Supplementary Information: *(This file can be accessed here)*

Decarbonization pathways for the residential sector in the United States

Peter Berrill[1,4,5], Eric J.H. Wilson[2], Janet Reyna[2], Anthony Fontanini[2], Edgar G. Hertwich[3]

[1]*Yale School of the Environment, New Haven CT, USA*

[2]*National Renewable Energy Laboratory, Golden CO, USA*

[3]*Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway*

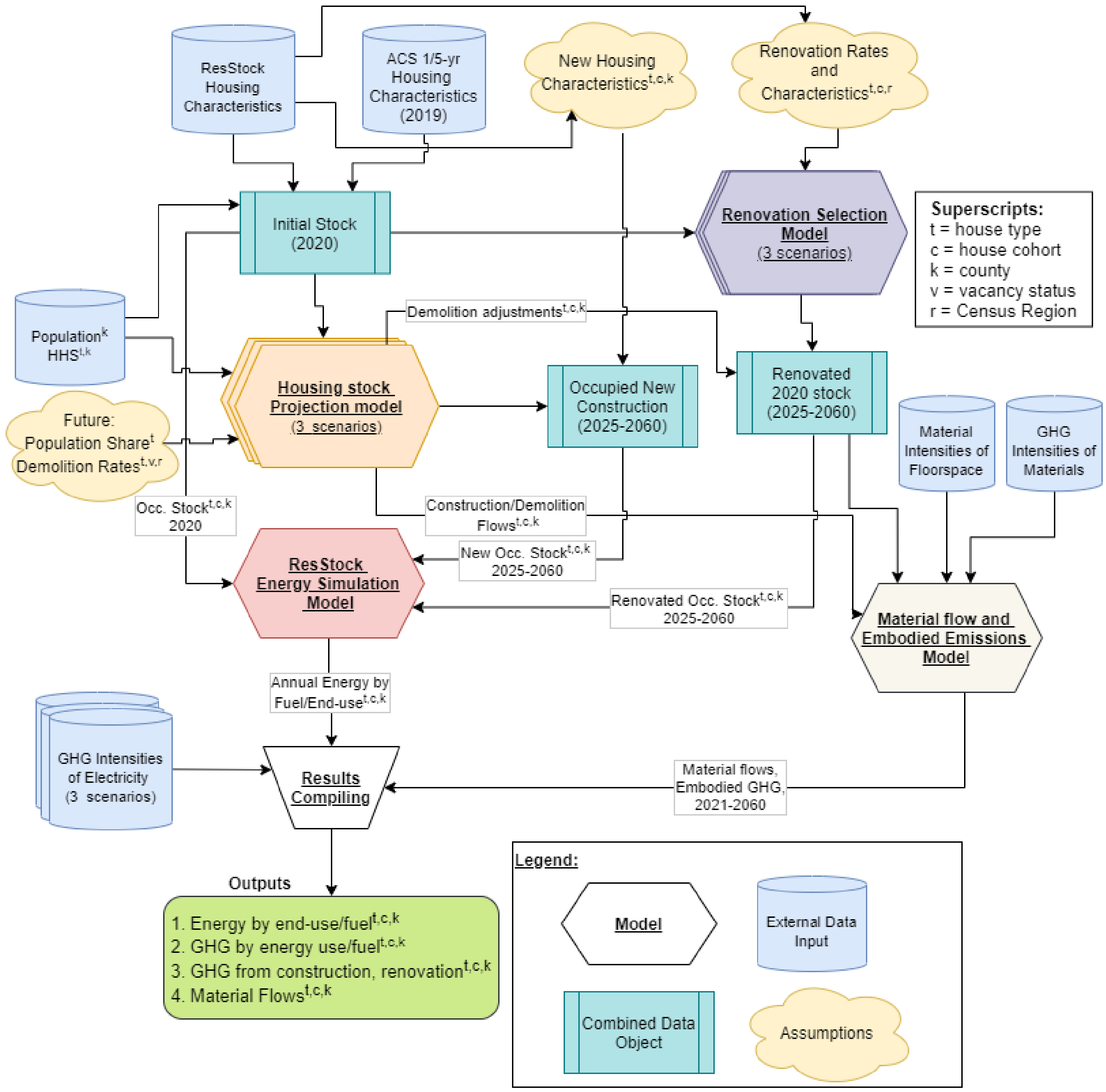
[4]*Technische Universität Berlin, Berlin, Germany*

[5]*Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany*

Contents

1 Model Overview

Supplementary Figure 1 gives an overview of the interconnection and integration of different model components. In Sections 2-5 we describe additional details of the housing stock model, renovation selection model, the characteristics of renovation scenarios, and electricity supply scenarios.

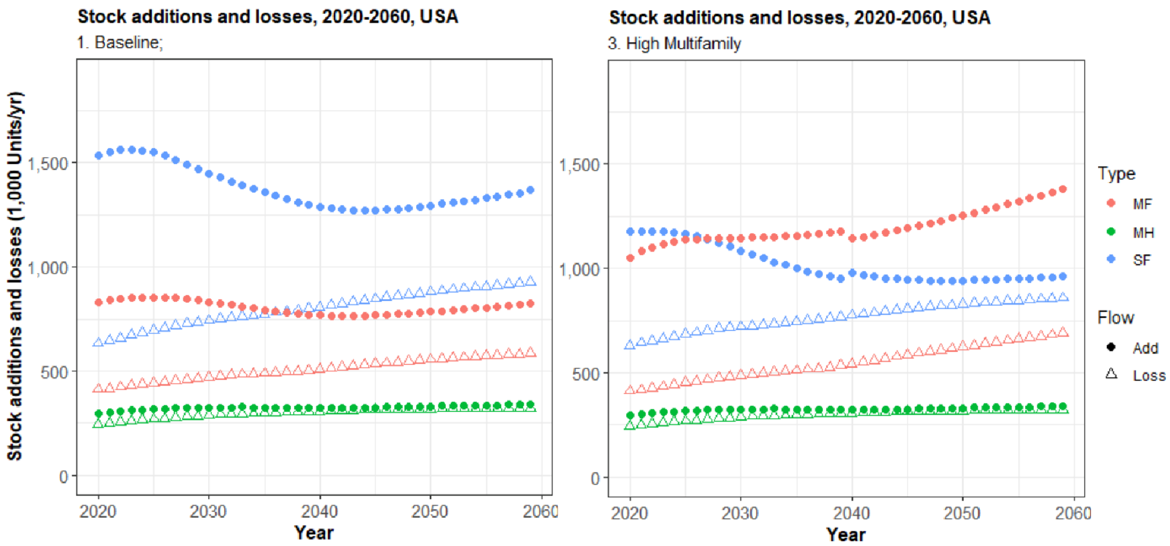


Supplementary Figure 1 Schematic overview of model

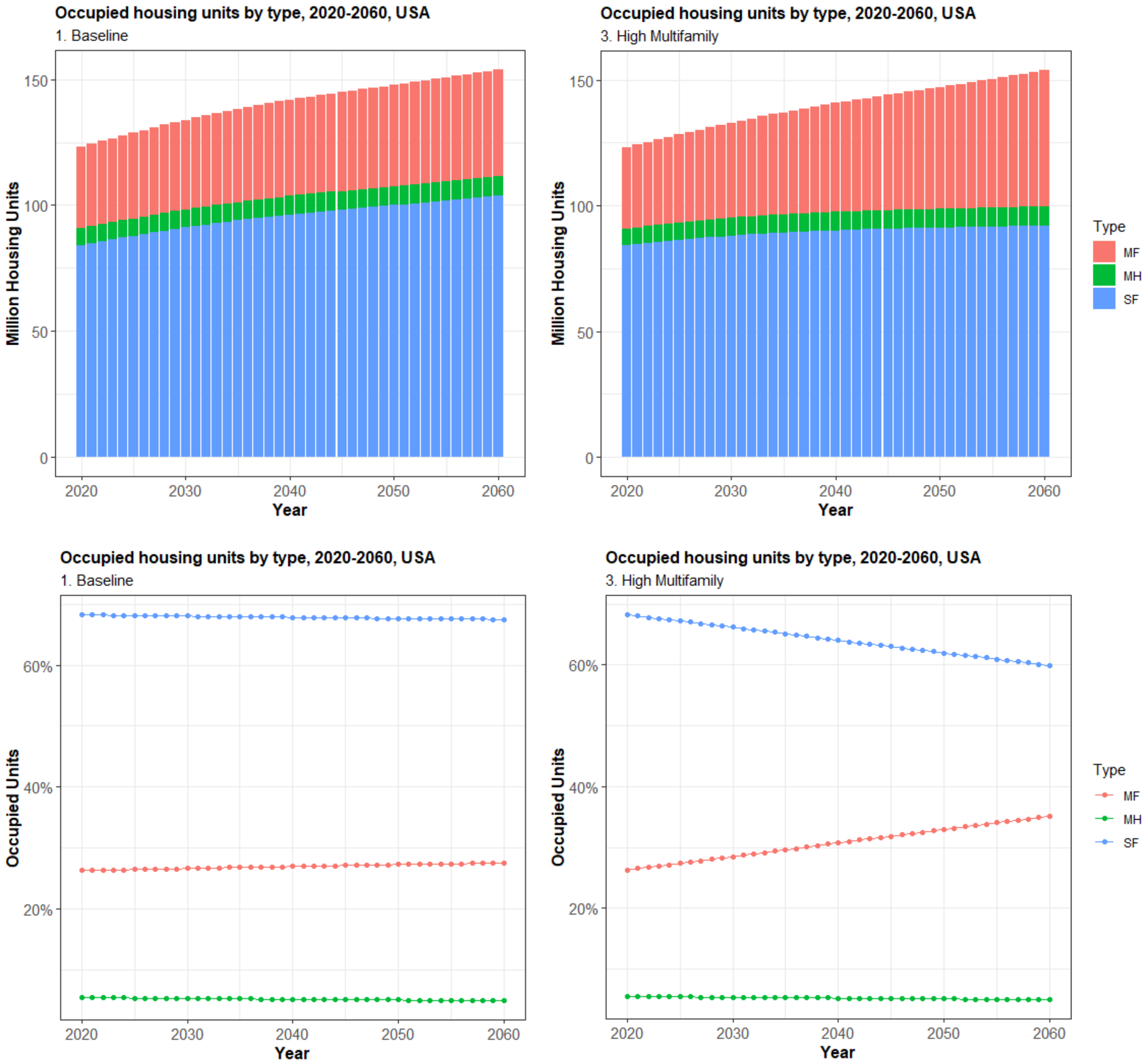
2 Housing stock model and scenarios

The Housing Stock Model 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[1]. Vacancy rates by Census Region and house type are assumed to gradually converge, which translates into higher construction rates in counties with lower than average 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 modeled 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. The baseline housing stock growth scenario projects increased construction in many urban areas, due to an assumption of converging vacancy rates by house type and Census Region[1]. Higher housing stock growth in areas with low vacancy rates, which are usually high-population urban and suburban counties with stringent land-use restrictions[2], could help to alleviate issues of housing affordability and supply[3].

Supplementary Figure 2 demonstrates the implications of a High Multifamily housing stock scenario on housing stock inflows by type. Multifamily inflows are substantially higher in the High Multifamily scenario, and exceed single-family inflows from about 2028. The difference between single-family inflows and outflows reduces notably from 2025 in the High Multifamily scenario, resulting in low absolute growth of single-family housing. Supplementary Figure 3 contrasts the growth in occupied housing, and the shares by type of occupied housing in the two scenarios. The High Multifamily scenario sees occupied multifamily housing increase to 54 million units (35.1% of occupied housing) by 2060, compared to 42 million units (27.5% of occupied housing) by 2060 in the Baseline scenario.



Supplementary Figure 2 Inflows and outflows of housing by type in Baseline and High Multifamily stock scenarios



Supplementary Figure 3 Growth in absolute occupied housing and share of occupied housing by house type in Baseline and High Multifamily scenarios

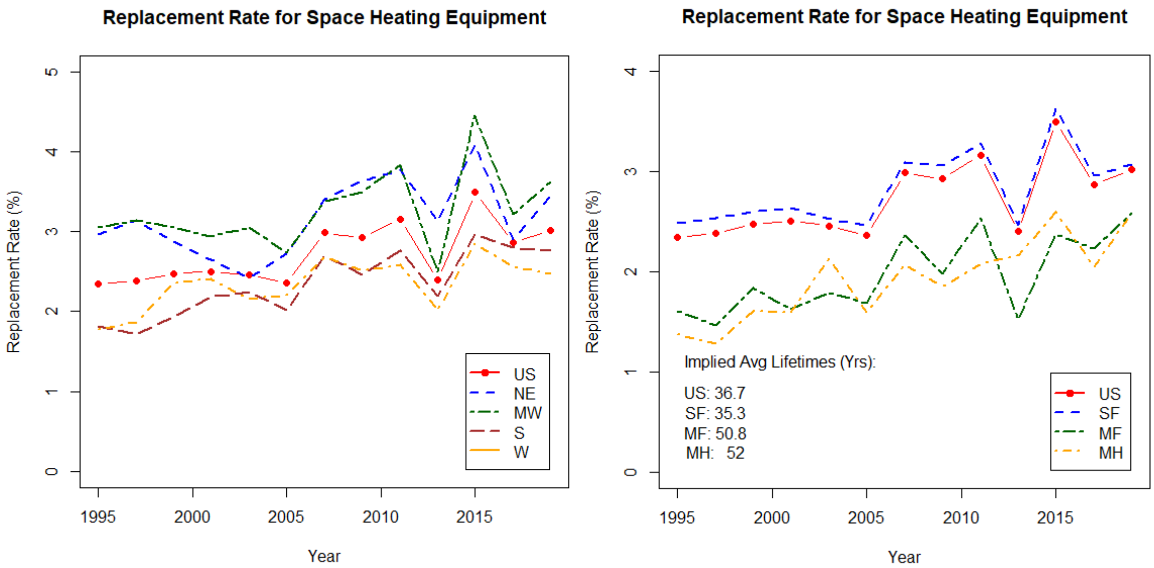
3 Renovation model and scenarios

The renovation selection model modifies the description of housing built pre-2020, for every year 2021-2060. Energy consumption in renovated pre-2020 housing is re-simulated every five years from 2025 - 2060 *if* there has been a renovation-induced change in housing characteristics since the previous simulation year. Renovation, in our modeling, describes the replacement of space heating, space cooling, and water heating equipment; the addition of space cooling equipment in some cases; the addition or increase of insulation to crawlspaces, unfinished basements, external walls, and unfinished attics; and the reduction of infiltration which accompanies an increase/upgrade in insulation. We outline in detail the approach for describing renovation rates and characteristics for space heating equipment, and then give summary statistics for renovation rates of other types. The same general approach applies to estimating renovation rates for all systems considered.

