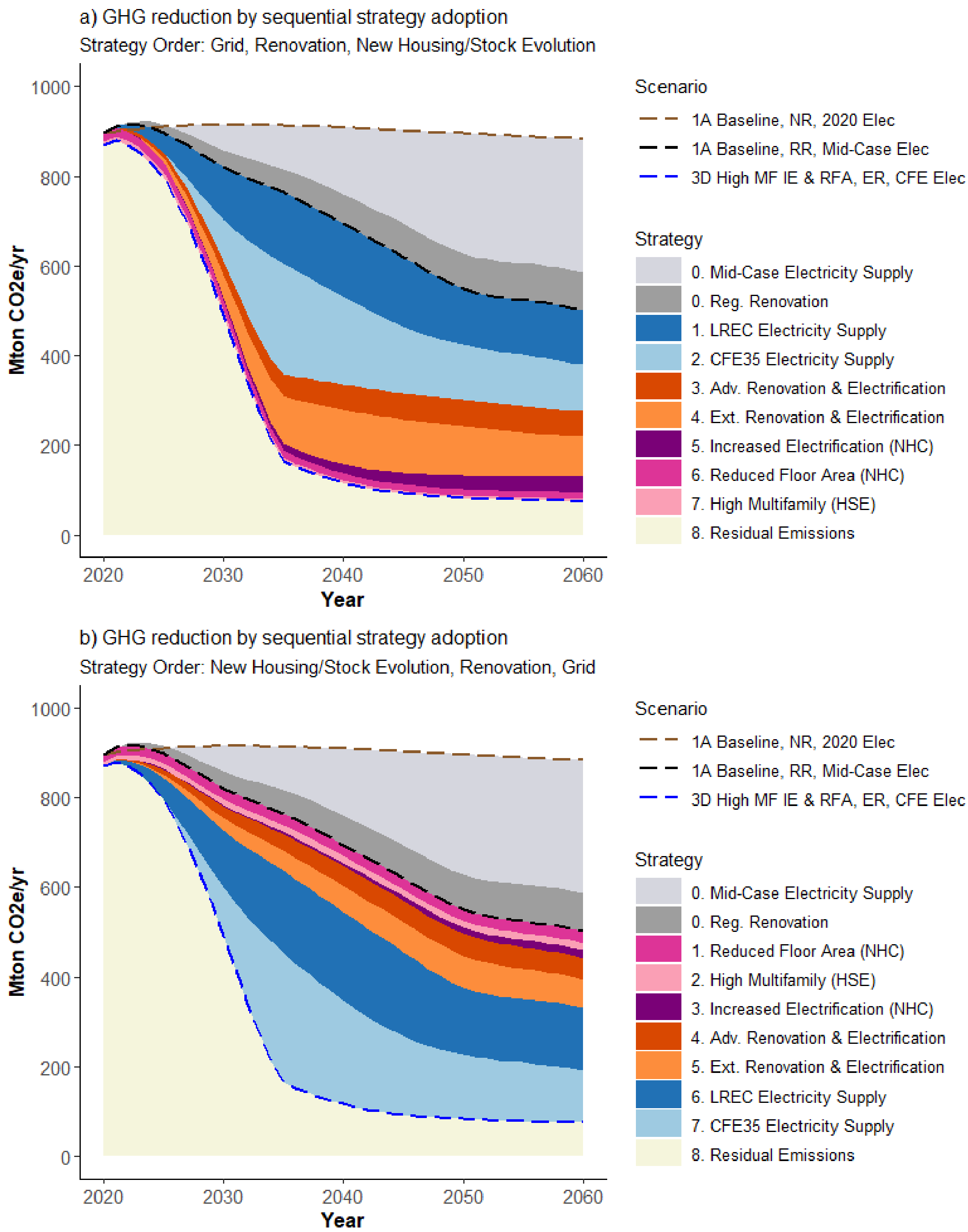


Fig. 4 Percent reductions in cumulative 2020-2060 emissions from individual strategies, by state. **a** Extensive Renovation, **b** Low Renewable Electricity Cost electricity supply, **c** Increased Electrification and Reduced Floor Area new housing characteristics, **d** High Multifamily stock evolution.

