Decarbonization pathways for the residential sector in the United States

Peter Berrill (peter.berrill@aya.yale.edu)
Yale University https://orcid.org/0000-0003-1614-3885
Eric J.H. Wilson
National Renewable Energy Laboratory https://orcid.org/0000-0003-3185-655X
Janet Reyna
National Renewable Energy Laboratory https://orcid.org/0000-0003-3336-2879
Anthony D. Fontanini
National Renewable Energy Laboratory
Edgar Hertwich
Norwegian University of Science and Technology https://orcid.org/0000-0002-4934-3421

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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 scenarios rely on very rapid decarbonization of electricity supply alongside extensive renovations to existing homes—focused on improving thermal envelopes and heat pump electrification of heating. Reducing the size, increasing the multifamily share, and increasing the electrification of new homes provide further emission cuts, and combining all strategies enables emissions reductions of 91% between 2020 and 2050. Construction becomes the main source of emissions in the most ambitious scenarios, motivating increased attention on reducing embodied emissions.

Introduction

Reducing GHG emissions rapidly from buildings is central to mitigating global climate change. As a considerable share of building energy use is already electrified[1,2], and complete electrification is technically feasible, emissions from building energy use can in principle reduce to zero through a combination of electrification and electricity decarbonization. In this paper we assess decarbonization pathways for the residential sector in the United States, which has one of the highest levels of per-capita residential energy use in the world (1.5 times the OECD average), and is second to China in terms of total residential energy use[2]. Recent reductions of residential energy-related emissions in the US have primarily derived from a decarbonizing electricity grid, with much smaller reductions coming from energy efficiency and increased use of electricity for space heating[3]. Complete decarbonization of electricity generation with renewable energy will be challenging[4,5]. Reducing residential energy demand through efficiency and sufficiency can alleviate this challenge, and support emissions reductions consistent with limiting global climate change to 1.5°C warming[6]. Two approaches to improve energy efficiency in buildings are 'retrofitting' - renovating existing buildings, and 'rebuilding' - replacing older stock with more efficient new buildings[7–10]. Comparing these approaches requires consideration of 'embodied' emissions from material production and construction activity, which constitute around 9% of residential emissions in the US[11]. This share will grow as buildings become more efficient and energy supply decarbonizes further[12]. Literature has not converged on which efficiency approach is preferable[13], but so far comparisons of retrofitting and rebuilding have largely focused on individual buildings or neighbourhoods; rarely have they been compared for building stocks of an entire country[10].

'Sufficiency' approaches to reducing GHG emissions are a recent addition to climate change mitigation literature, and target reduced demand for energy, materials and other natural resources, while delivering wellbeing for all[14,15]. For residential buildings, sufficiency can be translated into a global convergence of floor area per person[16,17] to somewhere in the range of 15–40 m^2/cap[18–21]. Current average floor area usage in the US is 67 m^2/cap in single-family homes, 41 m^2/cap in multifamily homes, and 60 m^2/cap across all house types[22]. This is one of the highest levels globally; floor area consumption in the UK and Japan is closer to 40 m^2/cap, while in many other countries it is lower, but growing[23].

Here, we assess emissions from operation, construction, and renovation of residential buildings in the US in 108 scenarios, from 2020 to 2060. The consideration of embodied emissions, detailed engineering-based energy modelling using high-resolution housing characteristics, and representation of specific technological and fuel-switching measures based on recent renovation trends are novel aspects of this work. The scenarios demonstrate GHG mitigation potentials of increased renovation and electrification in existing homes and modifications to the characteristics of new construction, under different electricity supply scenarios. Results show substantially higher emission reductions from renovation than rebuilding, and underline the necessity for rapid decarbonization of electricity supply.

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[22], four scenarios describing characteristics of new housing, three renovation scenarios, and three electricity supply scenarios[24,25] (Table 1). The scenarios reflect different approaches to climate change mitigation; sufficiency approaches are represented in the High multifamily growth and Reduced floor area scenarios, *retrofit*-efficiency approaches are represented in the Renovation scenarios, *rebuild*-efficiency approaches are represented in the High stock turnover and Increased Electrification scenarios, while energy supply decarbonization is represented in the Electricity supply scenarios. In most cases, alterations to historic trends are not implemented to maximum technical potential, but instead scale up strategies to optimistic but 'attainable' levels. The scenarios are not optimized to achieve any emissions reduction target. Further description of the scenarios, and the overall approach—including limitations—is provided in the Methods section.

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. Figures 17, 18, 21)	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. Figures 17, 18, 21)	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. Figure 16)	More rapid increase of all-electric new homes, based on 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) (c.f. SI Section 2)	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. Figure 23)	Reference scenario from NREL Standard Scenarios[24], 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[25]. Trajectory assumed to map LREC until 2025, reach half of 2025 intensity by 2030, and reach 0 $kgCO_2/kWh$ by 2035