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 4). Apart from the effect of replacing fossil heating equipment with heat pumps, neglecting renovation of newly built homes is not expected to have a large 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. Direct fossil energy emissions from new housing form a relatively low share of future emissions, especially with Increased Electrification of new housing (main text Fig. 3).

3.1 Renovation rates

We estimate renovations rates separately for combinations of four Census Regions (Northeast = NE, Midwest = MW, South = S, West = W) and three house types (single-family = SF, multifamily = MF, manufactured home = MH). Future renovation rates and fuel-switching trends are based on data from American Housing Surveys (AHS) covering the period 1995-2019[4], 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. Further, as our housing stock and energy simulation models do not distinguish tenure, the influence of split incentives between landlords and tenants was not included in our renovation scenarios. In Supplementary Figure 4 we show trends of replacement rates of space heating equipment over the period 1995-2019 by Census Region and by house type. Indicated on the figures is the implied equipment lifetime, i.e. the period between replacements, calculated as the inverse of the replacement rate. Over this period, replacement rates for heating equipment averaged around 2.7%, implying a lifetime of 36.7 years. Rates appear higher post-2005, and are notably higher in SF than MF or MH housing. Replacement rates are also higher in the colder NE and MW Census Regions.

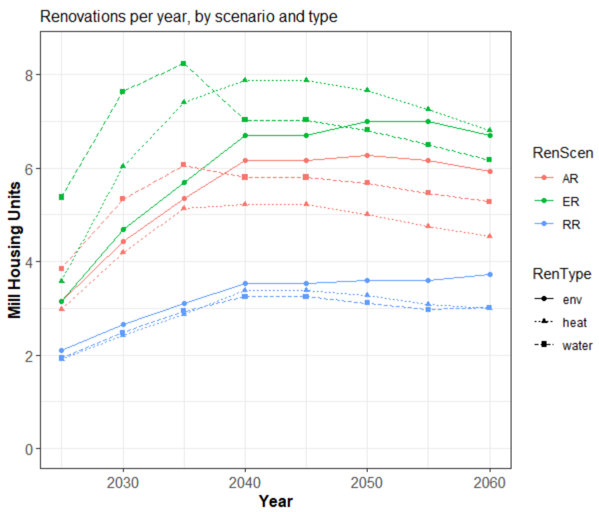


Supplementary Figure 4 Replacement Rate for Space Heating Equipment 1995-2019 by (a) Census Region (b) House Type.

For the renovation selection model, to calculate the probability of replacement for each house type and region combination, we use the average replacement rate for each housing type over the previous five surveys (2011-2019), and then multiply that rate by the ratio of the US average and each Region average over the same period. For instance, the mean replacement rate for all SF homes 2011-2019 was 3.1%, and replacement rates (for all housing types) in NE were on average 1.16 times higher than the national average over the same period, the heating equipment replacement rate for SF homes in NE was calculated as 1.16*3.1% = 3.6%, which corresponds to an average equipment lifetime of ~28 years. This approach was preferred to estimating the rates by combinations of region and type in the AHS data, due to insufficiently large sample sizes when splitting up survey data into house type, region, and renovation status. We show renovation rates calculated for each type-renovation system combination in each Census Region in Supplementary Table 1. We show average annual numbers of housing units undergoing renovations of heating, water heating, and envelope systems in Supplementary Figure 5.

Supplementary Table 1 Annual replacement/renovation rates (probabilities) by Census Region for house and renovation type

	House and renovation type											
Div.	SF heat	MF heat	MH heat	SF AC	MF AC	MH AC	SF H_2O	MF H_2O	MH H_2O	SF ins	MF ins	MH ins
NE	0.036	0.026	0.027	0.02	0.017	0.019	0.047	0.034	0.042	0.027	0.012	0.024
MW	0.036	0.027	0.027	0.026	0.022	0.024	0.051	0.037	0.046	0.023	0.01	0.021
S	0.028	0.02	0.021	0.039	0.033	0.037	0.044	0.032	0.039	0.018	0.008	0.016
W	0.026	0.019	0.019	0.023	0.02	0.022	0.047	0.034	0.043	0.019	0.009	0.017

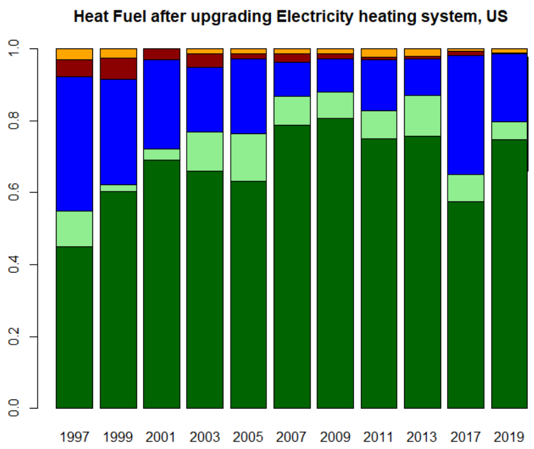


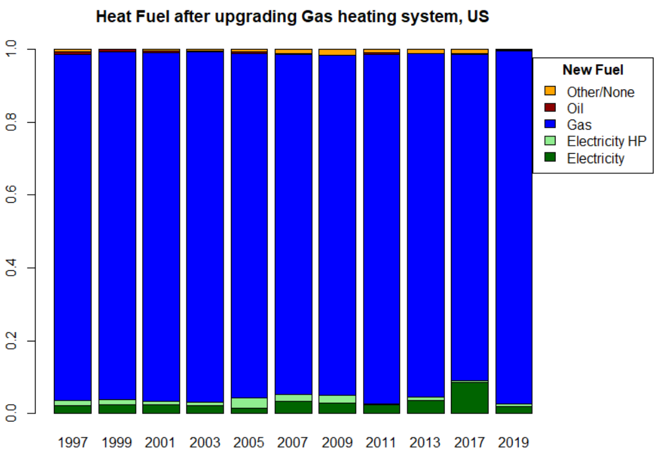
Supplementary Figure 5 Number of housing units undergoing envelope (env), heating equipment (heat), and water heating equipment (water) renovations each year, by renovation scenario, 2025-2060. Each year represents the mean of units renovated in the previous five years, i.e., 2025 refers to the mean annual units renovated from 2021 to 2025.

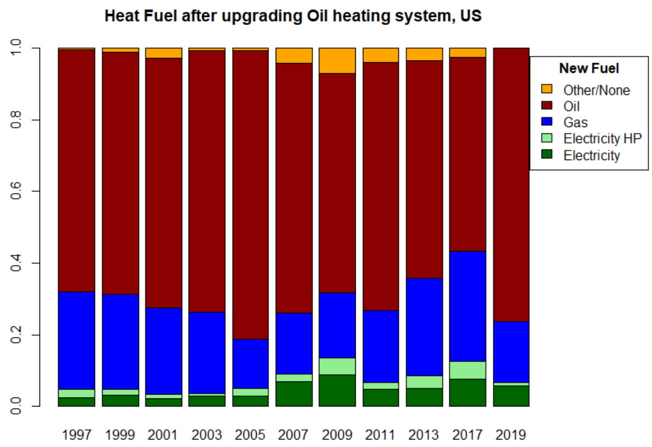
3.2 Renovation characteristics – space heating

For space heating renovations, we incorporate the possibility that a household changes main heating fuel, as well as the likelihood that the efficiency of the equipment increases. We assume however that there are no changes in heating distribution systems (ducted, un-ducted). For example, if a house has a gas-fired forced air furnace with ducted distribution, then that household could upgrade to a more efficient gas furnace, or a furnace heated by another fuel source, or a ducted air-source heat pump, but it could not upgrade to a non-ducted heating system, such as a gas boiler or a mini-split (un-ducted) heat pump. Further, fuel switching in housing units on a shared heating system was not modelled, as this would have required simultaneous changes to housing HVAC system components, which would have introduced numerous additional complexities to the renovation modelling. As shown in Supplementary Fig. 8-9, this limits the removal of fossil fuel heating from existing homes, and in the Extensive Renovation scenario, almost all remaining fossil-based heating by 2060 is shared heating.

From AHS data we estimate the probability of fuel switching by extracting the households who replaced/added space heating equipment in a given survey year (e.g. 1997), and comparing the main heating fuel of that same household in the given survey year against the previous survey year (e.g. 1997 vs 1995). In this way we calculate the probability of a heating equipment replacement being accompanied by a change in main heating fuel, and which fuel it is likely to be replaced by. We distinguished fuel switching by Census Region, as incumbent heating fuel and fuel switching trends can vary substantially by geography. We grouped the heating fuels as Electricity, Electricity Heat Pump, Gas (including propane), Fuel Oil, and Other/None, except for 2015-2019, when propane is distinguished as a separate heating fuel. Because this calculation requires knowledge of the main heating fuel during the previous survey, we cannot estimate switching rates for years 1995 or 2015 (when a new sample was drawn). In Supplementary Figure 6 we show the probability of heating fuel choice after a heating system renovation, conditional on the pre-renovation fuel. We see evidence for sizable switching from electricity and oil to natural gas, and smaller levels of switching to electricity from gas and oil.







Supplementary Figure 6 Likelihood of heating fuel change to specific fuels, during replacements of (a) electric, (b) gas, and (c) oil heating equipment, 1997-2019. Gas includes LPG/propane.

Based on trends of fuel switching during heating equipment replacement, we estimate probabilities of a fuel switch to fuel *y* when replacing heating equipment which uses fuel *x*, based on average switching rates over the five most recent surveys (2009, 2011, 2013, 2017, 2019). We then split out the rate of switching to gas and propane by disaggregating the rate of switching to gas, based on the gas:propane splits in 2017 and 2019. We show fuel switching rates implemented in the renovation scenarios for each fuel combination in each Census Region in Supplementary Table 2. The columns represent the previous heating fuel, and the rows depict the new heating fuel, so for example, a non-Heat Pump electric heating system being replaced under regular renovation has a 24% probability of converting to a gas-based system. For Regular Renovation scenarios, we adjust data for replacing incumbent electricity systems in NE to reflect a lower tendency to switch to oil in the future, compared to historic trends. For the Advanced Renovation, we reduce the likelihood of switching or remaining with fossil-based systems, and increase the likelihood of remaining or switching to electric, in particular electric heat pump systems. The likelihood of switching to electric heat pumps becomes far higher under Extensive Renovation, especially from 2025 onwards, when all renovations of fossil heating systems result in conversions to electric heat pump systems. These fuel switching probabilities apply only to housing units which are selected for heating system replacement in a given year, not to all housing.

Supplementary Table 2 Probability of new heating equipment using heating fuels (rows), by previous heating fuel (columns). ‘Electricity’ refers to all electric heat pumps which are not heat pumps, including baseboard, boiler, and furnace systems.

a) Regular Renovation

Northeast	Electricity	Elec. HP	Gas	Oil	Propane
Electricity	0.67	0	0.013	0.017	0
Electricity HP	0.01	0.978	0	0.008	0
Gas	0.24	0.022	0.959	0.150	0.081
Oil	0.045	0	0.009	0.767	0
Propane	0.035	0	0.020	0.058	0.919

Midwest	Electricity	Elec. HP	Gas	Oil	Propane
Electricity	0.729	0.008	0.025	0.100	0.028
Electricity HP	0.041	0.959	0.004	0.011	0.000
Gas	0.189	0.032	0.958	0.372	0.172
Oil	0.012	0	0.001	0.211	0.000
Propane	0.029	0	0.012	0.306	0.801
South	Electricity	Elec. HP	Gas	Oil	Propane
Electricity	0.757	0.037	0.071	0.199	0.210
Electricity HP	0.091	0.939	0.021	0.147	0.016
Gas	0.135	0.025	0.900	0.106	0.140
Oil	0.003	0	0.001	0.525	0.016
Propane	0.014	0	0.006	0.023	0.617
West	Electricity	Elec. HP	Gas	Oil	Propane
Electricity	0.731	0.022	0.041	0.252	0.283
Electricity HP	0.095	0.950	0.011	0.069	0.043
Gas	0.171	0.027	0.933	0.417	0.370
Oil	0	0	0.001	0.263	0.043
Propane	0.003	0	0.015	0	0.261

b) Advanced Renovation

Northeast	Electricity	Elec. HP	Gas	Oil	Propane
Electricity	0.75	0	0.02	0.1	0.02
Electricity HP	0.1	1	0.08	0.2	0.08
Gas	0.115	0	0.9	0.15	0.1
Oil	0	0	0	0.5	0
Propane	0.035	0	0	0.05	0.8
Midwest	Electricity	Elec. HP	Gas	Oil	Propane
Electricity	0.7	0	0.025	0.15	0.025
Electricity HP	0.2	1	0.1	0.35	0.1
Gas	0.09	0	0.875	0.35	0.125
Oil	0	0	0	0	0
Propane	0.01	0	0	0.15	0.75
South	Electricity	Elec. HP	Gas	Oil	Propane
Electricity	0.75	0	0.12	0.35	0.25
Electricity HP	0.25	1	0.13	0.55	0.15
Gas	0	0	0.75	0.1	0.1
Oil	0	0	0	0	0
Propane	0	0	0	0	0.5
West	Electricity	Elec. HP	Gas	Oil	Propane
Electricity	0.75	0	0.1	0.25	0.25
Electricity HP	0.2	1	0.1	0.5	0.25
Gas	0.05	0	0.8	0.25	0.25
Oil	0	0	0	0	0
Propane	0	0	0	0	0.25