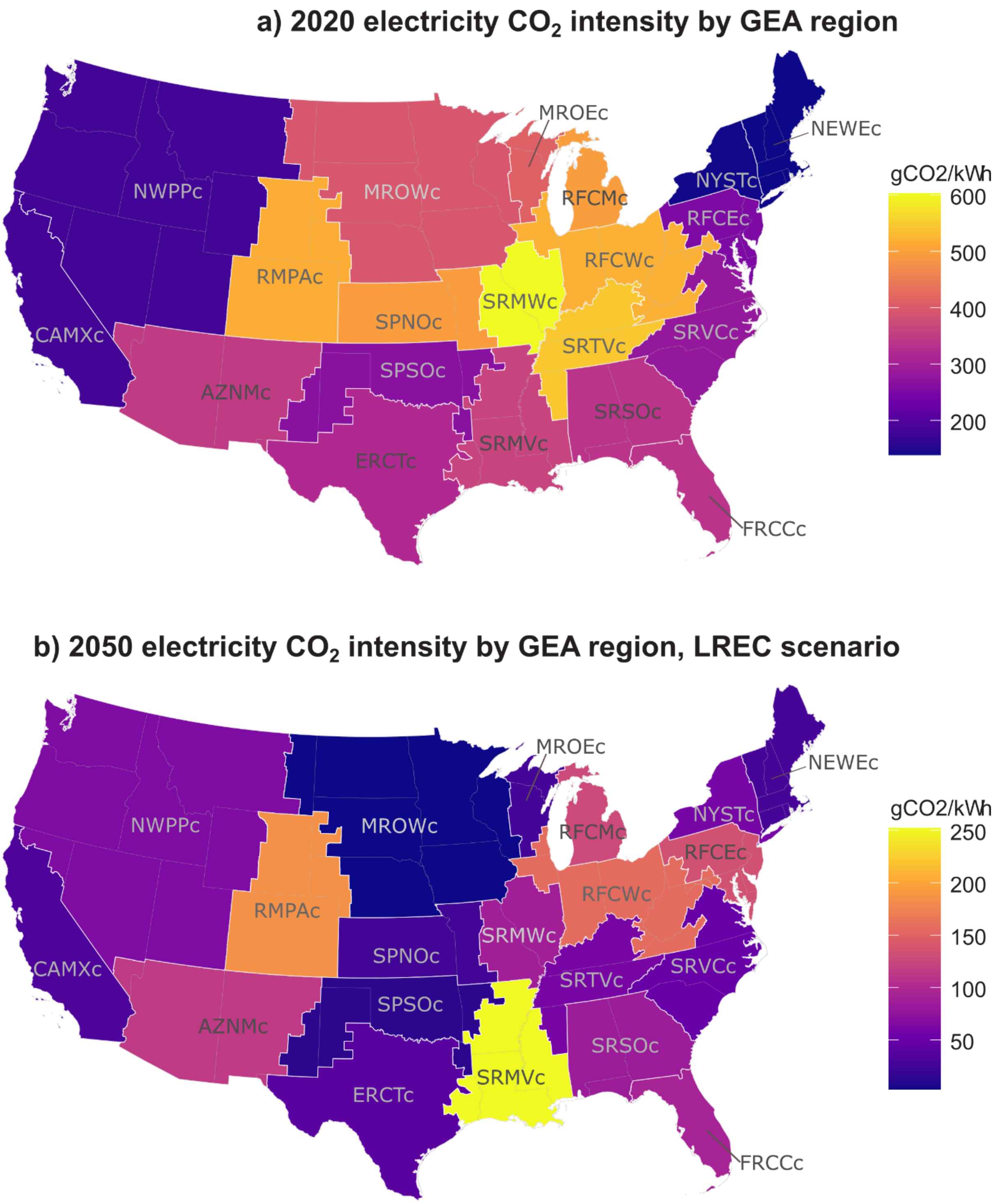
Extended Data Figures



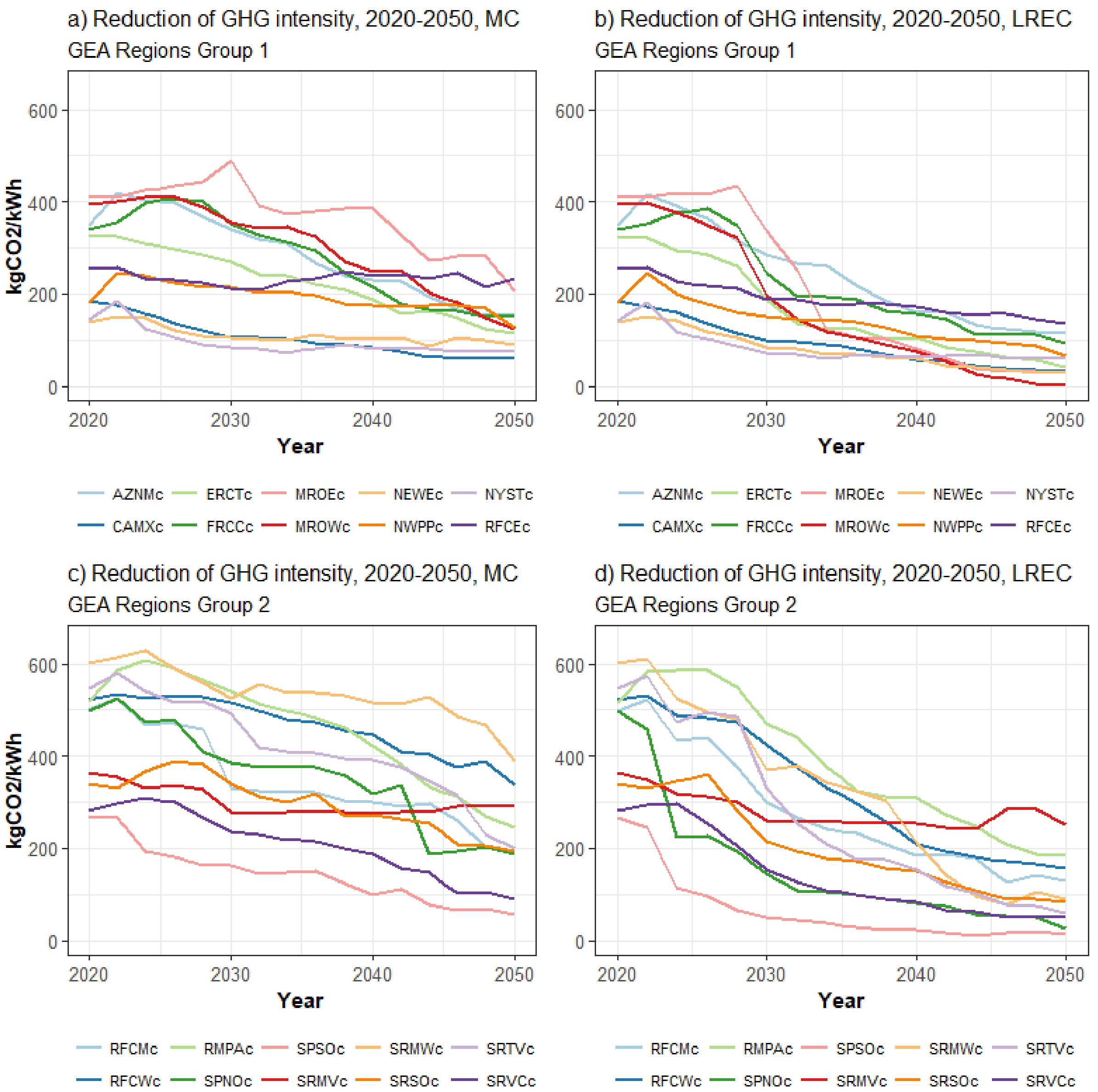
Extended Data Fig. 1 Mean floor area of housing by type and age cohort Values for cohorts up to 2010s are based on the housing stock as existing in 2020. Values for 2020s to 2050s cohorts are based on assumed characteristics of new housing in the Baseline and Reduced Floor Area (FA) new housing characteristics scenarios.