Assessment Of Climate Change Mitigation Strategies

All 108 scenarios meet the 2030 emissions target of 50% reduction compared to 2005[25] (825 $MtCO_{2e}$/yr), but none meet a 1.5°C-consistent 2030 target of 50% reduction compared to 2020[6] (450 $MtCO_{2e}$/yr), although some come close. For 2050 targets, 52 out of 108 scenarios meet the Paris 2015 target of 20% of 2005 emissions[26] (330 $MtCO_{2e}$/yr) (Fig. 1), but none comes close to a 1.5°C goal of (net-)zero emissions by 2050[6]. Electricity supply and renovation scenarios have the largest influence on future emissions (Fig. 1). Following the LREC electricity supply scenario results in substantially lower emission pathways than the MC scenario, approaching the 2050 Paris target if combined with advanced renovation, or exceeding it when combined with extensive renovation. Only the lowest-emission scenarios with carbon free electricity (CFE) from 2035 come close to the 2030 1.5°C target. Due to residual emissions from residential fossil fuels and construction, none of the CFE scenarios reach zero emissions in 2050. After electricity emissions reach zero in 2035, subsequent emissions reductions in CFE scenarios are more gradual, with emissions from fossil fuel combustion and construction declining very slowly from 2045 onwards (Fig. 1, Fig. 3d). Cumulative 2020-2060 emissions range from 11.9 - 28.7 $GtCO_{2e}$ in the scenarios assessed (Fig. 2). A current-population-based allocation of the remaining global carbon budget to meet 1.5°C with 50% likelihood[27] gives the US a carbon budget of 21 $GtCO_{2e}$ from all sources from 2020. This budget would be even smaller under fair effort-sharing allocations[28].

Within each electricity supply and renovation scenario set, the nature of housing stock evolution and the characteristics of new housing provide further, smaller variations in emissions. Building new homes with reduced floor area (RFA) and increased electrification (IE) lowers emissions. Annual emissions are lower by 34-56 $MtCO_{2e}$/yr by 2050 if building IE-RFA new homes, while cumulative 2020-2060 emissions see reductions of 1.1-1.8 $GtCO_{2e}$ (Fig. 2). With more gradual decarbonization of electricity (MC), 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[22] and the larger size of newer housing (Supp. Fig. 18), increasing the rate of stock turnover increases emissions in all scenarios (Fig. 2), despite improvements in efficiency which accompany faster growth of new housing. As a result, retrofitting is found to have greater emission reductions potential than rebuilding in all of our scenarios. As more existing buildings are renovated to become more efficient and electrified, there is a smaller reduction of energy-related emission resulting from higher stock turnover. This is because faster and deeper renovations lower the emissions avoided through accelerated retirement of older homes. Similar to the RFA new housing scenarios, increasing the share of multifamily housing in new construction reduces both embodied emissions, and future energy-related emissions. Depending on the electricity, renovation, and new housing characteristics scenario, high multifamily housing stock growth reduces cumulative 2020-2060 emissions by 0.30-0.84 $GtCO_{2e}$ (Fig. 2).

In scenarios with most rapid emission reductions, the majority of emissions occur by 2030 (Fig. 3d), while in the Baseline scenario (base stock evolution and new housing characteristics, MC electricity supply, regular renovation) or scenarios with moderate reductions (Fig. 3a, 3b), growth of cumulative emissions slows but remains steady throughout the coming decades. Comparing Fig. 3a and Fig. 3b illustrates the limitations of employing electricity supply or renovation-based strategies on their own. With extensive renovation, but gradual decarbonization of electricity supply (Fig. 3a), emissions from residential fossil combustion decline markedly, but emissions from electricity remain sizable. Conversely, reducing electricity emissions intensity with regular renovation of existing homes (Fig. 3b) produces large decreases in electricity emissions, but 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 decarbonization of electricity, extensive renovation, and construction of new homes which are smaller, electrified, and have a greater multifamily share. With the most optimistic combination of non-electricity scenarios, the additional benefits

from completely decarbonizing electricity by 2035 compared to a low- but not zero-carbon electricity scenario (i.e. CFE vs LREC) are still immense, reducing 2050 emissions from 222 to 84 $MtCO_{2e}$/yr (Fig. 3c, Fig. 3d) and reducing cumulative emissions to 2060 from 17.5 to 11.9 $GtCO_{2e}$. In these low emission (CFE-ER) scenarios, the majority of emissions from 2050 onwards are from construction. Construction related emissions incorporate assumed improvements in material production and construction activities - average embodied emissions per unit floor area fall from 201 to 155 $kgCO2_{2e}/m^2$ between 2020 and 2060[22]. Further reductions in the emissions intensity of new construction can result from building homes without basements or garages, substituting wood for concrete structural elements, using low-carbon cementitious materials, and avoiding insulation with high-GWP blowing agents[22,29–31]. A faster reduction of the emission intensity of construction materials and activities could alter the current finding that higher stock turnover generates higher emissions in all scenarios.

Our lowest emission scenario shows combined energy and embodied emissions of 0.22 ton $CO2_{2e}$/cap by 2050, down from 2.71 ton $CO2_{2e}$/cap in 2020. This is considerably lower than 2050 per-capita US residential emissions in the lowest emission scenario from Goldstein et al.[32] (0.62 ton $CO2_{2e}$/cap, energy emissions only), but higher than 0.15 ton $CO2_{2e}$/cap from the lowest emission scenario by Pauliuk et al.[20] (embodied emissions and energy emissions from heating, cooling, and hot water only) or 0.17 ton CO2e/cap from the IEA's sustainable development scenario[33] (energy emissions only).

Sequencing Of Mitigation Strategies

While some strategies are largely independent (e.g. renovating existing homes and building smaller new homes), the mitigation potentials of stock evolution, new housing characteristics, and renovation strategies are influenced by the extent of electricity decarbonization. Compared to a '2020 electricity grid' and 'no renovation' situation (not part of our scenario set, shown for reference by the brown dotted line in Fig. 4), our baseline scenario (dotted black line in Fig. 4) generates substantial emission reductions. Beyond this baseline, mitigation actions are ordered in Fig. 4a according to greatest cumulative emission mitigation potential, grouped into strategies affecting electricity supply (blue), renovation of existing homes (orange), and stock evolution/characteristics of new housing (pink/purple). Rapid electricity decarbonization delivers the greatest emission cuts, and increases the mitigation potential of extensive renovations (ER) and increased electrification (IE) of new homes. Stacking strategy groups in the reverse order (Fig. 4b) shows that the sufficiency strategies of reduced floor area and increased multifamily in new construction bring about greater emission cuts if the electricity grid decarbonizes less rapidly (MC), as the associated reductions in energy demand translate into larger emission reductions.