*c) Extensive Renovation, 2021-2024**

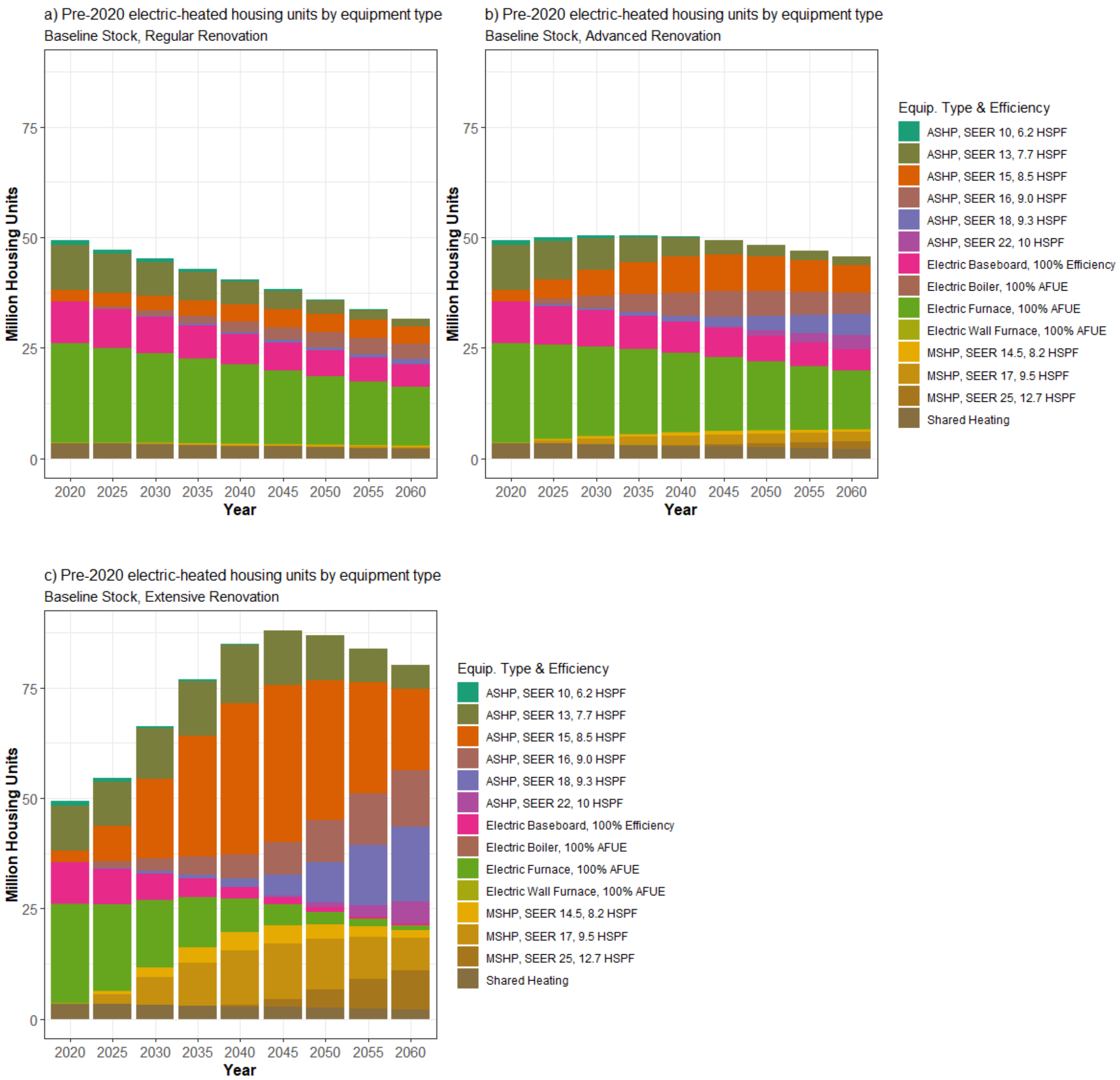
Northeast	Electricity	Elec. HP	Gas	Oil	Propane
Electricity	0.75	0	0.02	0	0
Electricity HP	0.25	1	0.25	0.5	0.25
Gas	0	0	0.75	0	0
Oil	0	0	0	0.45	0
Propane	0	0	0	0.05	0.75
Midwest	Electricity	Elec. HP	Gas	Oil	Propane
Electricity	0.65	0	0	0	0
Electricity HP	0.35	1	0.35	0.5	0.35
Gas	0	0	0.65	0.5	0
Oil	0	0	0	0	0
Propane	0	0	0	0.	0.65
South	Electricity	Elec. HP	Gas	Oil	Propane
Electricity	0.5	0	0	0.15	0
Electricity HP	0.2	1	0.5	0.8	0.5
Gas	0	0	0.5	0.05	0
Oil	0	0	0	0	0
Propane	0	0	0	0	0.5
West	Electricity	Elec. HP	Gas	Oil	Propane
Electricity	0.545	0	0	0	0
Electricity HP	0.364	1	0.3	0.75	0.75
Gas	0.082	0	0.7	0.25	0
Oil	0	0	0	0	0
Propane	0.009	0	0	0	0.25

**From 2025-2060 under Extensive Renovation, all fossil heating systems are converted to Elec. HP in all regions. 90% of non-HP electric heating systems are replaced with Elec. HP, while 10% remain as non-HP electric heating.*

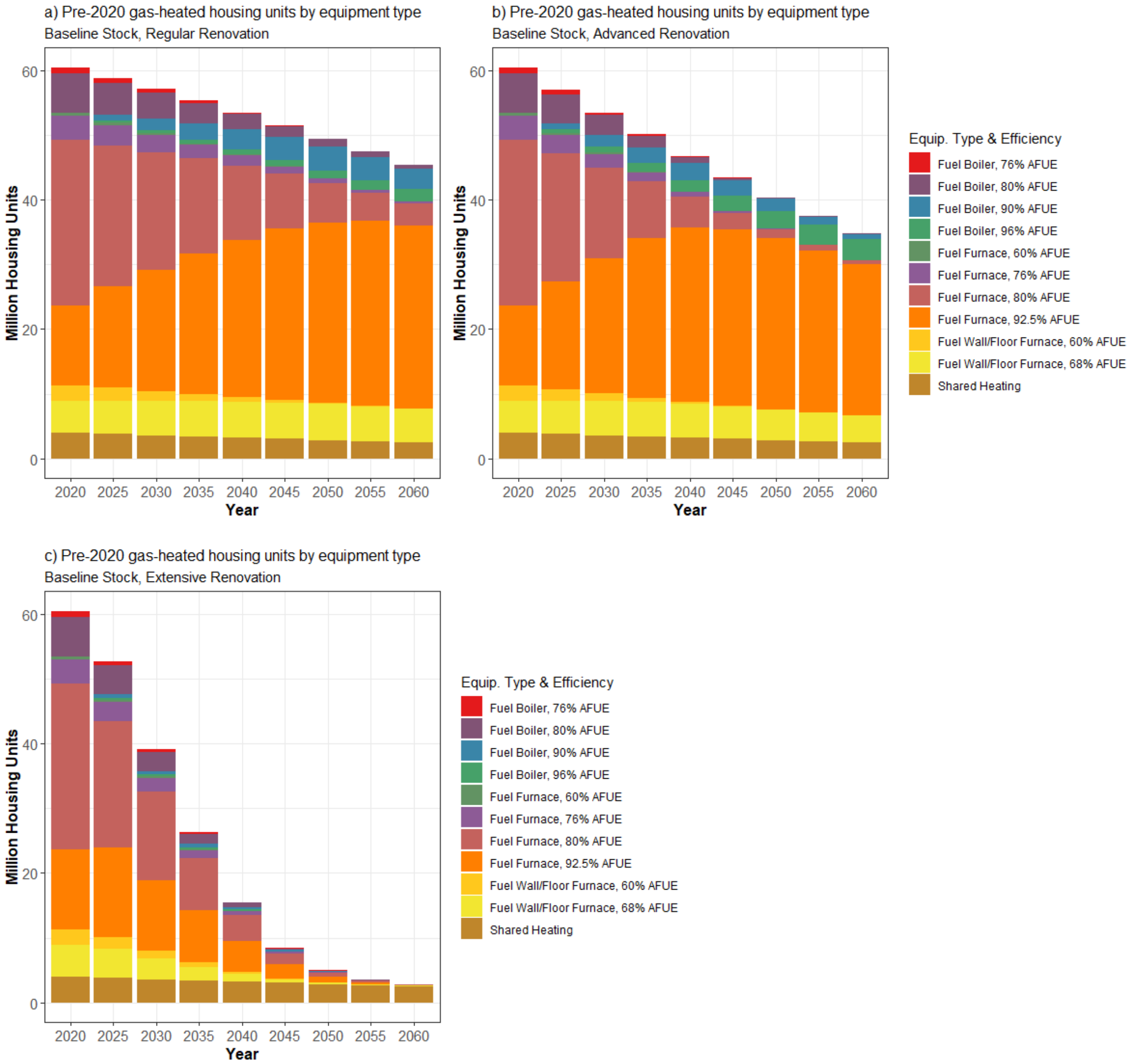
We see that fuel switching from electricity to gas is currently common, particularly in NE. Switching from fossil fuels to electricity, and to heat pumps, is a trend that is seen mostly in S and W regions. Although data are shown for the portion of households switching from Fuel Oil in each region, only in NE is there a significant number of houses using oil in the first place. The switching rates demonstrate that almost one quarter of NE homes replacing an oil heating system switch to a new fuel, which is most likely to be gas, followed by propane and electricity. Rates shown for switching from other/none to electricity, oil, and gas are approximations based on actual rates in 2017 and 2019, but in renovation scenarios we do not model changing of heating fuel from other/none, these remain unchanged. 'Other' heating fuels include firewood, but we do not estimate GHG emissions from this category, which is consistent with an assumption of zero global warming potential from biogenic emissions.

To reflect improvements in efficiency level associated with a renovation, the most commonly applied approach in the Regular Renovation scenario is that upon undergoing a renovation, a system moves up one or two efficiency levels with 50:50 probability, and in the Advanced and Extensive scenarios, the same change applied with 25:75 probability, so there is a higher diffusion of more efficient equipment.

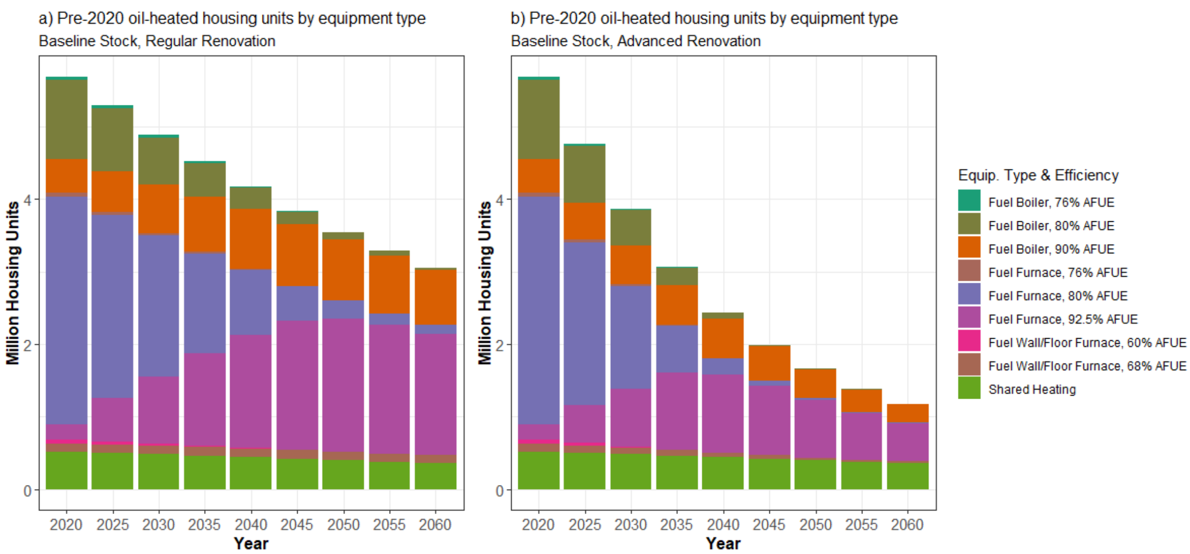
When systems are already at the second to highest efficiency level, a renovation is modelled as a replacement to the system of the highest efficiency level. If the incumbent system was already the highest possible efficiency, no change is made. Supplementary Figures 7-9 show the projection of pre-2020 housing units grouped by space heating fuel and technology/efficiency combinations for housing with electricity, gas, and oil as main heating fuels, for the baseline stock scenario and the three renovation scenarios. These figures incorporate both fuel switching and stock decay/demolition. The slower decay of units with electric heating under Advanced Renovation, and the large increase of units under Extensive Renovation, reflects the fuel switching that takes place from combustion fuels to electricity. In each scenario, we see progressively large increases in air source heat pump (ASHP) and mini-split heat pump (MSHP) heating systems as a share of electric heating systems.

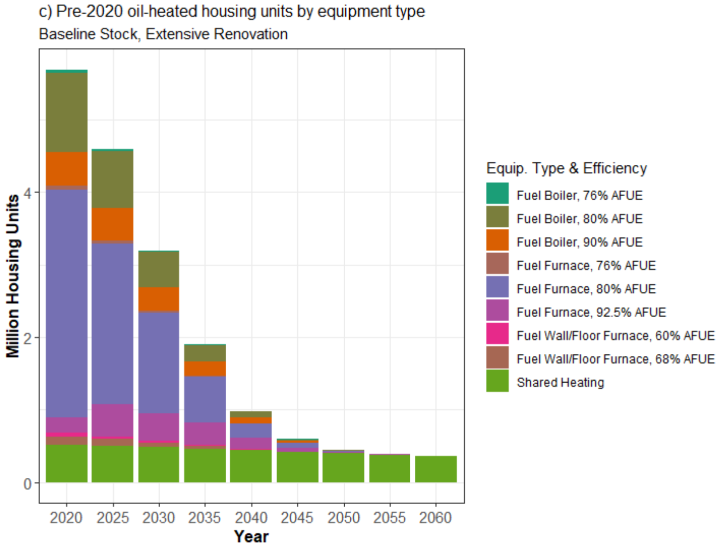


Supplementary Figure 7 Renovation scenario-based evolution of heating equipment efficiency in pre-2020 housing units with electric heating under Baseline Stock evolution