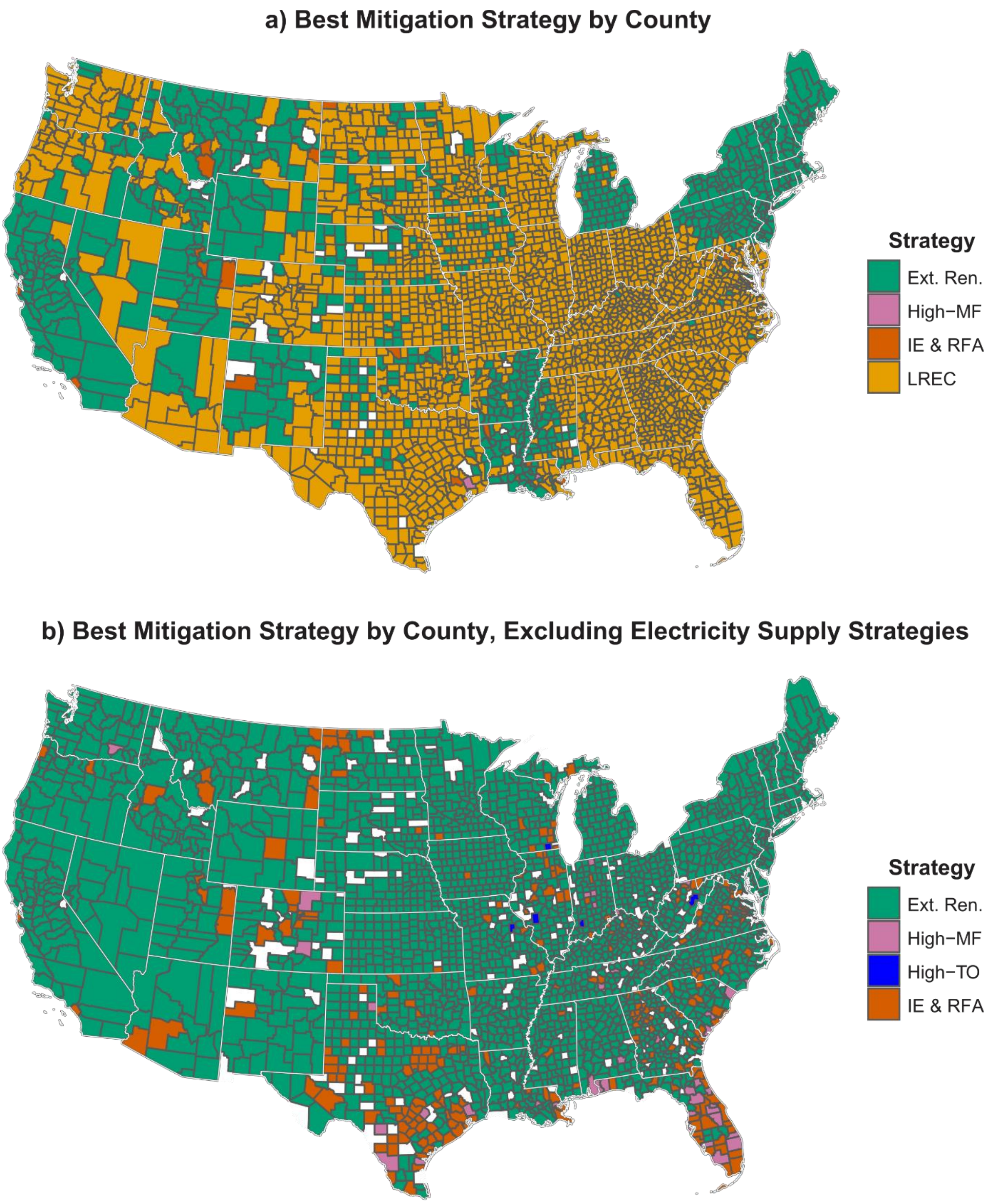
Extended Data Fig. 2 GHG emissions reduction by sequential strategy adoption. Mitigation actions beyond the Baseline scenarios (black dashed line) are grouped into strategies affecting electricity supply (blue), renovation of existing homes (orange), and housing stock evolution (HSE)/new housing characteristics (NHC) (pink/purple). **a** Strategies groups are ordered according to greatest cumulative emission mitigation potential. **b** Strategy groups are ordered according to reverse cumulative emission mitigation potential.



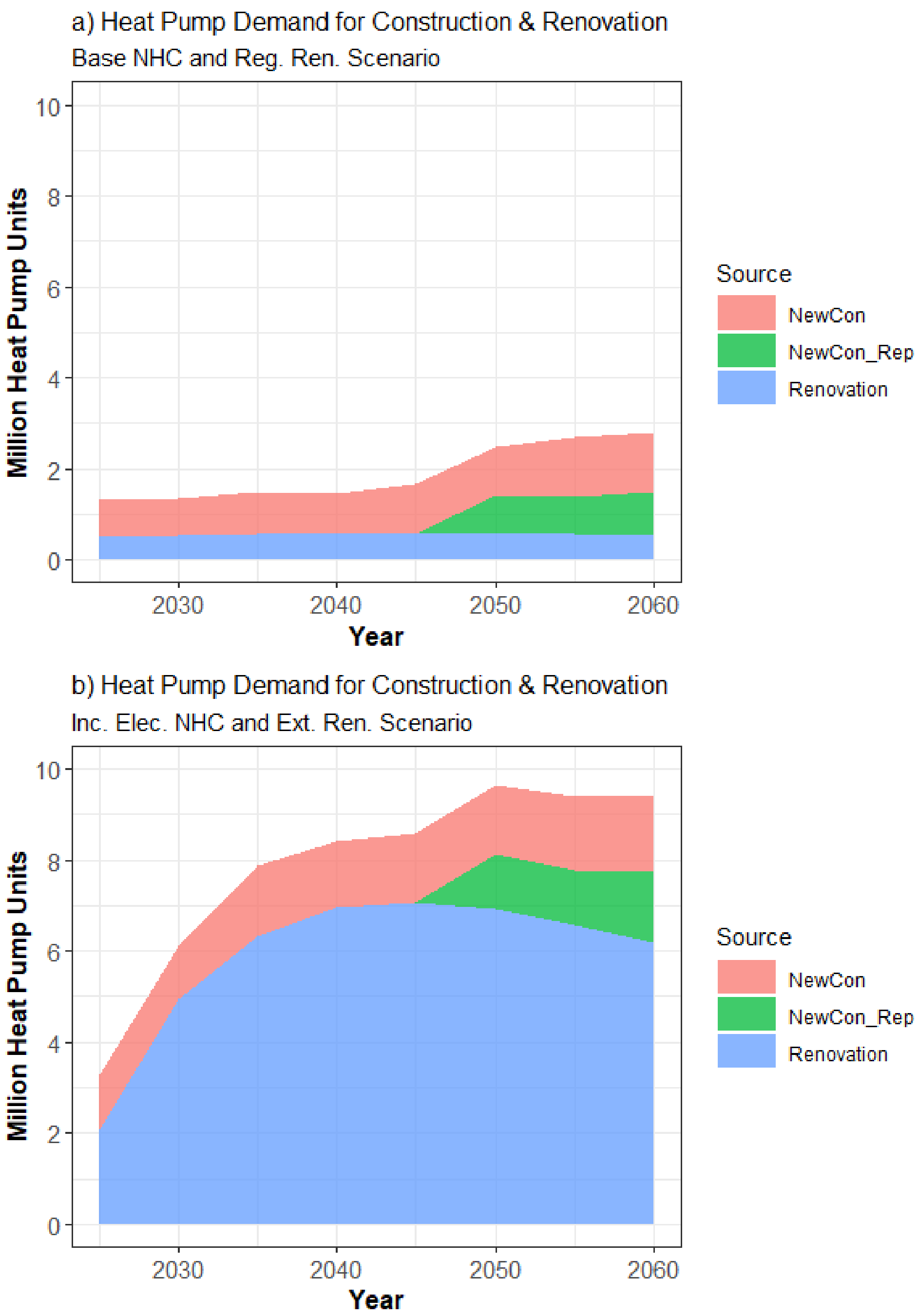
Extended Data Fig. 3 CO2 intensity of electricity generation in 2020 and 2050. a 2020 CO2 intensities. **b** 2050 CO2 intensities for the Low Renewable Electricity Cost electricity supply scenario. Emission intensities are aggregated into 20 Cambium Generation and Emission Assessment (GEA) regions46, weighted by total annual electricity generation in 134 balancing areas.