The reduction of residential sector emissions will be best achieved by prioritising rapid decarbonization of electricity supply *alongside* high-efficiency renovations of existing homes, with heat pump replacements for fossil-based heating equipment, and much improved building envelopes. Incorporating more multifamily and smaller single-family in new construction provides immediate reductions of embodied emissions[22], ensures energy-related emission independent of electricity supply scenario, and lowers peak electricity demand. These strategies lower 2050 annual electricity demand by around 6%. Lower electricity demand, particularly during peak hours, reduces the amount of electricity infrastructure required[28], lessening the challenges associated with rapidly deploying new of carbon-free generation[35].

Technological And Policy Challenges To Mitigation

The first pillar of reducing residential emissions is rapid decarbonization of electricity supply. Technical challenges for decarbonization relying on renewables include diurnal and seasonal balancing of supply and demand, and maintaining grid stability with very high penetration of inverter-based (wind and solar) technologies[5]. The MC / LREC scenarios[24] project factor 4.8 / 6 increases in wind and solar generating capacity between 2020 and 2050, with average annual

increases of 26 / 35 GW respectively. Between 2019 and 2020, wind and solar capacity grew by 30 GW[36]. Using current technology-specific land requirements[37], land use for wind and solar would grow to 1,994 / 2,691 ha by 2050, from 536 ha in 2020, in MC / LREC scenarios respectively. The closest description of an electricity supply system comparable to our CFE scenario is the 2050 100% renewable electricity scenario from Cole et al.[4], which requires average annual increases of wind and solar capacity of 60 GW between 2020-2050. Such an electricity grid is estimated to have non-linear increases in incremental carbon abatement costs above 95% renewable generation[4]. Increased transmission connection between Eastern and Western Interconnections in the US could facilitate up to 85% renewable generation by 2038 with a benefit-cost ratio that increases with higher penetration of renewables[38]. Increased transmission and electricity storage capacity help to smooth regional and temporal imbalances in electricity demand and supply, and are expected to feature heavily in future electricity grids with increased end-use electrification and high penetration of variable renewable generation[39]. For longer term (seasonal) temporal supply-demand imbalances, alternative solutions such as power-to-hydrogen may be required[5].

The second major pillar of decarbonizing the residential sector is extensive renovation of existing homes, involving major improvements to building envelopes through increased insulation and reduced infiltration, and replacement of space and water heating equipment with high efficiency heat pumps and electric water heaters. Section 2 of the Supplementary Information details the modelled changes in equipment and envelope characteristics in the renovation scenarios. With extensive renovation, envelope upgrades will improve 7 million housing units per year by 2040, while 6-8 million homes will replace heating equipment annually from 2030, with almost all of the replacements being heat pumps. Heat pumps typically cost more upfront than fossil-based heating systems[40], so some subsidy will likely be required to encourage adoption, although per-unit costs may decline with increases in heat pump sales[41]. In RR and AR scenarios, the greatest renovation energy reductions come from envelope retrofits. In ER scenarios, the greatest reductions come from heating equipment replacements (Supplementary Tables 7-8). The potential to reduce energy use through envelope and heating equipment renovations is particularly large in older (built <1960) single-family homes in cold climates.

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[42]. Very few state or utility efficiency programs reward energy or emissions savings from fuel switching[43], while numerous states discourage or prohibit fuel-switching[44]. The Better Energy, Emissions, and Equity initiative[45] 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[46].

Challenges surrounding building fewer very large homes or more multifamily homes are not technological, but relate to policy and societal norms. Policy options here include introducing size limits (as implemented in the RFA scenario), removing zoning and other local land-use restrictions on denser housing types[47,48], and restructuring Federal tax policies which increase the costs of multifamily construction relative to single-family[49] and subsidize ownership of large single-family homes for higher-income households[50,51]. Because older homes are smaller than new homes, RFA and high multifamily stock evolution could stabilize floor area per capita at current levels[22], but are not likely to induce substantial reductions (Supp. Figure 17). Reducing floor area consumption to 40 m^2/cap would thus require approaches beyond modifying the characteristics of new housing, such as household sharing[52], or dividing existing homes into multiple units (also commonly prevented by local land-use restrictions[47]). As construction becomes increasingly important in the lowest emission scenarios, these more extensive measures targeting reduced floor area could make zero emissions targets more

attainable. Otherwise, the elimination of embodied emissions will rely on material efficiency[20] and advances in low-carbon material selection and production[29,30].

Conclusion

In this analysis we assess decarbonization pathways for residential buildings in the US in 108 scenarios to 2060, incorporating embodied and energy-related emissions. Our study is the most comprehensive assessment of decarbonization pathways for housing in the US, delivering new insights into how much emissions can be reduced from different combinations of specific mitigation actions. The pathways with largest emission reductions rely on rapid decarbonization of electricity alongside extensive electrification-focused renovations of existing housing. As the US housing stock grows slowly, most of the energy related emissions in 2060 will be from housing units that exist today. Despite this, increasing the turnover of housing stock is not a promising strategy to reduce residential emissions, because the benefits from more efficient new homes are partially offset by new homes being larger, and due to increased embodied emissions from new construction. Retrofitting is therefore generally preferable to rebuilding as a means to reduce GHG emissions in the US housing stock. Envelope and heating equipment retrofits are particularly beneficial in cold climates with large shares of old single-family homes. In new homes, increasing the prevalence of electric heating facilitates greater emission reductions, particularly when combined with rapid grid decarbonization. Reduced floor area and increased multifamily in new housing generates immediate reductions in embodied emissions, and locks in lower future energy-related emissions. These sufficiency-oriented strategies for new homes can integrate with denser urban development, helping to reduce emissions from transport in addition to housing[53]. Approaching zero emissions by 2050 will require the elimination of all residential fossil combustion, zero-carbon electricity, and more comprehensive reductions of embodied emissions, through reduced floor area growth and innovations in material production.