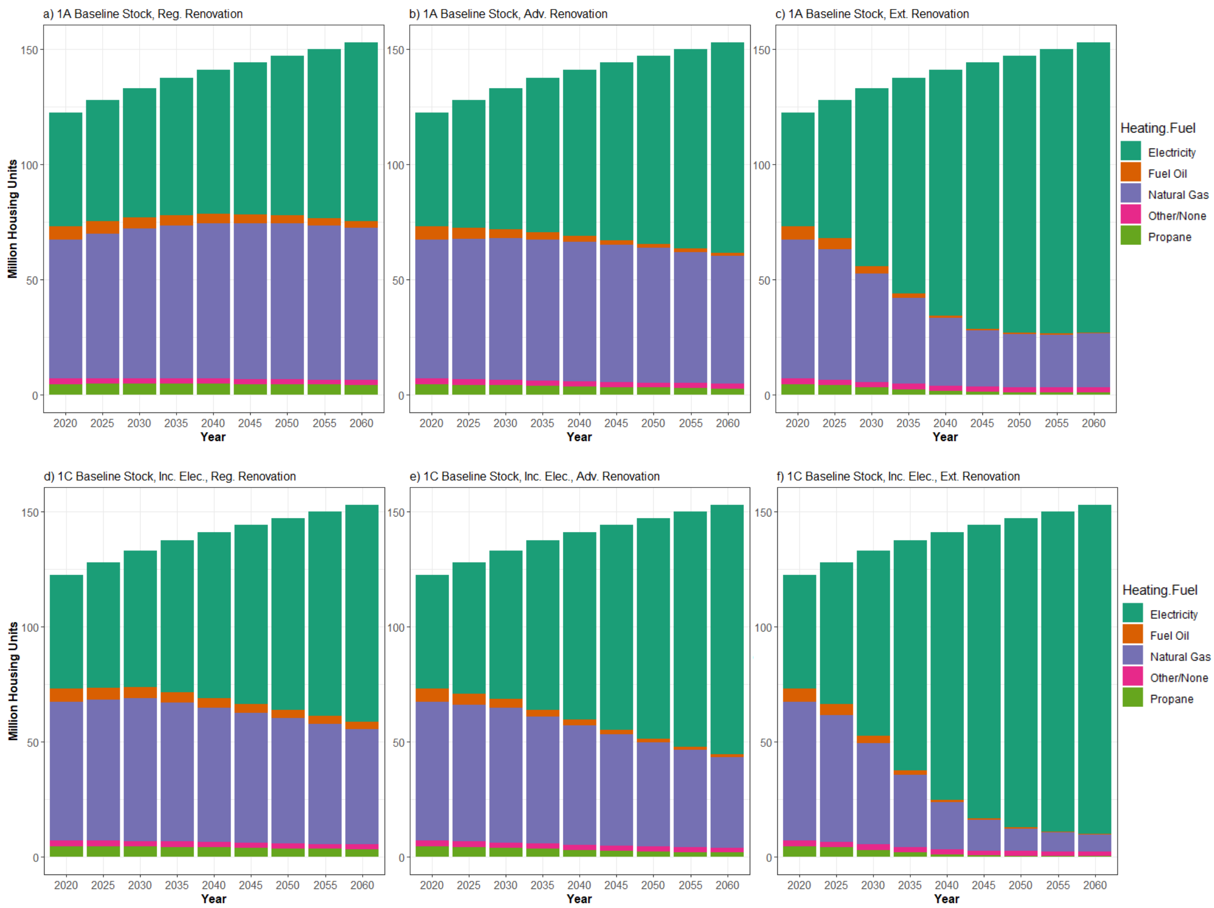
Supplementary Figure 8 Renovation scenario-based evolution of heating equipment efficiency in pre-2020 housing units with gas heating under Baseline Stock evolution





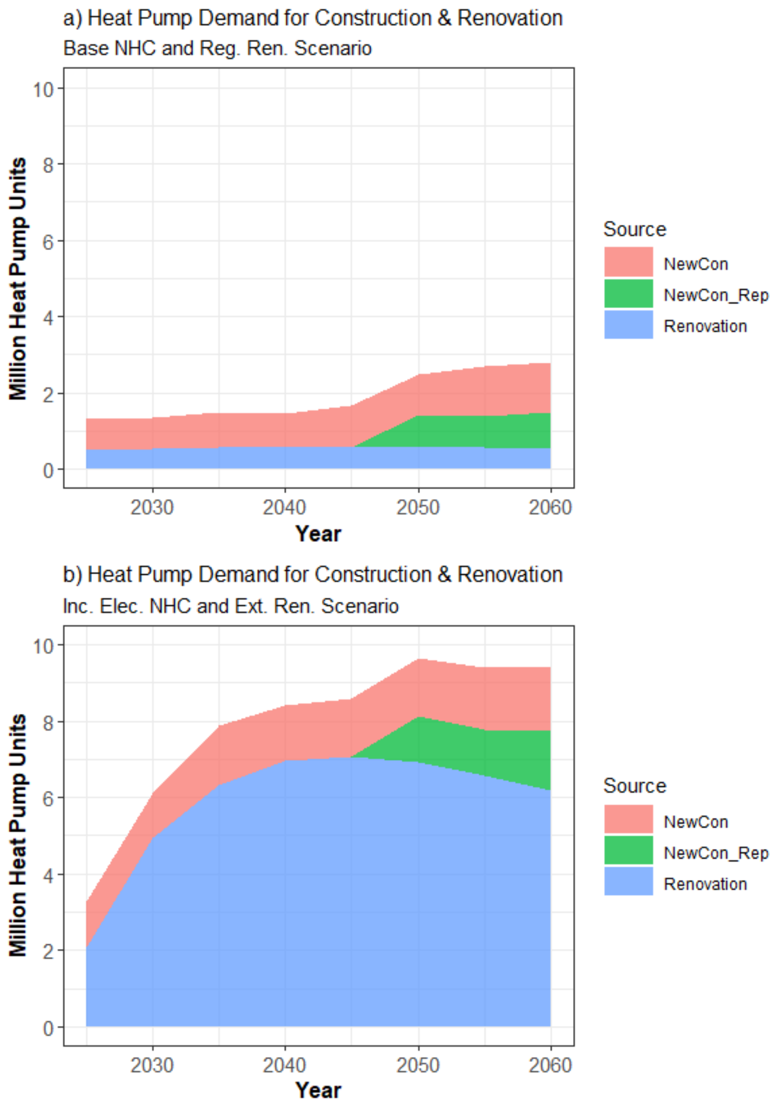
Supplementary Figure 9 Renovation scenario-based evolution of heating equipment efficiency in pre-2020 housing units with oil heating under Baseline Stock evolution

Supplementary Figure 10 shows the main heating fuel in total occupied housing for two of the housing stock scenarios (1A, 1C), each with Regular, Advanced, and Extensive renovation. In scenario 1A with Extensive Renovation (Supp. Fig. 10c), 83% use electricity as the main heating fuel by 2060, up from 40% in 2020. Adding increased electrification of new homes (Supp. Fig. 10f) brings that to 93%.

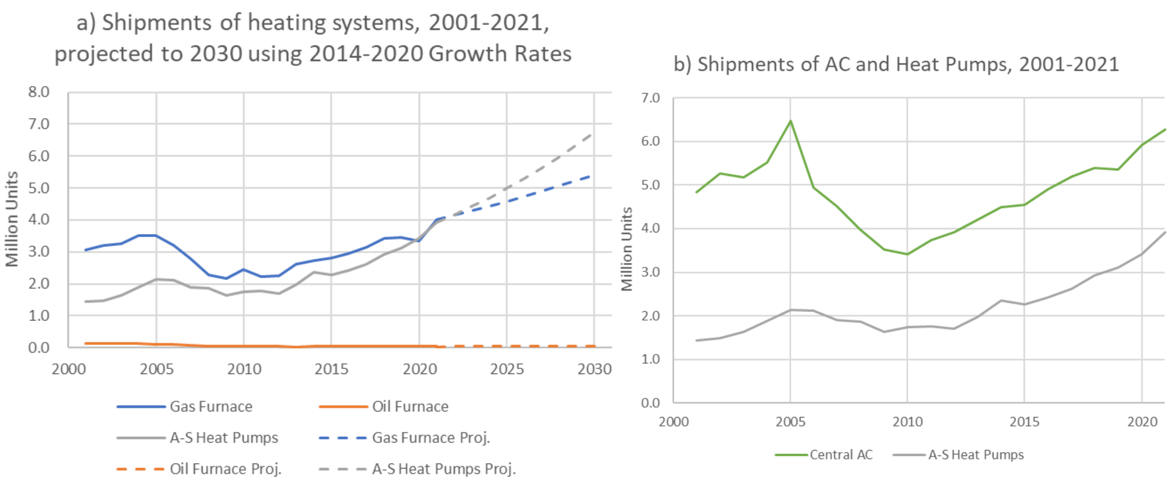


Supplementary Figure 10 Housing stock by main heating fuel 2020-2060, for two characteristics and three renovation scenarios

Supplementary Figure 11 shows growth in shipments of heat pumps for renovations and in new construction from 2025-2060, for two scenarios representing low growth (Base new housing characteristics, Regular Renovation) and high growth (Increased Electrification of new housing, Extensive Renovation) in heat pump demand. The main determinant of growth of heat pump demand is the extent of deployment in renovations. In the high demand case, demand grows to 9 million units in total by 2050, with 7 million units per year for renovations from 2040, and over 2 million units per year in new construction and replacement units in new construction (i.e. in homes built after 2020) by 2050. Replacement units in new construction are estimated using a simple assumption of a 25-year life span for heat pumps installed in new homes, and assuming no demolition of new housing units between 2020-2060. To test the feasibility of this strong growth in demand for heat pumps, in Figure 12a we plot growth of heating equipment shipments from 2001-2021, extended to 2030 using 2014-2020 growth rates. It appears that air-source heat pumps supply can approach 7 million shipments annually by 2030, if current growth rates are sustained. It is important to note that the data on past heat pump shipments are not only for residential buildings. Commercial buildings also make up some of the demand for heat pumps. Although data outlining the share of shipments going to residential and commercial buildings is not available, we assume that the majority go to residential buildings, as residential floorspace is about 70% of total US building floorspace[5]. Supplementary Figure 12b shows recent shipments of air-source heat pumps and central AC systems. As the manufacturing requirements are similar for AC and heat pump units, scaling up capacity in increase pump supply further (optionally by converting AC units to heat pumps) appears feasible.



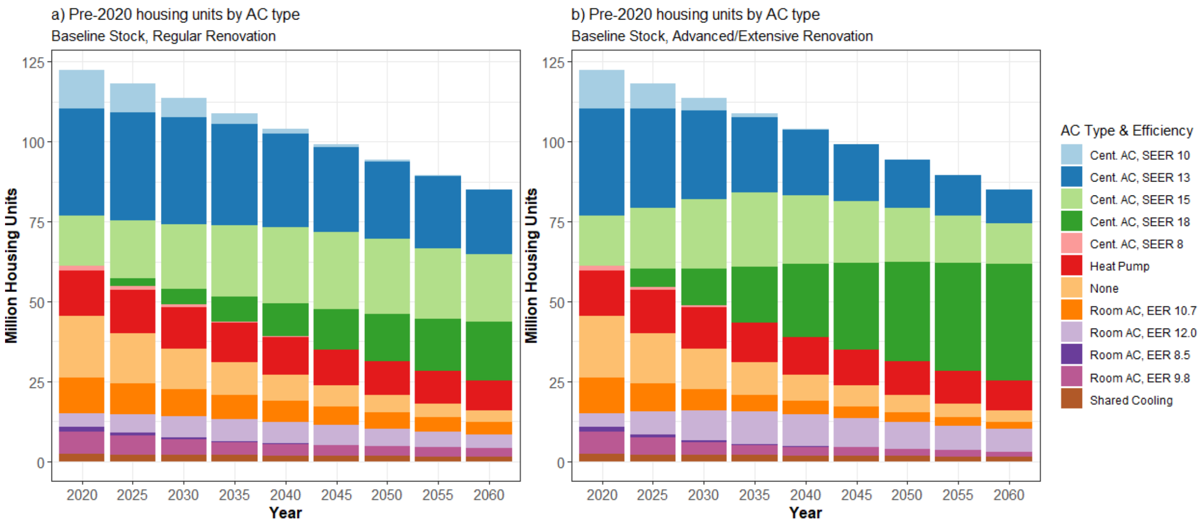
Supplementary Figure 11 Annual shipments of heat pumps 2025-2060 for use in residential new construction (NewCon), replacement units in new construction (NewCon_Rep), and renovation of existing homes, in two new housing characteristics and renovation scenario combinations – a) Baseline new housing characteristics and Regular Renovation, b) Increased Electrification of new housing, and Extensive Renovation and Electrification of existing homes.



Supplementary Figure 12 a) Comparison of shipments of gas furnaces, air-source heat pump, and oil furnace 2001-2021, projected to 2030 based on 2014-2020 growth rates. b) Shipments of central air conditioners and heat pumps from 2001-2021. Shipments are not exclusive to residential buildings. Data from AHRI[6]