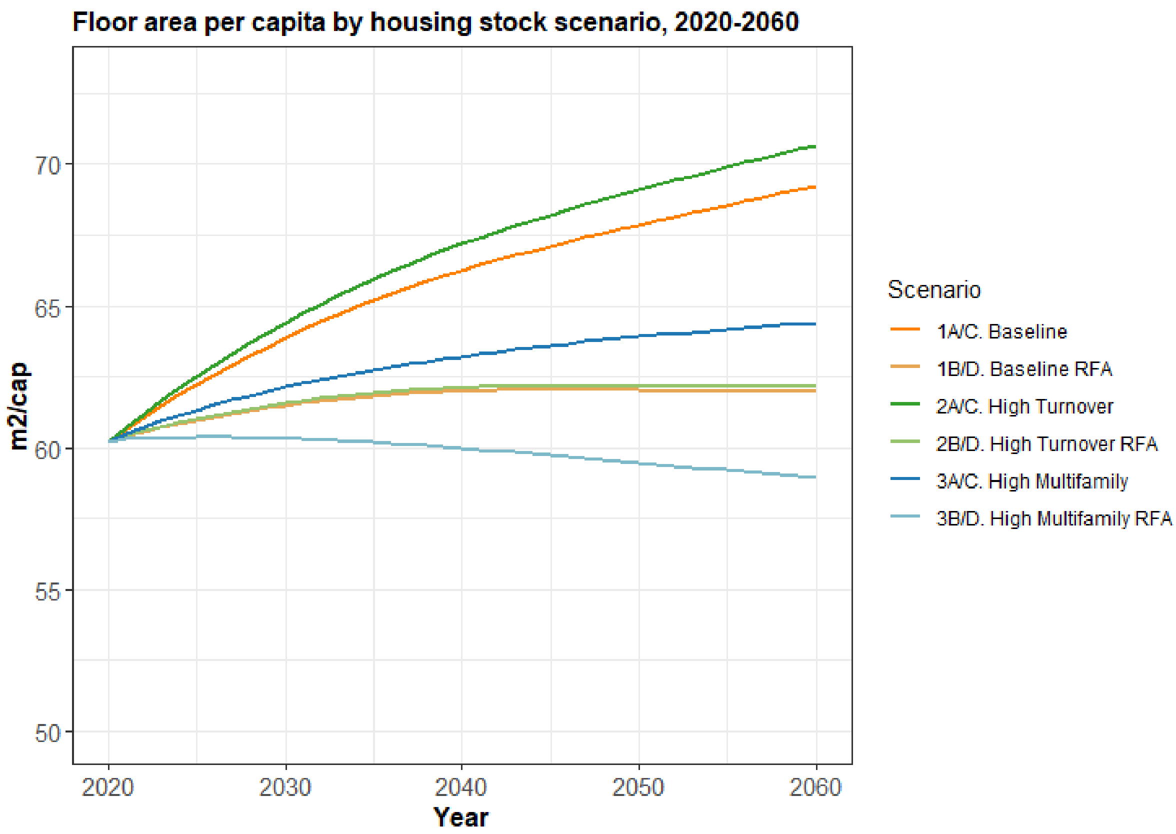
Extended Data Fig. 4 CO2 intensity of electricity generation, 2020-2050. Cambium Generation and Emission Assessment (GEA) regions46 are grouped in two groups based on alphabetical order, to facilitate legible legends. **a** Group 1 Mid-Case electricity supply, **b** Group 1 Low Renewable Electricity Cost electricity supply, **c** Group 2 Mid-Case electricity supply, **d** Group 2 Low Renewable Electricity Cost electricity supply. Further reductions of CO2 intensity of electricity were assumed beyond 2050, as described in Supplementary Information Section 5.



Extended Data Fig. 5 Identification of best individual strategy by county. a Strategies compared are Extensive Renovation (Ext. Ren.), High Multifamily (High-MF) and High Turnover (High-TO) stock evolution, (Increased Electrification and Reduced Floor Area (IE &RFA) new housing characteristics, and Low Renewable Electricity Cost (LREC) electricity supply. **b** Strategies compared include those considering in **a** except for Low Renewable Electricity Cost (LREC) electricity supply which is excluded.