Methods

- Housing Stock and Characteristics Scenarios

Housing stock evolution and new housing characteristics scenarios are based on scenarios developed by Berrill and Hertwich[22], 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[54] drive the housing stock model[22], and are scaled to the mid-range scenario from the most recent U.S. Census Bureau population projections to 2060[55]. The scenarios are extended for this work to include the new housing characteristics scenario of increased electrification in new housing, and to describe scenarios renovation of existing housing. The HSM is run at the resolution of US counties, and incorporates dynamics of region- and house-type-specific vacancy rates, which influences local demand for new construction. Vacancy rates by Census Region and house type are assumed to gradually converge, which translates into higher construction rates in counties with comparatively low vacancy rates. The Baseline stock scenario (1) assumes a continuation of historic loss rates, which are defined for each house type, age-range, Census Division, and vacancy status combination. High stock turnover (scenario 2) is simulated by increasing housing stock turnover rates by a factor of 1.5. High multifamily stock growth (scenario 3) is a scenario representing both sufficiency (as it lowers growth in floor-area per person) and more intensive urbanization, facilitated in part by lowering regulatory barriers to multifamily construction in urban centers. This is simulated by increasing the county multifamily population share by 0.25 percentage points annually in counties with population growth of at least 5% over twenty years, for two periods, 2020–2040, and 2040–2060. For instance, a county with a multifamily population share of 20% in 2020 and sufficiently high population growth to 2060 will see their multifamily population share grow to 30% by 2060. This approach avoids increasing of multifamily population share in counties with low or negative population growth, which we consider to be less likely.

Emissions from material production and onsite energy and transport in new construction are calculated for 51 housing archetypes[22], capitalizing on high resolution representation of US housing characteristics by house type, size, foundation type, heights, etc., in the ResStock housing characteristics data[46]. 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[22]. Embodied emissions from energy equipment such as furnaces and heat pumps are not considered. It is worth emphasizing that increased emissions from higher stock turnover are estimated at the entire stock level. It is probable that for certain homes with large renovation challenges which can be replaced with relatively low embodied emissions, demolition and rebuilding may be a more practical solution to lower life-cycle emissions. The baseline housing stock growth scenario already projects increased construction in many urban areas, due to an assumption of converging vacancy rates by house type and Census Region[22]. Higher housing stock growth in areas with low vacancy rates, which are largely urban areas with stringent land-use restrictions[47], could help to alleviate issues of housing affordability and supply[56], which are outside of the scope of the current analysis.

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[57], updates to federal energy appliance standards[58], and assumptions on 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.[59], 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, but more related to household preferences and energy and appliance prices, 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. Increases in electrification of new housing is defined for four Census Regions, based on projected price differences between electricity and natural gas[60]. Price differences are largest (and electrification rates assumed to be lowest) in the Northeast, while price differences are smallest (and electrification rates assumed to be highest) in the South. In between are the West and Midwest Regions, which are assumed to have similar moderate electrification rates, with West slightly higher than Midwest in the 2020s. While the rates of change are defined by Census Regions, individual characteristics are specified, and change, at higher spatial resolution. For instance, heating fuel characteristics are defined for every PUMA[61], so PUMAs with initially low shares of natural gas (for instance due to absence of gas distribution networks) will continue to have low shares of natural gas in new construction, which decline over time in line with the scenario.

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. This scenario represents a sufficiency measure aimed at limiting growth of floor area per person, by replacing 'very large' new homes with moderately large new homes (Supp. Fig. 17). 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) ranges with 50:50 probability (Supp. Fig. 21). Multifamily and manufactured housing are essentially unaffected by this change, as very few of those housing types exceed 279 m^2, but for single-family housing, this scenario reduces

mean floor area of new houses by 25%, from 258 m^2/house to 193 m^2/house[22] (Supp. Fig. 18). One alternative approach to modelling scenarios of reduced floor area in new housing would be to increase the share of homes built in the smallest size ranges, below 93 m^2 (1,000 ft^2), representing growth in accessory dwelling units currently seen in urban areas of the US with housing shortages[62]. 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. 16). 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 3 of the Supplementary Information.

- Renovation and Electricity Supply Scenarios

Our analysis represents the most comprehensive 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 Public Use Microdata Area (PUMA) level and empirical data on recent renovation trends, and estimating energy reductions of renovation actions with a detailed physical simulation model. 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 renovation categories capture the main types of retrofits which offer substantial potential for energy reductions[46]. 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. Our estimates of future renovation rates and fuel-switching trends are based on data from American Housing Surveys (AHS) covering the period 1995-2019[63], which include information on whether homes replaced or added central AC, space heating equipment, water heaters, or insulation. These questions were only asked of owner-occupied households. Without specific data for tenant-occupied households, we assume that the renovation rates and characteristics identified for owner-occupied homes apply to all homes.