3.3 Renovation characteristics – space cooling

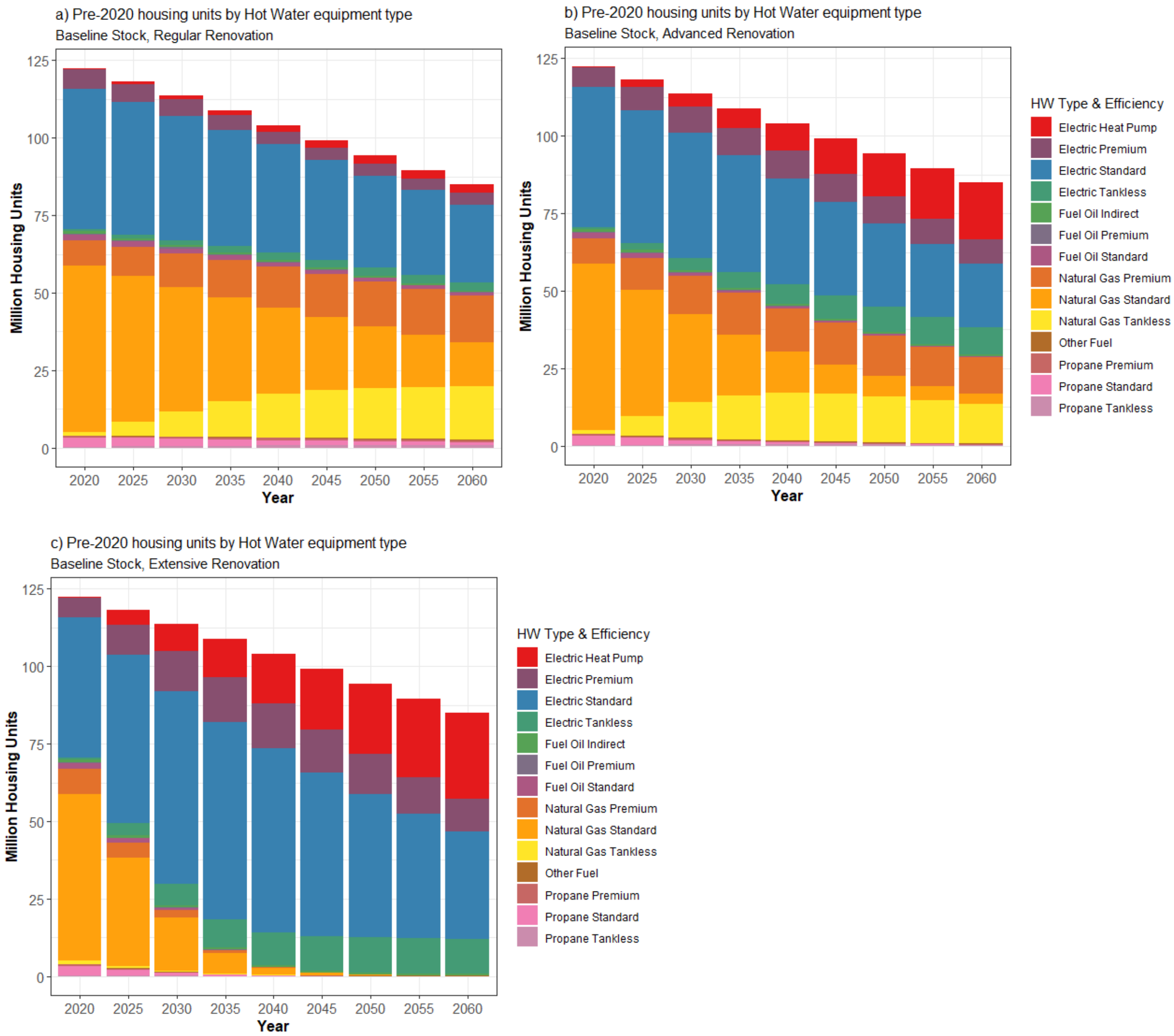
Rates for space cooling renovations shown in Supplementary Table 1 refer to replacement/addition of central AC systems in owner-occupied homes, but we use these rates to reflect renovation of room or central space cooling in all homes. Replacement rates are by far the highest in the South, and lowest in the Northeast. Similar to space heating, we calculate the average replacement rate for each housing type over the previous five surveys (2009-2019), and then multiply that rate by the ratio of the US average and each Regions average over the same period. For space cooling we represent the dynamic of increased cooling adoption in homes which currently do not have cooling equipment (c.f. reduction of housing units with 'None' AC type in Supp. Fig. 13). We also represent switching from room AC to central AC. These AC adoption and AC type switching rates are calculated separately from equipment replacement rates (which apply only to homes which currently have cooling equipment, and do not involve switching between room and central AC), and are based on data for all tenancy types and AC systems, not just central AC in owner-occupied homes. We assume that houses that have central AC remain on central AC, neglecting the small switches from central to room/none seen in historical data. Supplementary Figure 13 shows the projection of pre-2020 housing units grouped by AC technology/efficiency combinations for the baseline stock scenario and three renovation scenarios. There is no change in AC replacements between Advanced and Extensive Renovation scenarios.



Supplementary Figure 13 Renovation scenario-based evolution of AC systems in pre-2020 housing units under Baseline Stock evolution.

3.4 Renovation characteristics – water heating

Renovation rates for water heating systems vary less by region, and are more frequent than for space heating and cooling. National average replacement rates 1995-2019 are about 4.2%, implying an average product lifetime of about 23.7 years. Similar to space heating, fuel switching also sometimes occurs when water heating equipment is replaced, albeit at lower rates. Supplementary Figure 14 shows the projection of pre-2020 housing units grouped by water heating fuel and technology/efficiency combinations for baseline stock evolution and three renovation scenarios. We see a substantial increase in electric water heaters in Extensive Renovation scenarios.

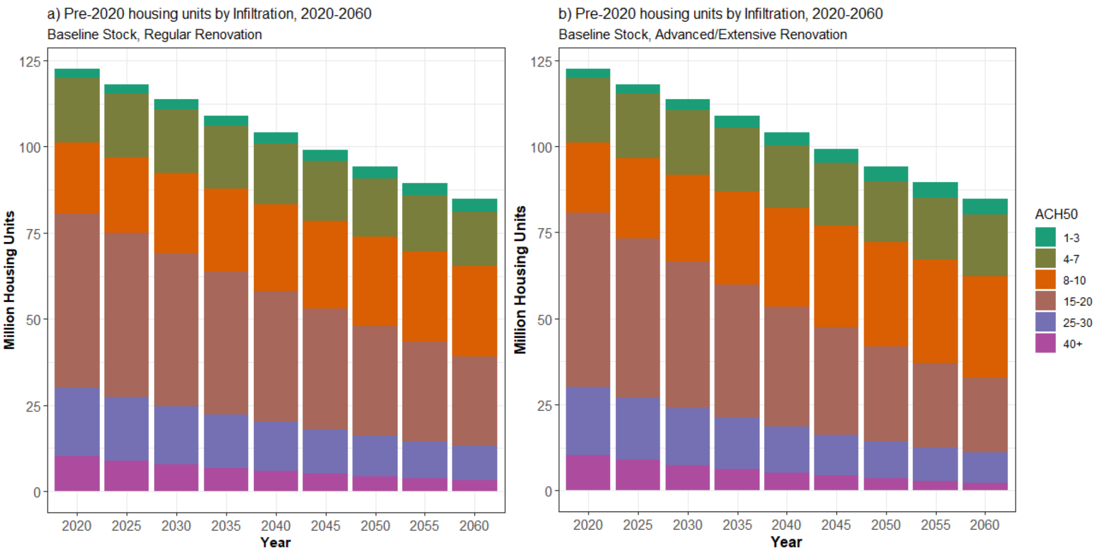


Supplementary Figure 14 Renovation scenario-based evolution of water heating systems in pre-2020 housing units under Baseline Stock evolution.

3.5 Renovation characteristics – insulation and infiltration

Insulation tends to be added/replaced at lower rates than heating and cooling equipment, as shown in Supplementary Table 1. Renovation rates are particularly low in MF housing, suggesting that replacing or adding insulation may be more difficult in MF buildings. In single family homes, the likelihood of replacing insulation is about 2% in a given year. Due to climatic differences, insulation upgrades are more common in NE and MW. Supplementary Figure 15 shows the projection of pre-2020 housing units grouped by wall and insulation systems for baseline stock and three renovation scenarios. Insulation levels usually increase by one or two levels and are more likely to increase to higher levels in AR and ER than RR. Supplementary Figure 16 shows the projection of pre-2020 units grouped by levels of infiltration, measured as air changes per hour at a pressure gradient of 50 Pa (ACH50). Envelope retrofits are assumed to reduce home infiltration to one level lower in the list of infiltration levels modelled in ResStock (1, 2, 3, 4, 5, 6, 7, 8, 10, 15, 20, 25, 30, 40 and 50 ACH50). This is consistent with existing literature on infiltration reductions in the range of 15-25% from envelope retrofits[7–9]. The extent of infiltration reductions does not vary by renovation scenario, but the likelihood of envelope renovations is 1.5 times higher in AR and ER.

Supplementary Figure 15 Renovation scenario-based evolution of wall insulation in pre-2020 housing units under Baseline Stock evolution. Insulation levels are approximately the same in Advanced and Extensive Renovation (AR, ER) scenarios



Supplementary Figure 16 Renovation scenario-based evolution of infiltration in pre-2020 housing units under Baseline stock evolution. Infiltration levels are approximately the same in Advanced and Extensive Renovation (AR, ER) scenarios

3.6 Environmental and economic assessment of individual renovation strategies

Supplementary Table 3 shows median cumulative GHG reductions, Net Present Value (NPV), and abatement costs for individual heating, hot water, envelope, and combined heating and envelope renovations, for renovation that occurred between 2021-2025. Cumulative GHG reductions and NPV calculations are made using projected electricity GHG intensities and fuel costs over the period 2026-2050, as documented in the Methods section of the main article under "Enviro-economic Assessment of Renovation Strategies". In New England, the median GHG reduction from heating system replacement is similar to that of envelope renovations; in all other Census Divisions, envelope renovations deliver higher emission reduction on average. Emission reductions from both heating and envelope renovations are highest in the colder divisions; New England, East North Central, Middle Atlantic, and West North Central. In these same divisions, reductions from combined envelope and heating system renovations are particularly high. Median abatement costs for heating and envelope renovations are generally negative (i.e., a net economic benefit), except for in the Pacific division, where they are positive. Renovations of hot water are highest in New England, Pacific, West North Central, and Middle Atlantic. NPV of hot water renovations are often negative, and outside of the Southern divisions (East South Central, West South Central, South Atlantic) median abatement costs are moderately high. Greater detail on environmental and economic performance of specific renovation types is given in the following subsections. All NPV and abatement cost estimates are subject to considerable uncertainty arising from differences in renovation costs by individual house[10], and uncertainty regarding future energy prices.

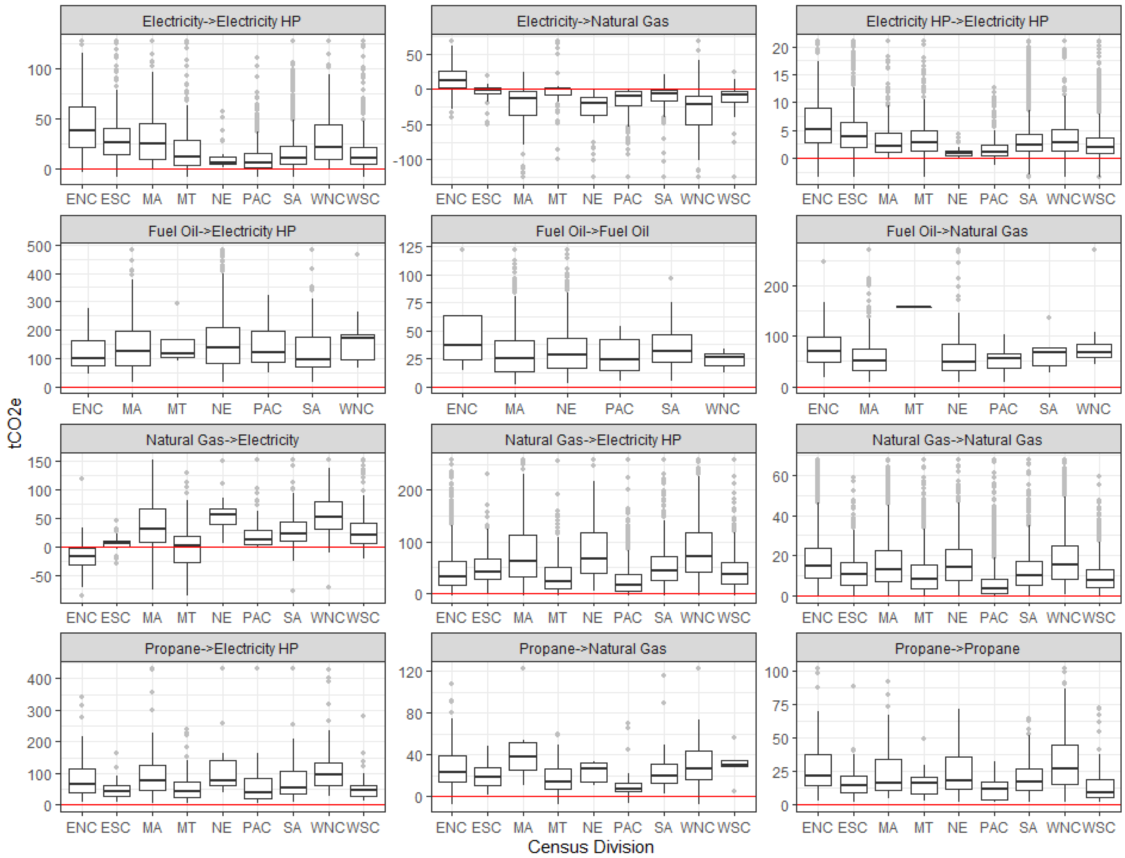
Supplementary Table 3 Median household cumulative 25 year (2026-2050) GHG reduction, NPV, and GHG abatement cost for four families of renovation strategies, by Census Division. DHW = Domestic Hot Water. Calculations use electricity CO_2 intensities from the LREC scenario. ESC = East South Central, ENC = East North Central, MA = Middle Atlantic, MT = Mountain, NE = New England, PAC = Pacific, SA = South Atlantic, WNC = West North Central, WSC = West South Central

Division	**Type**	**GHG Red. (tCO2)**	**NPV (2021$)**	**Abate. Cost ($/t)**	**Type**	**GHG Red. (tCO2)**	**NPV (2021$)**	**Abate. Cost ($/t)**
ENC	*Heat*	16.8	1,322	-96	*Envelope*	29.7	1,723	-57
ESC	*Heat*	7.8	1,371	-175	*Envelope*	15.8	1,257	-77
MA	*Heat*	18.9	1,727	-111	*Envelope*	25.8	2,701	-95
MT	*Heat*	7	598	-101	*Envelope*	12.8	178	-16
NE	*Heat*	30.1	2,682	-160	*Envelope*	30.6	5,571	-163
PAC	*Heat*	3.8	292	-88	*Envelope*	5.9	-236	10
SA	*Heat*	4.6	1,195	-227	*Envelope*	7.8	839	-100
WNC	*Heat*	18	1,704	-113	*Envelope*	23.3	1,883	-75
WSC	*Heat*	5.5	986	-149	*Envelope*	9.4	476	-52
ENC	*DHW*	3.4	-1,133	109	*Heat+Env*	50.8	2,292	-50
ESC	*DHW*	3.9	29	-50	*Heat+Env*	22.9	1,345	-64
MA	*DHW*	7.4	-1,084	179	*Heat+Env*	59.2	4,679	-86
MT	*DHW*	4.4	-974	86	*Heat+Env*	28.3	804	-31
NE	*DHW*	9.6	-1,092	151	*Heat+Env*	71.1	7,733	-135
PAC	*DHW*	7.7	-1,236	203	*Heat+Env*	11.3	-662	27
SA	*DHW*	3.5	118	-109	*Heat+Env*	14.4	1,946	-113
WNC	*DHW*	7	-741	101	*Heat+Env*	48.4	3,257	-72
WSC	*DHW*	4.5	46	-42	*Heat+Env*	16	1,099	-59