Extended Data Fig. 6 Estimated annual demand for new space heating equipment for two selected scenarios, 2025-2060. Heat pump demand is shown by contributions from new construction (NewCon), replacement of units installed in new construction (NewCon_Rep), and Renovation. Efficiency gains from replacement of units in new construction is not considered in the energy and emissions analysis. The two selected scenarios represent two extremes in terms of low and high growth of heat pump demand; **a** Baseline new housing characteristics (NHC) and Regular Renovation (Reg. Ren.) of existing homes, and **b** Increased Electrification (Inc. Elec.) new housing characteristics and Extension Renovations (Ext. Ren.) of existing homes.



Extended Data Fig. 7 Mean floor area per capita by housing stock evolution and new housing characteristics scenarios. RFA = Reduced Floor Area.

Methods

Housing Stock and Characteristics Scenarios

Housing stock evolution and new housing characteristics scenarios are based on scenarios developed by Berrill and Hertwich[19], which is the source of estimated embodied emissions from material production and construction, and where a full description of the housing stock model (HSM) can be found. County population projections[47] drive the housing stock model[19], and are scaled to the mid-range scenario from the 2017 U.S. Census Bureau population projections to 2060[48]. The scenarios are extended for this work to include the scenario of increased electrification in new housing, and to describe scenarios renovation of existing housing.

Emissions from material production and onsite energy and transport in new construction are calculated for 51 housing archetypes[19], capitalizing on high resolution representation of US housing characteristics by house type, size, foundation type, heights, etc., in the ResStock housing characteristics data[49]. Embodied emissions from renovation activities are included for envelope renovations only. For a given archetype, an envelope renovation is assumed to require 10% of the cement, gypsum, glass and wood products, and 70% of the insulation materials required for an equivalent new construction[19]. Embodied emissions from energy equipment such as furnaces and heat pumps are not considered. Our calculations of embodied emissions from construction[19] incorporate moderately optimistic assumptions on reduction in GHG-intensity of material production by 10-50% between 2020 and 2060 depending on the material[50]. This reduces emissions per m^2 floorspace by on average 23%.

The new housing characteristics scenarios are implemented by altering the ResStock housing characteristics data for new housing cohorts before generating a representative sample of new housing built in eight five-year periods spanning 2021-2060 (2021-2025, 2026-2030, etc.). Future housing characteristics are modified depending on anticipated adoption of residential building energy codes by states[51], updates to federal energy appliance standards[52], and assumptions on increased electrification and efficiency improvement of equipment and insulation. Building energy codes mostly apply to building envelope characteristics, such as insulation and infiltration levels, energy ratings of windows, etc.[53], while the federal efficiency standards apply to energy consuming equipment and appliances such as space and water heaters, air-conditioning systems, refrigerators, etc. We also incorporate assumptions regarding changes and trends in housing and energy appliance characteristics that are not directly based on codes and standards, such increased adoption of electric equipment used for space and water heating, increased use of heat pumps, and continued growth of air-conditioning equipment ownership.

In the Base new housing characteristics scenario (A), housing built in the next four decades has the same regionally-specific characteristics as housing built in the 2010s. The exception is fuel choice for space and water heating, cooking, and clothes drying, where we assume electricity to be a more common choice in new housing, and the electricity share to increase every decade (Supp. Fig. 22).

In the Reduced Floor Area scenario (B), no new housing unit exceeds a size of 279 m^2 (3,000 ft^2), an arbitrary limit which is chosen based on the floor area bins used in the ResStock housing characteristics database, and originate from the American Housing Survey[54]. Housing that previously fit into the two largest size categories of 279-371 m^2 (3,000–3,999 ft^2) or 372+ m^2 (4,000+ ft^2) are reassigned to be in one of the 186-232 m^2 (2,000–2,499 ft^2) or 232-279 m^2 (2,500–2,499 ft^2) categories with 50:50 probability (Supp. Fig. 25). In the Increased Electrification scenario (C), electrification of new housing is much more rapid, with all Regions reaching complete electrification by 2030 except the Northeast, which is fully electric by 2040 (Supp. Fig. 22). The Increased Electrification and Reduced Floor Area scenario (D) simply combine the new housing characteristics scenarios B and C. Further information on new housing characteristics scenarios is provided in Section 4 of the Supplementary Information.

Renovation and Electricity Supply Scenarios

Our analysis represents the most comprehensive existing assessment of the emission reductions from residential retrofits over the coming decades, incorporating energy-relevant characteristics of existing housing units up to the county and PUMA level and most recent empirical data on recent renovation trends, and estimating energy reductions of renovation actions with a detailed engineering-based simulation. We consider energy related renovations applying to addition/replacement of space heating, space cooling, and water heating equipment, and envelope upgrades for crawlspaces, unfinished basements, external walls, and unfinished attics, which increase the R-value of those building assemblies and reduce the infiltration of the building envelope. These measures capture the main types of renovations which offer substantial potential for energy reductions[49]. Two pieces of information are required for each renovation, the rate of renovation in the housing stock (i.e. the probability of a housing unit making a specific type of renovation in a given year), and the characteristics of a given system post-renovation, conditional on its pre-renovation status.

We define three renovation scenarios, ‘Regular’, ‘Advanced’, and ‘Extensive’. The Regular Renovation scenario is based on a continuation of recent trends, a moderately optimistic implementation of the depth of renovations, and low-moderate rates of replacing fossil heating equipment with electric alternatives. In the Advanced Renovation scenario, we multiply the probability of undergoing renovations by a factor of 1.5, and we give stronger preference to higher efficiency replacements, including a moderately higher shift towards electric space and water heating systems, and heat pumps in particular. In the Extensive Renovation scenario, much higher rates of electrification of space and water heating takes place, with 100% of replacements of fossil heating renovations with electric heat pumps from 2025 on. This does not mean that all existing fossil heating equipment is replaced by heat pumps in 2025, but *if* a fossil-based heating system is replaced, it is replaced by a heat pump. Tables and figures showing the assumptions and results of the renovation scenarios are presented in the Supplementary Information Section 3.