We define three renovation scenarios, which we term ‘regular’, ‘advanced’, and ‘extensive’. The standard 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 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 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 2. Renovations are only applied to housing built before 2020, the energy efficiency of homes built between 2020-2060 is assumed to remain static (Supp. Table 6). Apart from the effect of replacing fossil heating equipment with heat pumps, neglecting renovation of newly built homes is not expected to have an influence on overall results, as renovation of new homes would only start to take effect from ~2040 onwards, and most homes built from 2020 onwards already have relatively high efficiency.

We calculate energy related GHG emissions using standard emission factors for combustion of fossil fuels[64], 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[24], and a scenario involving 100% Carbon Free Electricity (CFE) by 2035[25] (Supplementary Figure 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 a detailed electricity supply scenario detailing 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. Electricity GHG intensities are combined with electricity consumption calculations at the level of 18 regional transmission organizations (RTOs). Regarding coverage of different GHGs from different stages of supply chains, energy-related emission intensities describe CO_2 emissions from combustion only[24], 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[64]. Embodied emissions from material production and construction[22] 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[24], we divide the generating capacity of onshore wind, utility PV, and distributed PV[65] by technology-average power density coefficients for renewable electricity in the US[37]; 3.1 W_e/m^2 for onshore wind, 5.8 W_e/m^2 for utility PV, 6.7 W_e/m^2 for distributed PV, and 9.7 W_e/m^2 for concentrate solar power. Our estimates of land area for wind generation capacity do not include the offshore area required for offshore wind.

- Energy Simulation

Calculation of energy consumption in the US housing stock is done 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[46,61]. 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. Without a reliable approach to estimate, or reduce energy consumption in vacant housing, we do not incorporate 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[46], 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[22].

- Model integration

Supplementary Figure 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[66]. As a basis for the Paris 2050 target and 50% 2030 target in Figure 1, we calculate total residential emissions in 2005 by combining residential energy emissions[67] with emissions from investment in new housing in 2005, using data from Berrill et al.[11], scaled by 0.99 to exclude Alaska and Hawaii. As a basis for the 1.5°C target in 2030, we use total 2020 residential emissions as calculated by our model.

- 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 usually grow larger as the time period gets further into the future. In place of sensitivity analyses to assess the uncertainty around each input parameter, for this study we generated a large scenario space by selecting 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 however intended to represent all possible future emission pathways. Parameter values excluded from our scenarios space which would likely result in notable differences to the range of emission pathways estimated include higher or lower population and housing stock growth trajectories, electricity supply scenarios resulting in slower decarbonization of electricity, and slower renovation rates. A rather pessimistic scenario, assuming fixed electricity GHG intensity at 2020 levels and no renovation of existing housing, is however included in our illustration of annual emissions 2020-2060 in Figure 4. This could reasonably 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.

Our calculations of embodied emissions from construction are based on a previous study[22], and incorporate moderately optimistic assumptions on reduction in GHG-intensity of material production, which reduces emissions per m^2 floorspace by on average 23% from 2020-2060. More ambitious 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[29], 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 even with much faster decarbonization of construction.

To keep the number of required simulations to a reasonable level, we only assess renovations to housing built until 2020, none of the new housing built 2021-2060 are assumed to undergo renovation. This results in overestimations of energy emissions from new housing, particularly in the later decades of the analysis. However, as average energy intensity is already lower in housing built after 2020 than existing housing, pre- and post-renovation (Supplementary Tables 5-6), and as even in 2060 most energy-related emissions come from existing housing (Figure 3), this simplifying assumption is considered to have negligible influence on our results and overall findings. Scenarios with increased electrification of new housing can serve as a proxy for futures in which the housing stock built after 2020 undergoes greater electrification-focused renovation.

Finally, in the estimation of GHG emissions from electricity generation we use projections of annual average emissions for 18 regional transmission organizations (RTOs). Although Standard Scenario GHG intensities are available at a spatial higher resolution of 134 local balancing areas[39], the larger RTOs were preferred to represent the average energy supply mix of electricity consumed by households. Further, annual average emission intensities were used instead of short-run or long-run marginal emission rates, as the annual average were readily available from the Cambium scenario data downloader[65]. Using marginal emission rates may be more suitable when considered the time of day of residential electricity demand vis-à-vis electricity demand from other sectors, or when considering the longer term growth in electricity demand from residential buildings compared to other sectors. Such temporal considerations and intersectoral interactions were outside of the scope of the present analysis, and represent a promising avenue for future research considering increased electrification in all sectors[39].

Declarations

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Data Availability Statement

The datasets generated during the current study are available from the corresponding author on reasonable request. All figures in the main text have accompanying raw data available in supplementary information file 2.

Code Availability Statement

The code developed for the current study are available at https://github.com/NREL/resstock/tree/feature/projections

References

1. Mai, T. *et al.* An electrified future: Initial scenarios and future research for U.S. Energy and electricity systems. *IEEE Power Energy Mag.* **16**, 34–47 (2018).
2. IEA. *World Energy Balances 2020*. https://www.iea.org/data-and-statistics/data-product/world-energy-balances (2020).
3. 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).
4. 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).
5. Denholm, P. *et al.* The challenges of achieving a 100% renewable electricity system in the United States. *Joule* **5**, 1331–1352 (2021).
6. 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.
7. 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).
8. Dubois, M. & Allacker, K. Energy savings from housing: Ineffective renovation subsidies vs efficient demolition and reconstruction incentives. *Energy Policy* **86**, 697–704 (2015).
9. Ding, G. & Ying, X. Embodied and operating energy assessment of existing buildings – Demolish or rebuild. *Energy* **182**, 623–631 (2019).
10. 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).