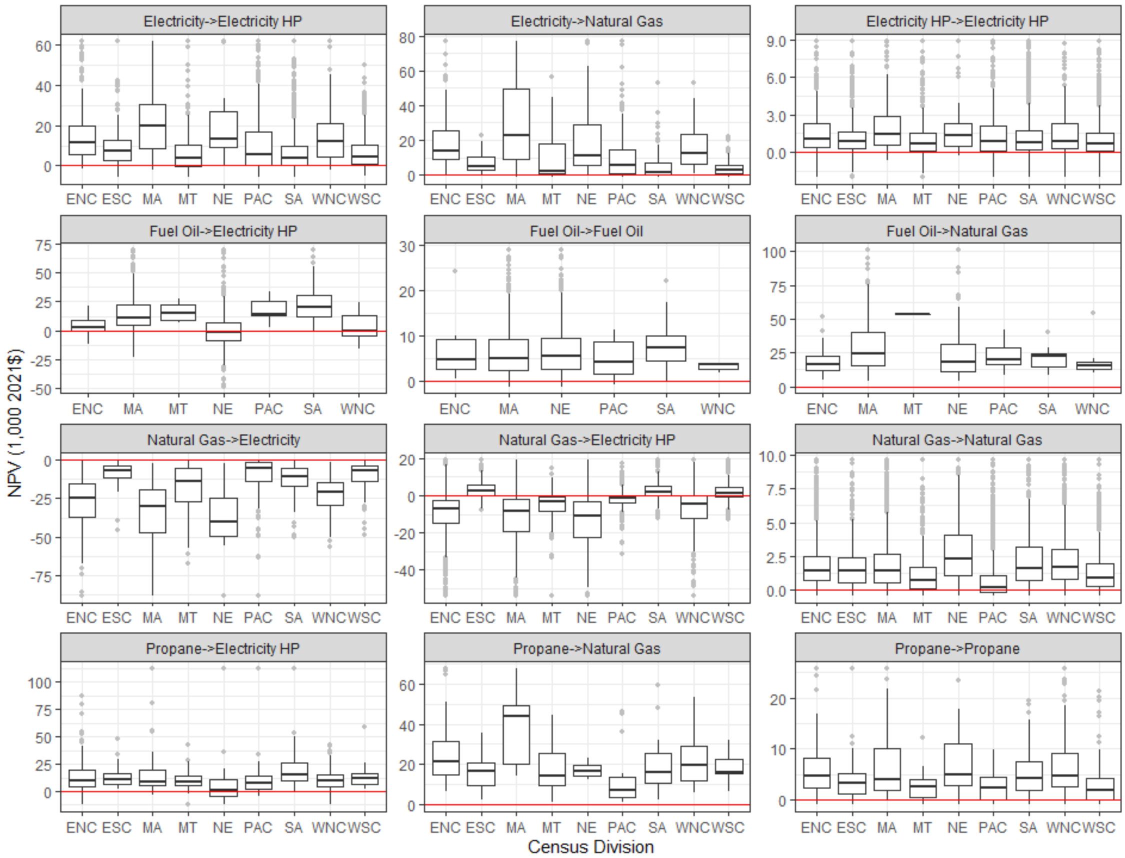
3.6.1 Space heating renovations

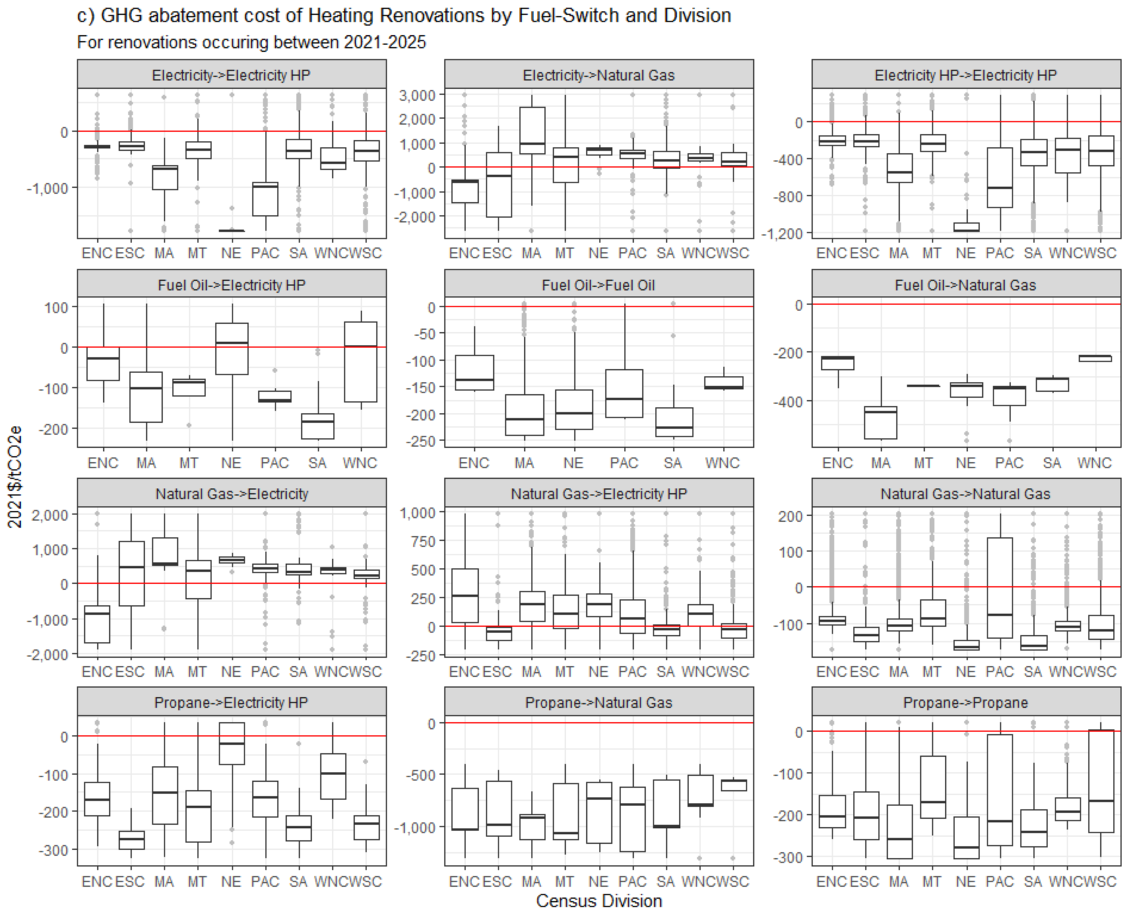
Considerable GHG reductions are available from replacing fuel oil heating systems with electric heat pumps, where median cumulative reductions range from 100-200 tCO_{2e} while some instances offer much higher reductions (Supp. Fig. 17). Propane and natural gas to heat pump replacements also offer very high GHG reductions. The emission reductions from switching from fossil-fuel heaters to electric heat pumps are highest in the cold divisions New England, West North Central, and Middle Atlantic. Emission reductions from fossil to heat pump switches are lower in East North Central than the other cold climate divisions due to higher GHG intensity of electricity there. For fuel oil/propane, these heat pump replacements almost always come with positive NPV and negative abatement costs. For natural gas to heat pump replacements however, abatement costs are often high (>100 $/t) outside of the southern divisions (West South Central, East South Central, South Atlantic) where heating requirements and electricity prices tend to be lower. Replacing electric resistance with electric heat pump heating systems is very likely to give large GHG reductions (especially in divisions such as East North Central with high GHG intensity of electricity) and substantial cost savings. In East North Central (and to a limited extend Mountain division), GHG and cost savings could hypothetically be gained from switching from electricity resistance to natural gas, due to the higher GHG intensity of electricity there. In practice this would be limited by lack of access to gas networks in regions where electric resistance heating is common. However, switching from electricity resistance to heat pump offers much higher GHG reductions, in addition to cost savings. In all regions, switching from fuel oil/propane to natural gas, and replacing fossil-based heaters with more efficient replacements without switching fuel, offer notable GHG savings, but the GHG reductions are always much greater when switching to electric heat pumps.

a) Cumulative 25-year household GHG emission reductions of Heating Renovations by Fuel-Switch and Division
For renovations occuring between 2021-2025



b) NPV of Heating Renovations by Fuel-Switch and Division
For renovations occuring between 2021-2025