We calculate energy related GHG emissions using standard emission factors for combustion of fossil fuels[55], and annual average CO_2 intensity for three electricity supply scenarios; Mid-Case (MC) and Low Renewable Energy Cost (LREC) from NREL's standard scenarios[22], and a scenario involving 100% Carbon Free Electricity (CFE) by 2035[23]. The MC is the baseline electricity supply scenario, while LREC is the NREL standard scenario with the fastest decline of electricity GHG intensities. For CFE, in the absence of data describing regional projected electricity generation by source, we assume the same intensities as LREC until 2025, which then half between 2025 and 2030, before reaching zero by 2035. Weighted average electricity GHG intensities are calculated at the level of 20 Generation and Emission Assessment (GEA) regions[46] (Extended Data Fig. 4), which are defined to approximately match EPA's eGRID regions. The GEA regions are aggregations of the smaller 134 balancing areas used to define future electricity generation and consumption. Aggregation to GEA region was preferred to using the higher resolution balancing area GHG intensities, as the intensities for individual balancing areas will fluctuate a lot as a result of electricity trading, whereas the eGRID (and GEA) regions are designed to be more reflective of average electricity grid characteristics in larger areas, with reduced influence of electricity trading. Energy-related emission intensities describe CO_2 emissions from combustion only[22], excluding upstream emissions such as fugitive methane releases from fossil fuel extraction or embodied emissions from electricity generation and transmission infrastructure. Residential fossil combustion includes non-CO_2 combustion products, but CO_2 emissions account for over 99% of total combustion GHGs[55]. Embodied emissions from material production and construction[19] are based on material life cycle assessment databases, environmental product declarations and literature, and include non-CO_2 GHGs. To estimate the land requirements of wind and solar generation in the electricity supply scenarios[22], we divide the generating capacity of onshore wind, utility PV, and distributed PV[56] by technology-average installed capacity density coefficients for renewable electricity in the US. Based on available literature we use capacity densities of 3 W/m^2 for onshore wind[57], 50 W/m^2 for utility PV[58], and 25 W/m^2 for concentrated solar power[59]. Land requirements for offshore wind and distributed PV (which largely corresponds to rooftop PV) are assumed to be zero. Without information on types or quantifies of biomass feedstocks used for bio-electricity generation (which is negligible in MC and LREC, but shows notable growth in later years of CFE), land use for growing feedstocks for biomass electricity is not considered.

Growth of residential rooftop solar PV is incorporated in the electricity supply scenarios via the Distributed Generation Market Demand Model (DGen)[60], not on the demand side through residential renovations. As growth of DPV is already reflected in the electricity supply scenarios, we do not consider it as an additional residential renovation measure, to avoid double-counting.

Energy Simulation

Calculation of energy consumption in the US housing stock is performed using ResStock, a residential energy simulation tool with high resolution characterization of the US housing stock. Built on the

OpenStudio/EnergyPlus building energy simulation engine, ResStock draws on an extremely rich description of US residential building characteristics at various geographical resolutions ranging from national to county and PUMA depending on the characteristic in question[49,61]. County-specific weather files are used to reflect local climate, and simulations are made over a representative year (TMY3) at a 10-minute resolution. Changes in weather files due to climate change are not incorporated. Variation in energy demand for electronic appliances by Census Division and House Type is represented, but we do not simulate future changes in this energy demand segment, although it could grow in line with increasing number and size of personal electronics per household[2]. Such growth could be balanced by decreased TV ownership and increased appliance efficiency. Housing stocks in Hawaii and Alaska are not included in ResStock (or the analysis presented here) due to limited availability of housing characteristics data in these states. We do not include current or future energy consumption in vacant housing units in this analysis.

Energy simulations representing the entire contiguous US housing stock are made for the year 2020, and for every 5 years between 2025 and 2060, for each housing stock, new housing characteristics, and renovation scenario combination. Energy-related GHG emissions are calculated based on energy consumption by energy carrier in each year, and are interpolated for the intervening years in which energy demand is not simulated (e.g. 2021-2024) using the *spline()* function in R. In order to capture the heterogenous characteristics of the US housing stock in a representative manner[49], we simulate energy consumption in a large number of houses for each scenario and simulation year, so that one simulation represents somewhere in the range of 590-800 homes. 180,000 simulations are used to represent the 2020 occupied housing stock of 122,516,868 homes. In all, 3.412 million building simulations are used to represent the complete set of scenarios. For each simulation, the weighting factor (how many homes are represented) is modified over the projection period to reflect the loss of housing of a given type, cohort, and county combination from the occupied housing stock, based on the housing stock model outputs[19].

Model integration

Supplementary Fig. 1 summarizes the data inputs, assumptions, and various components of the model, which produces outputs of annual energy consumption by end-use and fuel, GHG emissions associated with energy use and material flows and GHG from new construction, for housing stocks by type and cohort in each county. As ResStock does not contain data for Alaska and Hawaii, our scenario results apply to the contiguous United States, where 99% of national energy-related GHG emissions occur[62]. As a basis for the 2030 and 2050 emission reduction targets indicated in Fig. 1, we calculate total residential emissions in 2005 and 2020 by combining residential energy emissions[63] with emissions from construction of new housing in 2005 and 2020, scaled by 0.99 to exclude Alaska and Hawaii. Historical emissions from construction is calculated by multiplying numbers of single- and multi-family housing units completed[64] and manufactured housing shipments[65], by year- and type-specific average house floor area[65,66], by the average embodied GHG intensities per unit floor area of each house type[19].