11. 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).
12. Röck, M. *et al.* Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. *Appl. Energy* **258**, 114107 (2020).
13. 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).
14. Saheb, Y. COP26: Sufficiency Should be First. *Buildings & Cities* (2021).
15. 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).
16. Lorek, S. & Spangenberg, J. H. Energy sufficiency through social innovation in housing. *Energy Policy* **126**, 287–294 (2019).
17. Thomas, S. *et al.* Energy sufficiency policy for residential electricity use and per-capita dwelling size. *Energy Effic.* **12**, 1123–1149 (2019).
18. 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).
19. 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).
20. Pauliuk, S. *et al.* Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. *Nat. Commun.* **12**, 5097 (2021).
21. 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).
22. Berrill, P. & Hertwich, E. Material flows and GHG emissions from housing stock evolution in US counties, 2020-2060. *Build. Cities* **2**, 599–617 (2021).
23. Ellsworth-Krebs, K. Implications of declining household sizes and expectations of home comfort for domestic energy demand. *Nat. Energy* **5**, 1–6 (2019).
24. 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).
25. 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).
26. 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).
27. 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.
28. 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).
29. Churkina, G. *et al.* Buildings as a global carbon sink. *Nat. Sustain.* 1–8 (2020) doi:10.1038/s41893-019-0462-4.
30. 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).

31. 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).
32. 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).
33. IEA. *World Energy Outlook 2020*. https://www.iea.org/reports/world-energy-outlook-2020 (2020).
34. Langevin, J. *et al.* US building energy efficiency and flexibility as an electric grid resource and flexibility as an electric grid resource. *Joule* **5**, 2102–2128 (2021).
35. Nelson, S. & Allwood, J. M. The technological and social timelines of climate mitigation: Lessons from 12 past transitions. *Energy Policy* **152**, 112155 (2021).
36. EIA. *Electric Power Annual 2020 (Table 4.2B)*. https://www.eia.gov/electricity/annual/ (2021).
37. van Zalk, J. & Behrens, P. The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy* **123**, 83–91 (2018).
38. 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).
39. 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).
40. Deetjen, T. A., Walsh, L. & Vaishnav, P. US residential heat pumps: the private economic potential and its emissions, health, and grid impacts. *Environ. Res. Lett.* **16**, 084024 (2021).
41. Gross, R. & Hanna, R. Path dependency in provision of domestic heating. *Nat. Energy* **4**, 358–364 (2019).
42. 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.
43. 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).
44. 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).
45. 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).
46. Wilson, E. *et al.* Energy Efficiency Potential in Stock Energy Efficiency Potential in the U. S. Single-Family Housing Stock. (2017).
47. 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).
48. 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.
49. 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).
50. Schwartz, A. F. *Housing Policy in the United States*. (2015).
51. Glaeser, E. L. Killing (or Maiming) a Sacred Cow: Home Mortgage Deductions. *New York Times* (2009).
52. Ivanova, D. & Büchs, M. Household sharing for carbon and energy reductions: the case of EU countries. *Energies* (2020).
53. Ewing, R. & Cervero, R. "Does Compact Development Make People Drive Less?" The Answer Is Yes. *J. Am. Plan. Assoc.* **83**, 19–25 (2017).

54. 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).
55. 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).
56. Landis, J. & Reina, V. Eleven Ways Demographic and Economic Change Is Reframing American Housing Policy. *Hous. Policy Debate* **29**, 4–21 (2019).
57. EIA. Status of State Energy Code Adoption. https://www.energycodes.gov/adoption/states (2020).
58. 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).
59. International Code Council. Residential Energy Efficiency. in *2018 International Energy Code* (2020).
60. EIA. Annual Energy Outloot 2021. https://www.eia.gov/outlooks/aeo/ (2021).
61. NREL. ResStock. https://github.com/NREL/resstock (2021).
62. Freddie Mac. *Granny Flats, Garage Apartments, In-Law Suites : Identifying Accessory Dwelling Units from Real Estate Listing Descriptions Using Text Mining*. http://www.freddiemac.com/research/insight/20200716_identifying_accessory_dwelling_units_from_real_estate.page (2020).
63. US Census Bureau. American Housing Survey. (2020).
64. EPA. *Subpart C—General Stationary Fuel Combustion Sources*. *Federal Register - Rules and Regulations* vol. 74 (2009).
65. NREL. Cambium - Scenario Viewer and Data Downloader. *Standard Scenarios 2020* https://cambium.nrel.gov/ (2020).
66. EIA. State Energy Data System (SEDS): 1960-2018. https://www.eia.gov/state/seds/seds-data-complete.php?sid=US (2020).
67. EPA. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2018*. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks (2020).