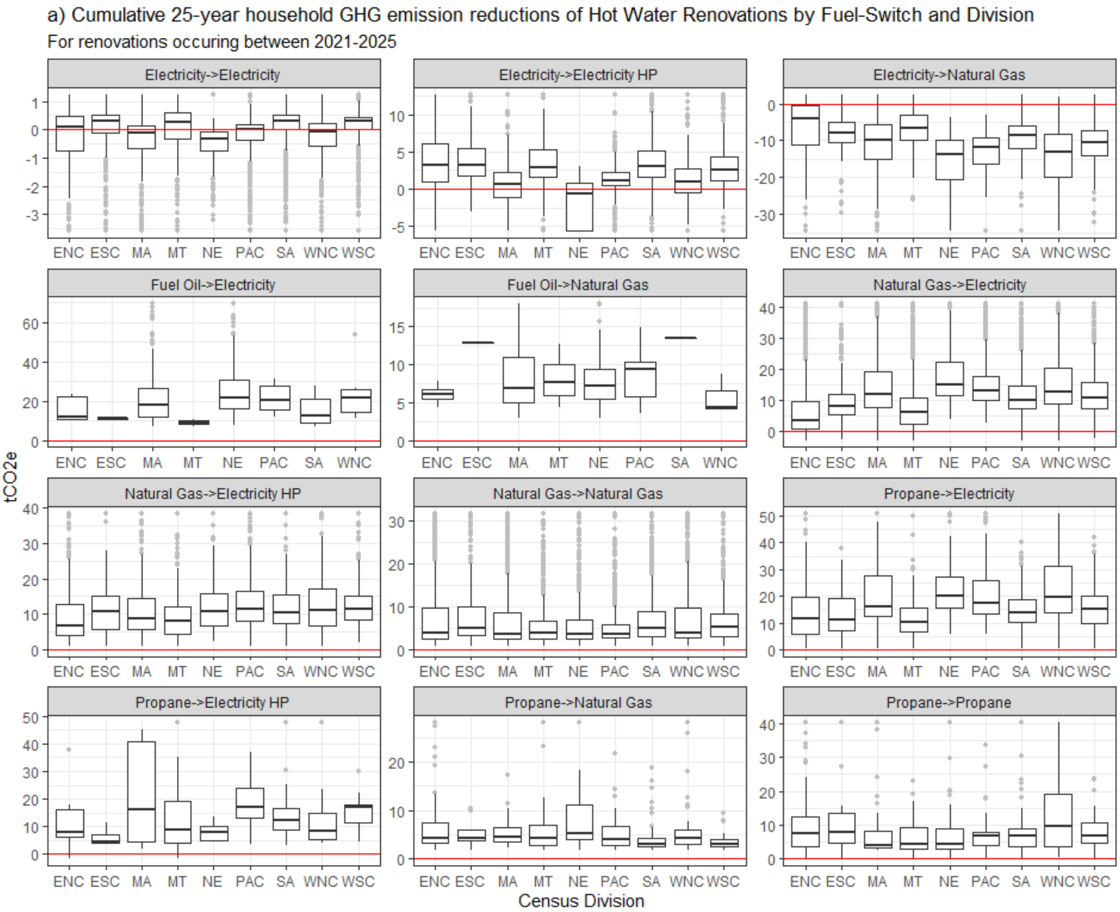


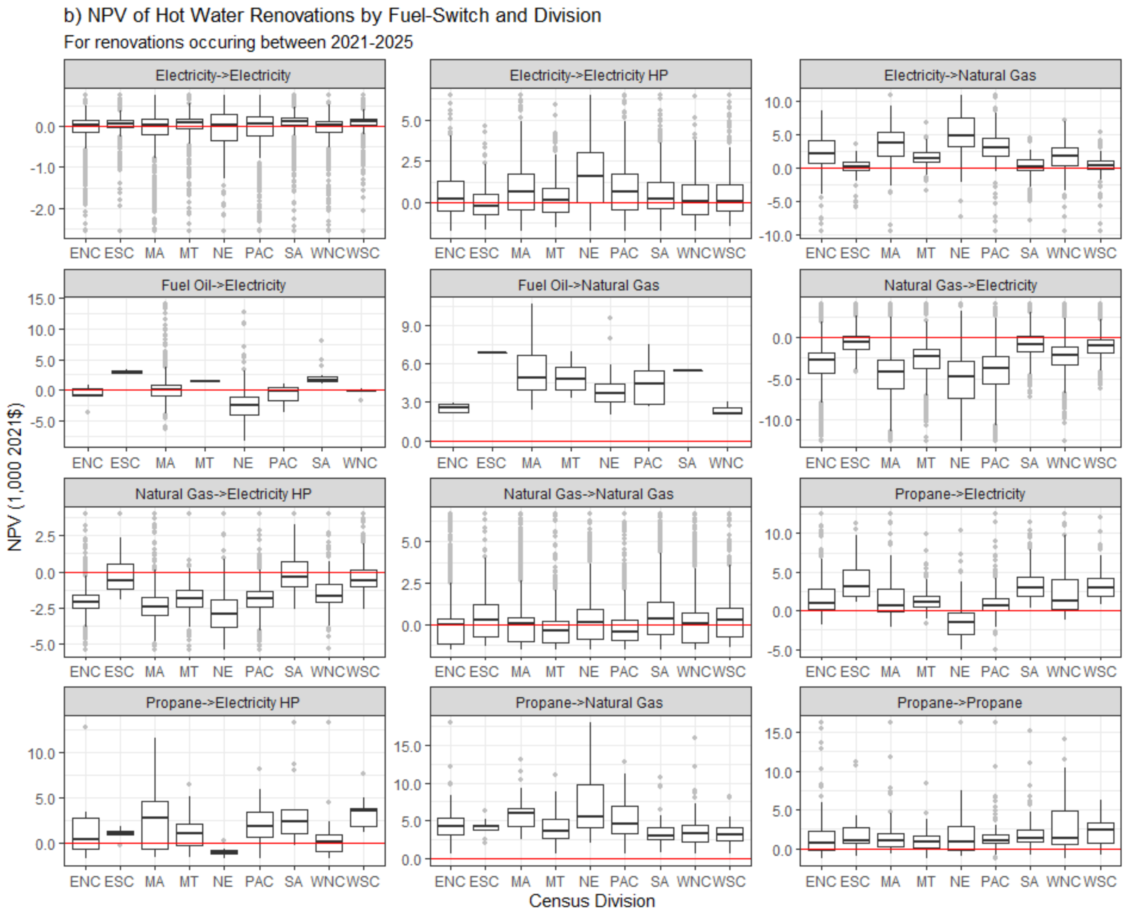


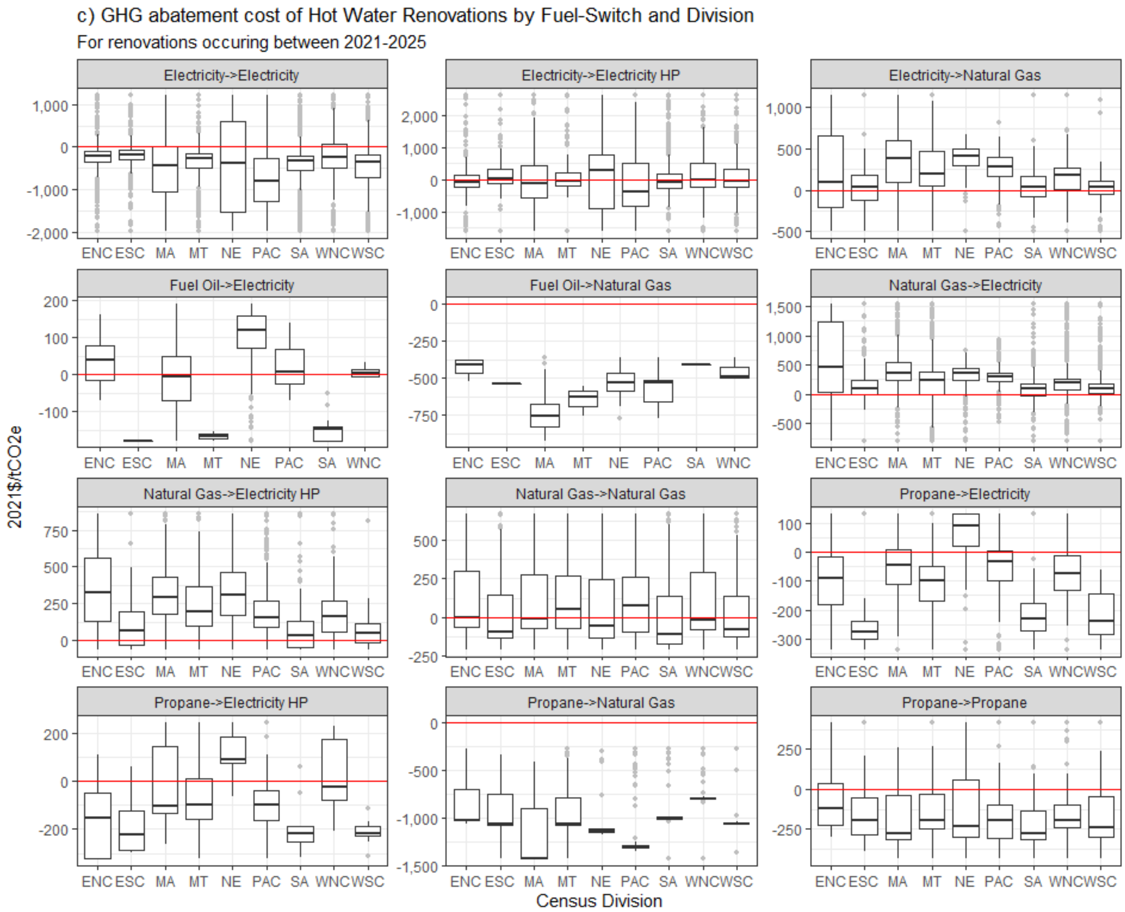
Supplementary Figure 17 Boxplots showing distribution of a) Cumulative household GHG emission reduction potential, b) NPV, and c) implied GHG abatement costs for household heating system renovations/replacements occurring between 2021-2025, by Census Division and main pre-post heating fuel combinations. Cumulative emission reductions and NPV are calculated over a 25 year horizon (2026-2050), and incorporate projected changes in GHG intensity of electricity following the LREC scenario, and fuel costs. For ease of presentation, outliers outside of the 1^{st} and 99^{th} percentiles for GHG reduction and NPV, and 5^{th} and 95^{th} percentiles for abatement costs, are omitted from the figures. ESC = East South Central, ENC = East North Central, MA = Middle Atlantic, MT = Mountain, NE = New England, PAC = Pacific, SA = South Atlantic, WNC = West North Central, WSC = West South Central

3.6.2 Hot water renovations

Greatest GHG reductions come from fuel oil/propane to electric (resistance and HP) water heaters, and natural gas to electric HP water heaters (Supp. Fig. 18). In some cases converting from fossil to HP water heating leads to an increase in GHG emissions, because HP water heaters have less heat losses and so this switch can cause an increase in space heating requirements, leading to higher emissions. This can be avoided if switching both space and water heating equipment to HP. Large reductions are also available from replacing gas and propane water heaters with most efficient alternatives without fuel change. The economic case for fuel oil/propane to electric water heaters is usually good. However, natural gas to electric (HP) replacements usually have a negative NPV. Implied GHG abatement costs from such replacements are high; for gas to heat pump it can range from 100-500 $/ton in the colder divisions, and abatement costs are even higher for gas to electric resistance water heaters. In East South Central, South Atlantic, and West South Central divisions, substantial GHG savings can be made usually with low (below 100 $/ton) or sometimes negative abatement costs. Whereas fuel oil water heating is mainly constrained to New England and Middle Atlantic, propane water heating is present across the country. Here, large GHG reductions can be achieved be switching to electric (HP) water heating, usually at negative or low abatement cost. The long tail of negative emission reductions from electric->electric water heating replacements come from replacing electric tank with electric tankless water heaters, suggesting that this is usually not an effective renovation for reducing emissions.



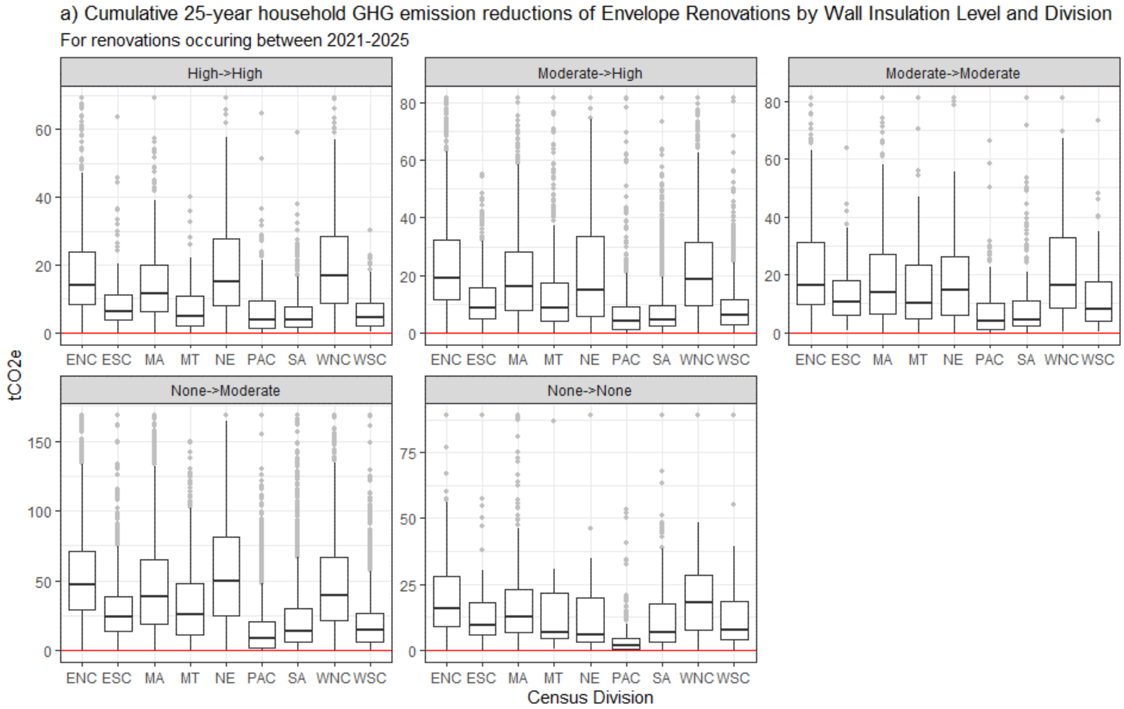

b) NPV of Hot Water Renovations by Fuel-Switch and Division
For renovations occuring between 2021-2025
Electricity->Electricity
Electricity->Electricity HP
Electricity->Natural Gas
Fuel Oil->Electricity
Fuel Oil->Natural Gas
Natural Gas->Electricity
Natural Gas->Electricity HP
Natural Gas->Natural Gas
Propane->Electricity
Propane->Electricity HP
Propane->Natural Gas
Propane->Propane
ENC ESC MA MT NE PAC SA WNC WSC
NPV (1,000 2021$)
Census Division

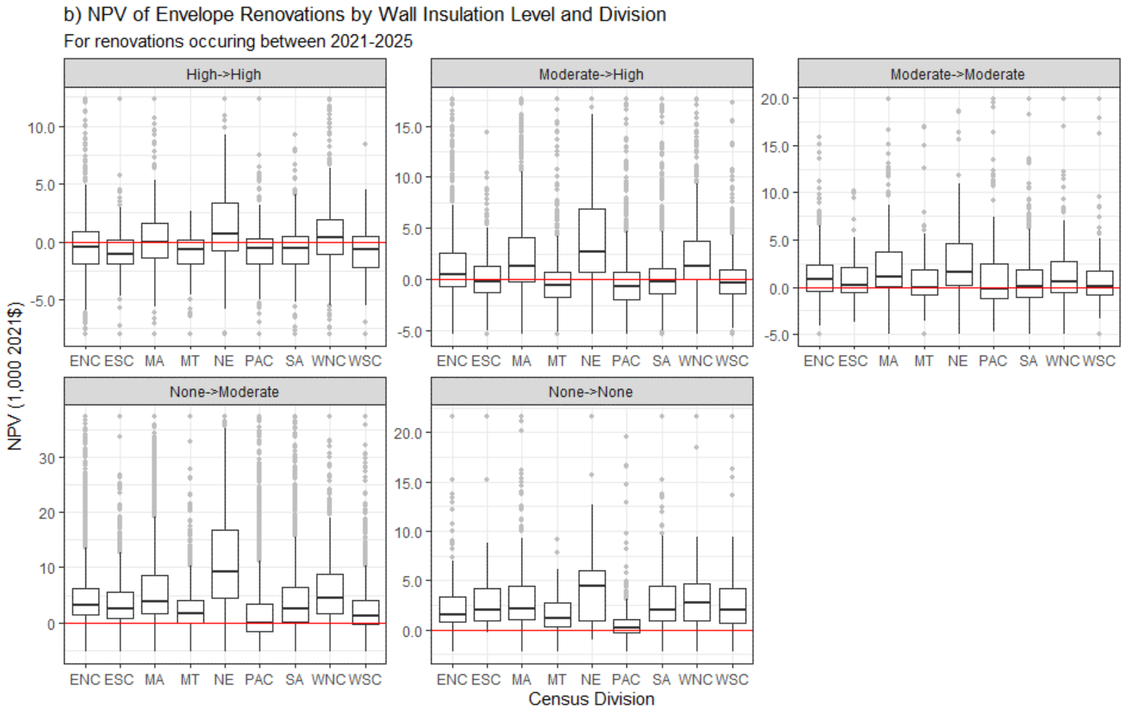


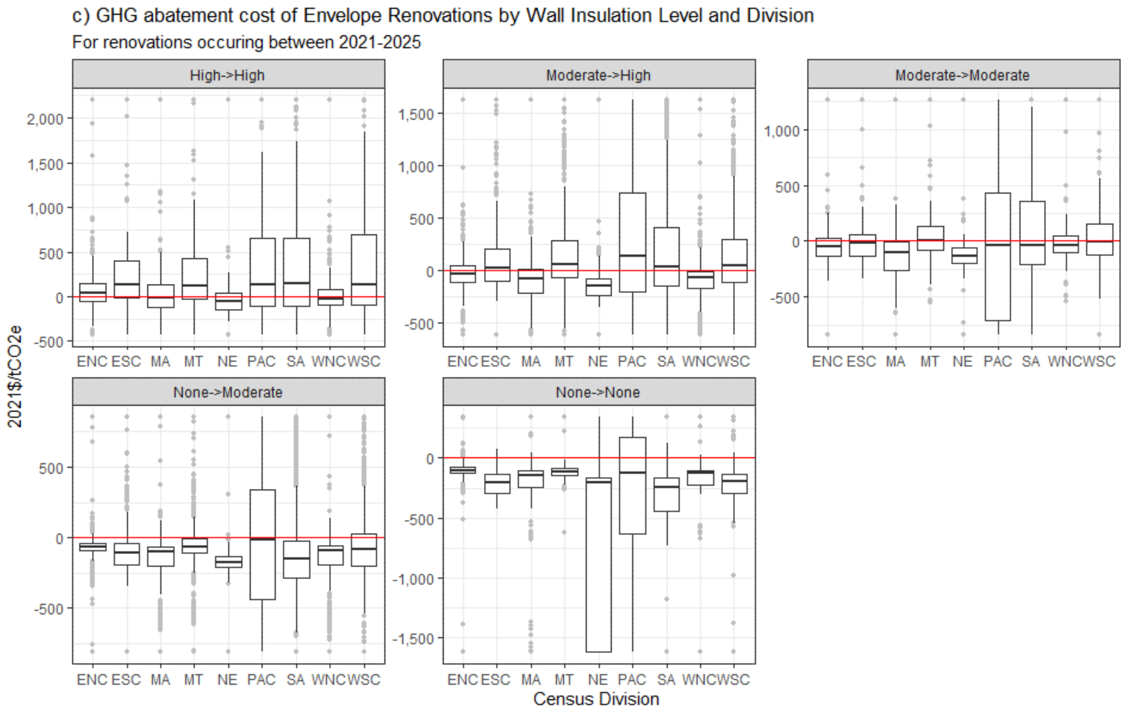
Supplementary Figure 18 Boxplots showing distribution of a) Cumulative household GHG emission reduction potential, b) NPV, and c) implied GHG abatement costs for household water heating system renovations/replacements occurring between 2021-2025, by Census Division and main pre-post fuel combinations. Cumulative emission reductions and NPV are calculated over a 25 year horizon (2026-2050), and incorporate projected changes in GHG intensity of electricity, and fuel costs. For ease of presentation, outliers outside of the 2^{nd} and 98^{th} percentiles for GHG reductions, 1^{st} and 99^{th} percentiles for NPV, and 5^{th} and 95^{th} percentiles for abatement costs, are omitted from the figures.