Enviro-economic Assessment of Renovation Strategies

We compare costs and benefits (private economic costs/savings, GHG reductions) for detailed renovation measures that take place between 2021-2025 over a 25-year time horizon (2026-2050), in order to assess their emission reduction potential and economic feasibility. Only private costs and benefits were quantified in economic terms; no societal costs or benefits (e.g., related to air quality, health impacts, economic damages from GHG emissions) were quantified. Net Present Value (NPV) and abatement costs should be interpreted accordingly as the private economic value of investments in efficiency and energy equipment. They do not reflect the socially optimal performance of efficiency investments which would result from a comprehensive analysis considering all private and public costs and benefits. We used capital costs for energy equipment and renovations based on mean values from the NREL National Residential Efficiency Measures Database (NREMD)[67]. In some cases capital costs for the precise technology deployed in a renovation measure was not available in this database, and for such cases we defined proxy capital costs, based on the ranges of costs that are present in the database. A full list of the assumed costs and indication where costs were assumed due to missing values in the database is available on the archived code repository[68]. It is important to note that renovation costs can vary widely case by case, and our use of average values does not incorporate that variation[69]. As renovations are implemented based on observed empirical renovation rates for different renovation types, it is assumed that each piece of energy equipment is replaced at end-of-life. Thus the capital cost used for the NPV calculation is the difference in cost between the new equipment type (e.g., a heat pump), and a replacement of the same equipment type being replaced (e.g., a gas furnace). Heat pumps replacements are assumed to replace heating equipment only, not combined cooling and heating equipment, which would improve the NPV of such renovations. Envelope renovations are priced by the material and installation costs per area of the building that receives a certain type of insulation (e.g., external wall, basement ceiling, roof, etc.). The cost of an envelope renovation is calculated as the cost of going to the post-renovation state (e.g., R-15 wall insulation) minus the cost of installing the pre-renovation state (e.g. R-7 wall insulation). Thus, costs for homes with little/no pre-renovation insulation will be higher. We assume no difference in renovation costs by building age. Future retail energy prices (in 2021$) by Census Division were taken from the reference case of EIA's annual energy outlook[70]. Our cost benefit analysis is restricted to renovations taking place by 2025 for two reasons: first, fuel price projections are not available past 2050 (meaning a cost-benefit analysis with a 25-year horizon cannot be calculated for investments later than 2025). Second, future energy equipment costs are uncertain and may change considerably from the values in the NREMD database. For instance, heat pump unit costs may decline with large increases in sales[71].

The Net Present Value (NPV) of energy renovations was estimated using a 3% real discount rate. The analysis incorporates future electricity GHG intensities at the GEA region level. Results of GHG reduction potential, NPV, and GHG abatement costs (calculated as -1 multiplied by the NPV divided by the reduction in GHG emissions over the equipment lifetime) are calculated and shown in Supplementary Information Section 3.6, using the projected GHG intensities from the LREC scenario only.

Limitations

Here we draw attention to several limitations of our modelling approach. Similar to any prospective scenario analysis, there are uncertainties inherent to the model input parameters, which grow larger as the model gets further into the future. In place of sensitivity analyses to assess the uncertainty around each input parameter, we generated a large scenario space by selecting feasible ranges of input values for parameters considered to be influential on future emission trajectories, such as the rate and depth of renovations, decarbonization of electricity supply, etc. Combining the selected values for each varying input parameter created 108 unique scenarios (Table 1). The range of emissions trajectories demonstrated by these scenarios are not intended to represent all possible future emission pathways. Parameter values excluded from our scenarios space which would likely result in notable differences to emission pathways estimated include higher or lower population and housing stock growth trajectories, slower decarbonization of electricity, slower renovation rates, and increased growth in size of new single-family housing. A rather pessimistic scenario, assuming fixed electricity GHG intensity at 2020 levels and no renovation of existing housing, is included in our illustration of annual emissions 2020-2060 in Extended Data Fig. 3. This can be considered as a worst-case outcome for future emissions, and shows almost no change in the level of annual emissions over the next forty years. Other measures to reduce residential energy and emissions were excluded from our analysis. These include behavioural changes[72] and reduction of per-capita floor space in existing homes through household sharing (increased household size) or subdividing large homes to multiple smaller units.

For embodied emissions, faster reductions in the GHG intensity of construction could result from greater technological advances in the production of high-emitting materials such as cement, steel, and insulation products, increased use of lower-carbon materials in construction[28], and low-carbon electrification of construction site energy use and transport. A faster decarbonization of construction activity could alter our current conclusions on increased emissions from faster housing stock turnover. However, the finding of much greater emission reduction potential from renovation of existing housing, compared to faster rebuilding, would not be changed.

Annual average electricity emission intensities were used instead of short-run or long-run marginal emission rates, as the annual average intensities are more appropriate for very large changes in electricity use across the entire residential sector[56]. Using long-run marginal emission rates would be more suitable for quantifying the emission impacts of incremental changes to the housing stock, or individual renovations. In broad terms, average emission intensities happen to be similar in magnitude to long-run marginal rates, so we would not expect major differences if we were to use long-run marginal rates instead of the averages intensities used in this analysis. Using hourly emission rates may be more suitable when considering the time of day of residential electricity demand vis-à-vis electricity demand from other sectors, but was outside the scope of the present analysis. Further, complex interactions can exist between energy efficiency measures and demand response strategies such as peak-load shedding and load shifting – which provide additional benefits to electricity grids, such as flexibility and reduced peak generation capacity, and can facilitate higher levels of variable renewable generation[73]. Such temporal considerations and intersectoral interactions were outside of the scope, and represent a promising avenue for future research considering increased electrification in all sectors[35].

Costs and benefits of residential renovations extend beyond the capital and energy expenses considered here. Substantial human health benefits have been demonstrated from changes in indoor and outdoor air quality associated with building efficiency improvements and fossil fuel to electricity fuel switching[74,75]. Additional health and mortality benefits, associated with reduced exposure to excessively low and high temperatures, can be expected from improvements in envelope efficiency[76,77]. Quantification of these health impacts was outside beyond the capability of our model; our cost benefit analysis of renovations therefore does not incorporate health related costs or benefits.

While a cost benefit analysis could have been applied to other families of mitigation measures, we limit the cost benefit analysis to the renovation strategies. In the electricity supply scenarios, costs and benefits would result from changes in electricity prices, and changes in GHG and other environmental emissions. Due to model input assumptions in the dispatch model which generated the MC and LREC scenarios, electricity prices are lower by around 10-15% from 2030 onwards in LREC, compared to MC[56]. Our CFE electricity scenario is not generated by an electricity dispatch model, although the 100% renewable electricity scenarios generated by Cole et al[3] are conceptually similar. The system cost estimates provided by these models represent power system costs including costs of building and retiring capital assets as well as energy costs, but exclude transmission maintenance, distribution, and administration costs[3,46]. These costs are not designed to reflect retail electricity rates, and thus a cost comparison of electricity supply scenarios for end-use consumers is not feasible. There are numerous costs and benefits associated with other scenario dimensions (high-MF, RFA, IE, high-TO) as these would influence transportation patterns, housing costs, access to urban amenities, privacy, etc. These are highly dependent on location and individual preferences, and quantification of these costs and benefits was excluded.