Figures

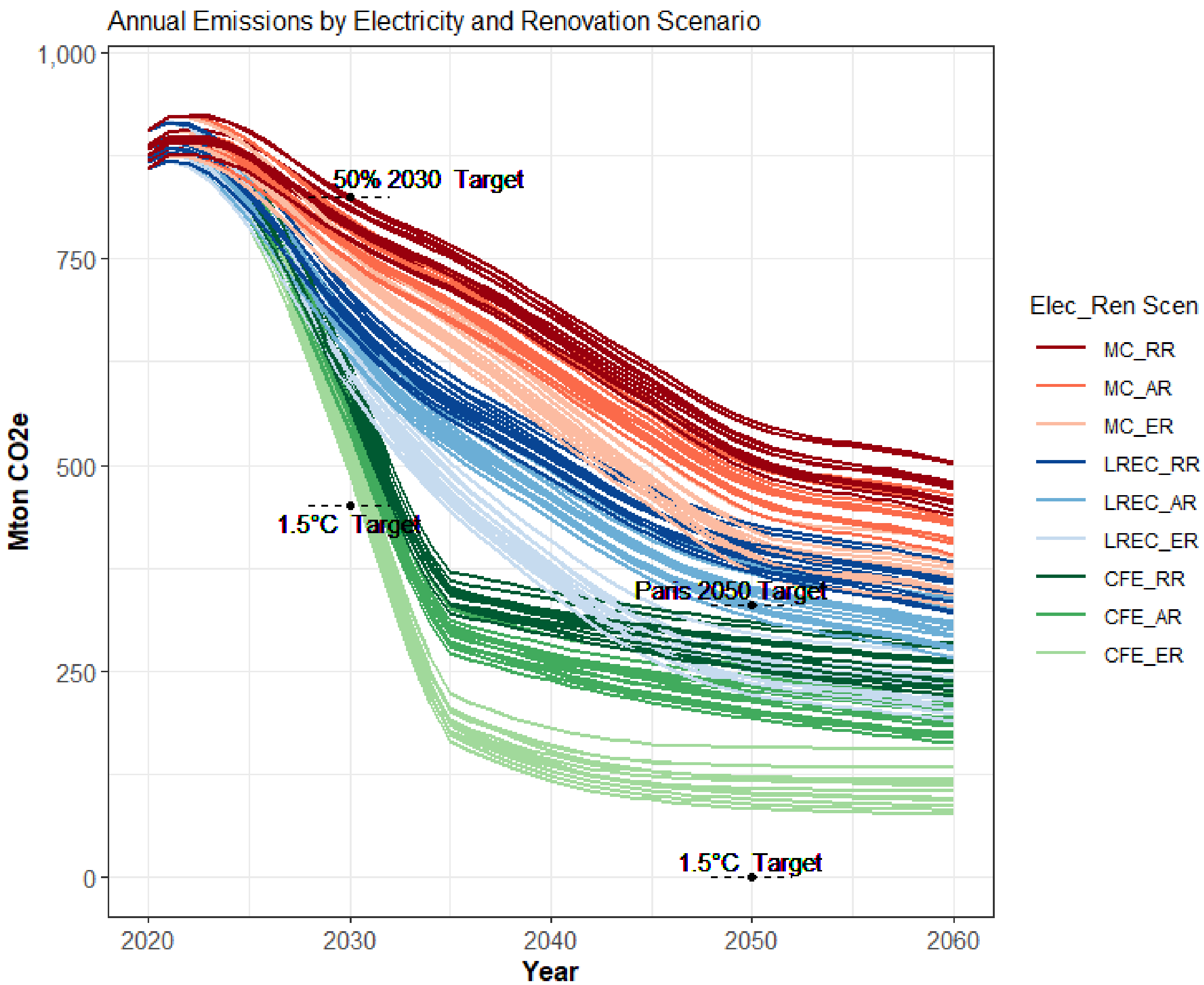

Figure 1

Annual emission trajectories for all 108 scenarios of strategy combinations, with respect to emission reduction targets in 2030 and 2050. Trajectories are grouped by combinations of electricity supply and renovation scenarios; MC = Mid-Case Electricity, LREC = Low-Cost Renewable Electricity; CFE = Carbon Free Electricity by 2035. RR = Regular Renovation, AR = Advanced Renovation, ER = Extensive Renovation. Variations within electricity and renovation scenario combinations result from differences in new housing characteristics and stock evolution scenarios

Figure 2

Cumulative 2020–2060 emissions in each scenario, grouped by electricity supply scenarios. RE = Renewable Electricity; Red. FA = reduced floor area; Inc. Elec. = Increased Electrification; TO = turnover; MF = multifamily; RR = Regular Renovation; AR = Advanced Renovation; ER = Extensive Renovation