Exclusion of housing tenure overlooks the possibility for higher energy consumption and lower propensity to invest in energy efficiency renovations in rental housing. We investigate this issue further in Supplementary Information section 6.3. Demographic variables such as household income, race, and ethnicity are also excluded from the housing stock model, and the energy simulation model. As such, assessment of access to energy efficiency renovations by population groups, and estimation of distributional effects of the various emission reduction strategies, was not possible within our current modelling framework.

Data Availability

All input and post-processed data supporting this analysis are available at https://doi.org/10.5281/zenodo.6651589.

Code Availability

All code to prepare and post-process the results supporting this analysis is available in an archived repository at https://doi.org/10.5281/zenodo.6656201, the active version of this repository is available at https://github.com/peterberr/resstock_berrill/tree/feature/projections. Code to prepare the housing stock evolution scenarios can be found at https://github.com/peterberr/US_county_HSM.

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Methods References

47. Hauer, M. E. Population projections for U.S. counties by age, sex, and race controlled to shared socioeconomic pathway. *Sci. Data* **6**, 1–15 (2019).

48. US Census Bureau. 2017 National Population Projections Tables Projections for the United States: 2017 to 2060. https://www.census.gov/data/tables/2017/demo/popproj/2017-summary-tables.html (2017).

49. Wilson, E. *et al.* Energy Efficiency Potential in Stock Energy Efficiency Potential in the U . S . Single-Family Housing Stock. (2017).

50. Berrill, P. & Hertwich, E. G. Material GHG Intensities. *Material flows and GHG emissions from housing stock evolution in US counties, 2020-2060* https://github.com/peterberr/US_county_HSM/blob/main/Housing Archetypes/MatGHGint.xlsx (2021).

51. EIA. Status of State Energy Code Adoption. https://www.energycodes.gov/adoption/states (2020).

52. Electronic Code of Federal Regulations. PART 430—ENERGY CONSERVATION

PROGRAM FOR CONSUMER PRODUCTS Subpart C—Energy and Water Conservation Standards. https://www.ecfr.gov/cgi-bin/text-idx?rgn=div8&node=10:3.0.1.4.18.3.9.2 (2020).

53. International Code Council. Residential Energy Efficiency. in *2018 International Energy Code* (2020).

54. US Census Bureau. American Housing Survey. (2020).

55. EPA. *Subpart C—General Stationary Fuel Combustion Sources*. *Federal Register - Rules and Regulations* vol. 74 (2009).

56. NREL. Cambium - Scenario Viewer and Data Downloader. *Standard Scenarios 2020* https://cambium.nrel.gov/ (2020).

57. Mai, T., Lantz, E. & Mowers, M. *The Value of Wind Technology Innovation: Implications for the U.S. Power System, Wind Industry, Electricity Consumers, and Environment*. https://www.nrel.gov/docs/fy17osti/70032.pdf (2017) doi:NREL/TP-6A20-70032.

58. Mai, T. *et al*. *Renewable Electricity Futures Study: Vol 1 of 4 Exploration of High-Penetration Renewable Electricity Futures*. https://www.nrel.gov/docs/fy12osti/52409-1.pdf (2012) doi:NREL/TP-6A20-52409-1.

59. Ong, S., Campbell, C., Denholm, P., Margolis, R. & Heath, G. *Land-Use Requirements for Solar Power Plants in the United States*. https://www.nrel.gov/docs/fy13osti/56290.pdf (2013) doi:NREL/TP-6A20-56290.

60. Sigrin, B., Gleason, M., Preus, R., Baring-gould, I. & Margolis, R. *The Distributed Generation Market Demand Model (dGen): Documentation*. *NREL/TP-6A20-65231* https://www.nrel.gov/docs/fy16osti/65231.pdf (2016).

61. NREL. ResStock. https://github.com/NREL/resstock (2021).

62. EIA. State Energy Data System (SEDS): 1960-2018. https://www.eia.gov/state/seds/seds-data-complete.php?sid=US (2020).

63. EPA. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020*. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020 (2022).

64. US Census Bureau. Housing Units Completed. *New Residential Construction - Historical Data* https://www.census.gov/construction/nrc/historical_data/index.html (2022).

65. US Census Bureau. *Manufactured Housing Survey*. https://www.census.gov/programs-surveys/mhs.html (2022).

66. US Census Bureau. *Characteristics of New Housing*. https://www.census.gov/construction/chars/ (2021).

67. NREL. National Residential Efficiency Measures Database v3.1.0. https://remdb.nrel.gov/measures.php (2018).

68. Berrill, P. peterberr/resstock_berrill: Supporting code for 'Decarbonization pathways for the residential sector in the United States'. https://github.com/peterberr/resstock_berrill/tree/feature/projections (2022) doi:https://doi.org/10.5281/zenodo.6656201.

69. Less, B. D., Núria, I. S. W., Leo, C.-M. & Rainer, I. *The Cost of Decarbonization and Energy Upgrade Retrofits for US Homes Energy Technologies Area*. https://eta-publications.lbl.gov/sites/default/files/final_walker_-_the_cost_of_decarbonization_and_energy.pdf (2021) doi:10.20357/B7FP4D.

70. EIA. *Annual Energy Outlook 2022*, *Table 3 Energy Prices by Sector and Source*. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2022&cases=ref2022&sourcekey=0 (2022).

71. Gross, R. & Hanna, R. Path dependency in provision of domestic heating. *Nat. Energy* **4**, 358–364 (2019).

72. Khanna, T. M. *et al.* A multi-country meta-analysis on the role of behavioural change in reducing energy consumption and CO2 emissions in residential buildings. *Nat. Energy* **6**, (2021).

73. Gerke, B. F. *et al.* Load-driven interactions between energy efficiency and demand response on regional. *Adv. Appl. Energy* (2022) doi:10.1016/j.adapen.2022.100092.

74. Gillingham, K. T., Huang, P., Buehler, C., Peccia, J. & Gentner, D. R. The climate and health benefits from intensive building energy efficiency improvements. *Sci. Adv.* **7**, (2021).

75. Wilkinson, P. *et al.* Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. *Lancet* **374**, 1917–1929 (2009).

76. World Health Organisation. 4: Low indoor temperatures and insulation. in *WHO Housing and Health Guidelines* (2018).

77. Tham, S., Thompson, R., Landeg, O., Murray, K. A. & Waite, T. Indoor temperature and health: a global systematic review. *Public Health* **179**, 9–17 (2020).