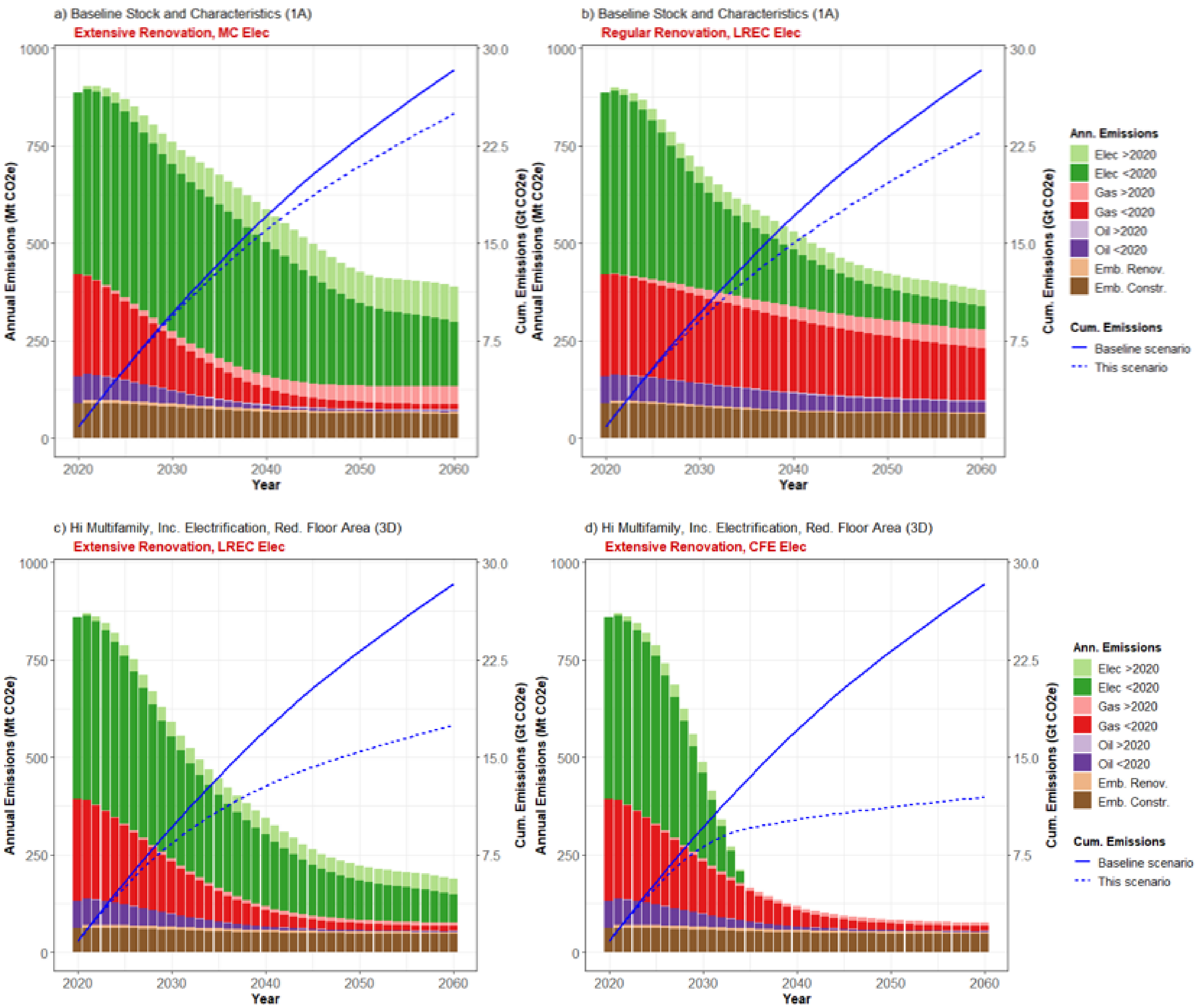

Figure 3

Annual (Ann.) and Cumulative (Cum.) GHG emissions by source for four selected scenarios. Energy emissions are disaggregated by energy carrier in housing built before 2020 (<2020) and after 2020 (>2020). Embodied (Emb.) emissions are split into emissions from new construction (Constr.) and renovation (Renov.). 'Oil' includes fuel oil and propane/LPG.

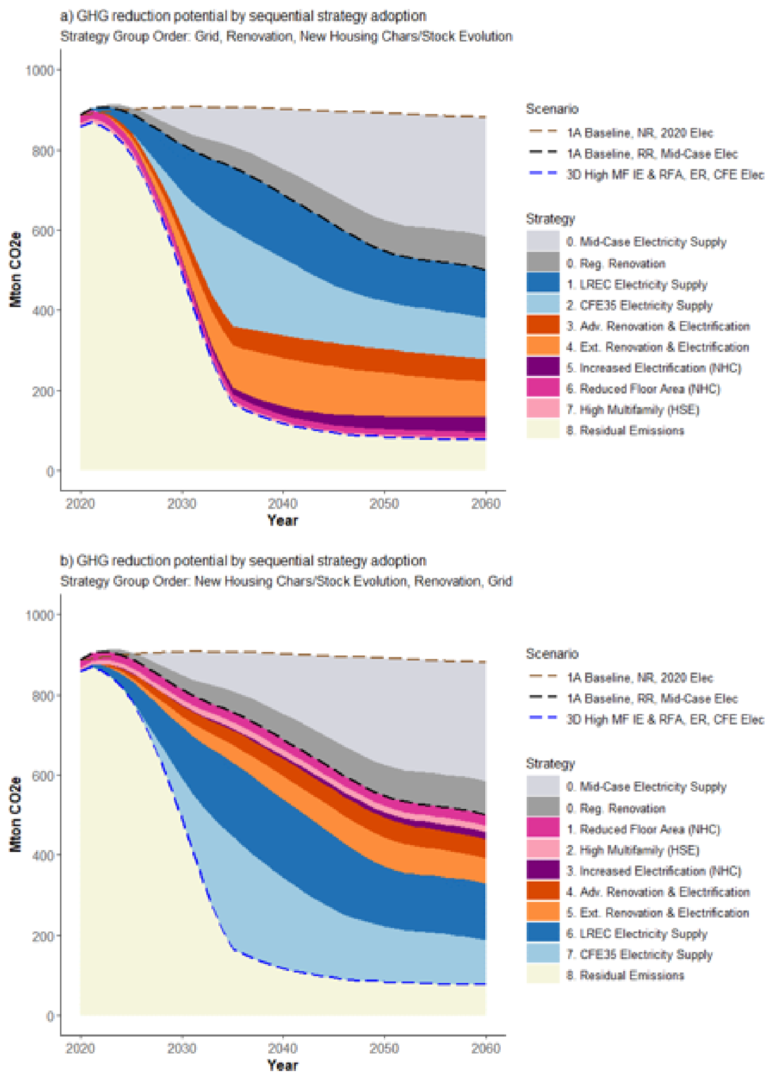

Figure 4

Emission reduction potential of individual strategies sequenced by their total reduction potential, relative to emissions in the Baseline stock, Base Housing Characteristics, Regular Renovation, and Mid-Case electricity GHG scenario. Strategies are grouped by those relating to electricity grid (blue), renovation (orange), and new housing characteristics (NHC) or housing stock evolution (HSE) (pink/purple). NHC and HSE strategies apply only to housing built after 2020. The residual emissions correspond to the scenario with lowest emissions – with all 5 indicated strategies employed. NR = No Renovation

Supplementary Files

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