3.6.3 Envelope renovations

Reliable and substantial reductions in GHG emissions are available from all envelope renovations, in all regions (Supp. Fig. 19). For simplicity of presentation, envelope renovations are grouped by levels of wall insulation pre- and post-renovation; but envelope renovations also address crawlspaces, unfinished basements, external walls, and unfinished attics, and lead to reductions in infiltration. 'None->None' renovations occur in homes with brick walls which received no wall insulation, but increased insulation on other building assemblies, as well as achieving infiltration reduction. 'Moderate->Moderate' and describe renovations whose wall insulation was between R7 and R11, while 'High->High' describe wall insulation levels of R15 or higher, both pre- and post-renovation. The greatest reductions are seen for households going from 'None->Moderate' wall insulation. By division, the greatest reductions are seen in the colder divisions of New England, West North Central, East North Central, and Middle Atlantic. There is very wide variation in NPV of envelope renovations, as seen by the large inter-quartile ranges and whiskers in some divisions. Abatement costs are mostly negative for None->None and None->Moderate envelope renovations. In homes with moderate or high pre-renovation wall insulation levels, abatement costs range from very negative to very high, but median costs are usually negative (i.e. positive NPV) except in East South Central, Mountain, Pacific, and West South Central divisions. These divisions tend to have less heating demand and benefit less from going from moderate to high levels of insulation. In the colder divisions, large GHG reductions are available from going to high levels of insulation, and abatement costs for such renovations are often negative, especially in New England.





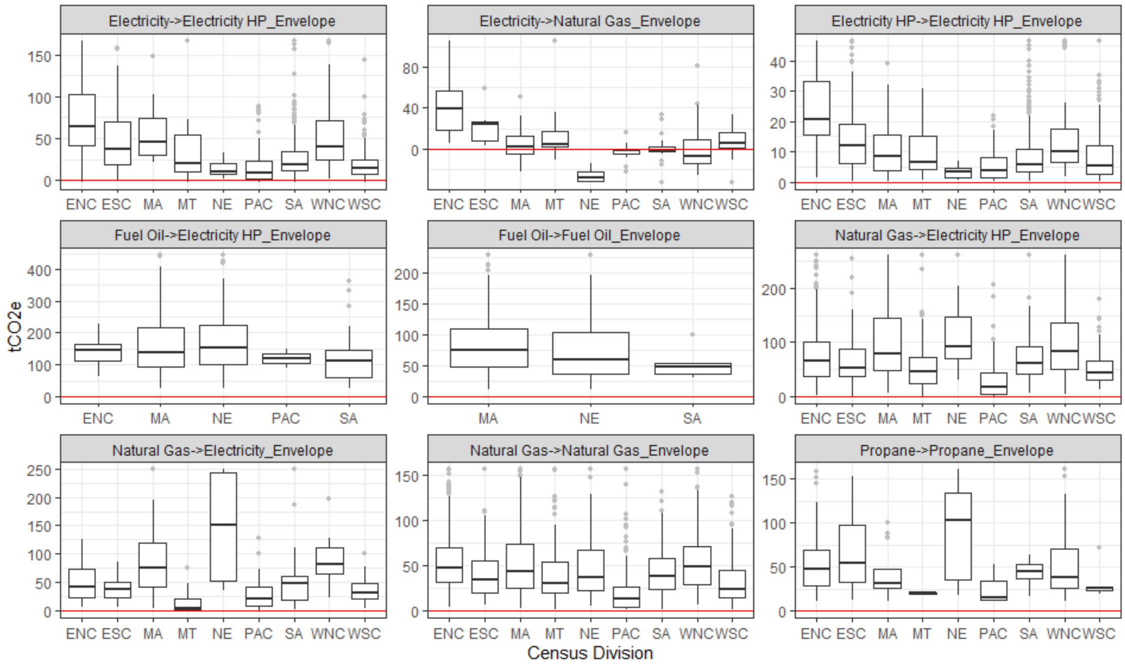


Supplementary Figure 19 Boxplots showing distribution of a) Cumulative household GHG emission reduction potential, b) NPV, and c) implied GHG abatement costs for household envelope renovations occurring between 2021-2025, by Census Division and pre-post wall insulation levels. 'None->None' renovations describe homes with brick walls which received no additional wall insulation, but increased insulation on other building assemblies, as well as infiltration reduction. Cumulative emission reductions and NPV are calculated over a 25 year horizon (2026-2050), and incorporate projected changes in GHG intensity of electricity, and fuel costs. For ease of presentation, outliers outside of the 1st and 99th percentiles for GHG reductions and NPV, and 5th and 95th percentiles for abatement costs, are omitted from the figures.

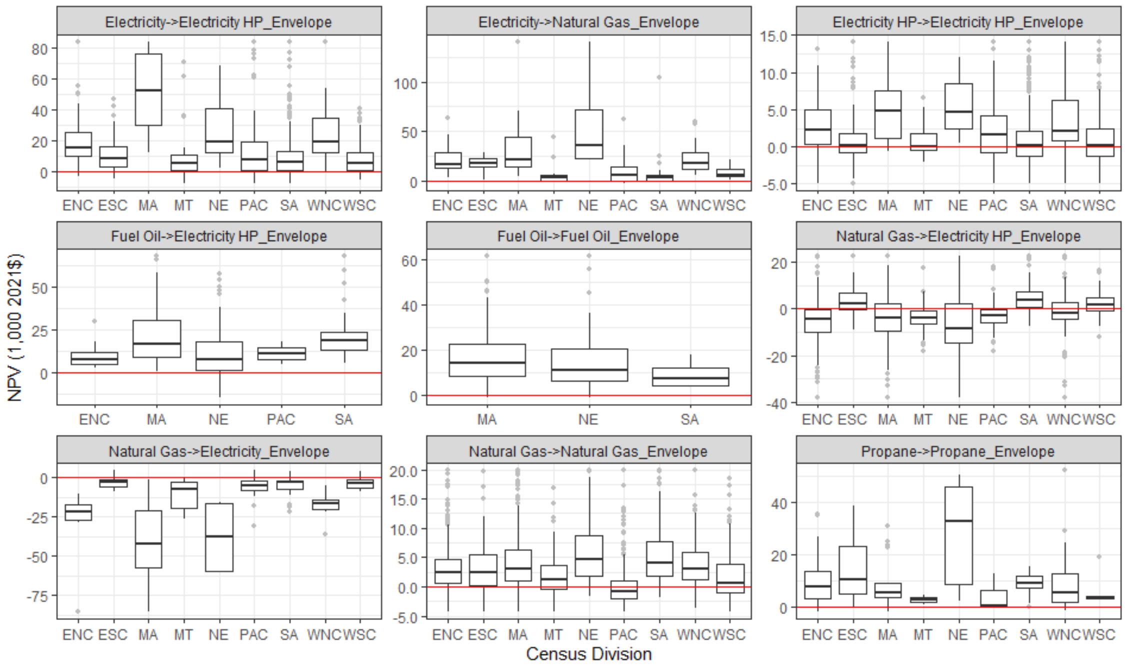
3.6.4 Combined heating and envelope renovations

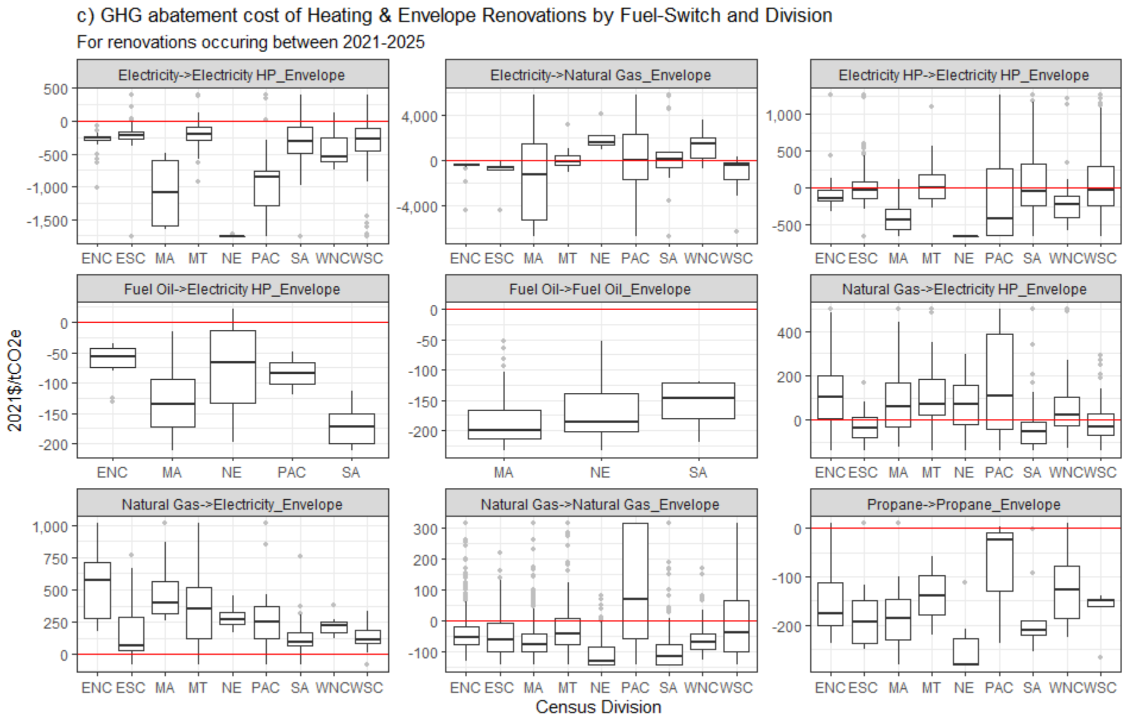
The greatest GHG reductions from combined heating system and envelope renovations again occur for fuel oil to heat pump plus envelope renovations (Supp. Fig 20). Here median 25-year GHG reductions range from 112-152 tCO_{2e} depending on the division, with many renovations offering considerably higher reductions, especially in New England and Middle Atlantic. With very few exceptions, these renovations also have positive NPV and negative abatement costs. Natural gas to electric (resistance and heat pump) plus envelope renovations offer the next largest GHG reductions (the very large natural gas to electricity GHG reductions in New England are from a very small sub-sample with four data points). These renovations generally have negative NPV, although the economics are much preferable when switching to electric heat pump than electric resistance. For gas to heat pump plus envelope renovations, the median abatement costs are quite low, ranging from -52 $/ton to +108 $/ton depending on the division (only in East North Central and Pacific is it greater than $100/ton), while outside of the Pacific Division, 75% percentile abatement costs range from negative (South Atlantic) to 200 $/ton (East North Central). In Middle Atlantic, New England, and West North Central, where the greatest emission reductions arise from natural gas to heat pump plus envelope renovations, median/75th percentile abatement costs are 61/165, 69/154, and 25/105 $/ton respectively.

a) Cumulative 25-year household GHG emission reductions of Heating & Envelope Renovations by Fuel-Switch and Division
For renovations occuring between 2021-2025



b) NPV of Heating & Envelope Renovations by Fuel-Switch and Division
For renovations occuring between 2021-2025

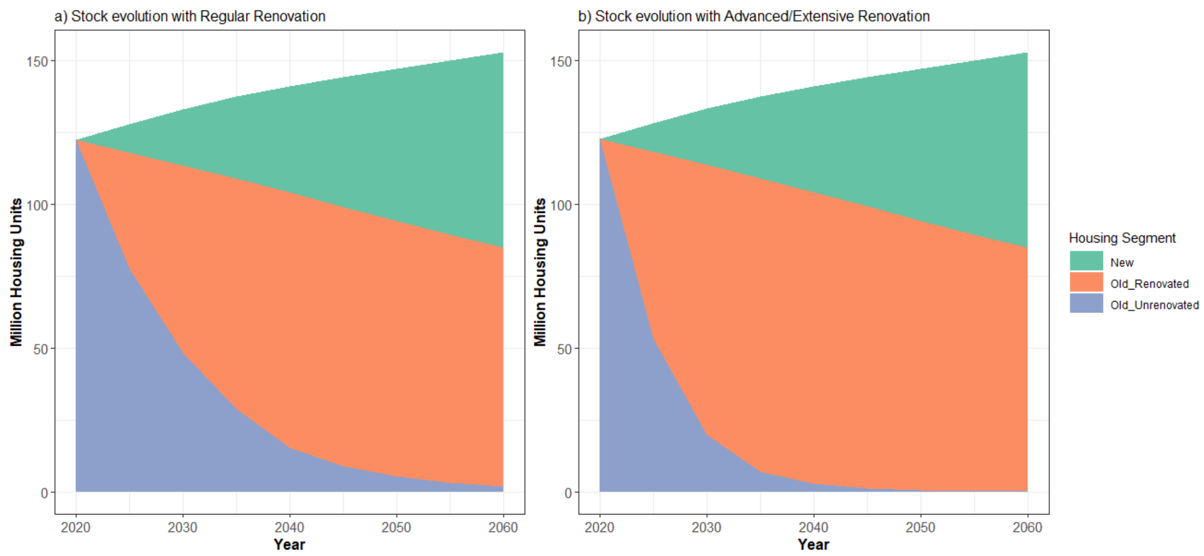




Supplementary Figure 20 Boxplots showing distribution of a) Cumulative household GHG emission reduction potential, b) NPV, and c) implied GHG abatement costs for household heating system plus envelope renovations/replacements occurring between 2021-2025, by Census Division and main pre-post heating fuel combinations. Cumulative emission reductions and NPV are calculated over a 25 year horizon (2026-2050), and incorporate projected changes in GHG intensity of electricity, and fuel costs. For ease of presentation, outliers outside of the 2nd and 98th percentiles for GHG reductions, 1st and 99th percentiles for NPV, and 5th and 95th percentiles for abatement costs, are omitted from the figures.

3.7 Energy efficiency improvements in renovation scenarios

In Supplementary Figure 21 we show the evolution of the housing stock from 2020-2060 in three categories: new (post-2020), renovated (pre-2020), and un-renovated (pre-2020) housing. The definition of 'renovation' in this context relates to housing units which replace any of their heating/cooling/insulation systems as described above. In some cases houses will replace multiple systems either in the same year or over the course of a small number of years, and these will add up to create a deeper overall renovation. By 2050, with regular Renovation, 94% of pre-2020 housing units have undergone at least one type of renovation; with Advanced and Extensive Renovation, 99% of pre-2020 housing units have undergone at least one renovation. Supplementary Table 4 shows average final energy intensity of these housing stock segments every 5 years from 2020 to 2060, while Supplementary Table 5 compares regular/advanced/extensive renovated and unrenovated final energy intensities for house types and cohorts in 2020 and in 2060. Supplementary Tables 6 and 7 show the average reduction in final (site) energy per household resulting from a given heating, cooling, water heating, and insulation/infiltration replacement or renovation. In Supplementary Table 6, negative values are observed for some cooling renovations, most notably among older homes in the West. This is because in addition to efficiency upgrades, cooling renovations include switching from no AC to AC, and from window AC to central AC, both of which would increase energy consumption for cooling.



Supplementary Figure 21 Evolution of housing stock disaggregated by old (renovated and un-renovated) and new housing

Supplementary Table 4 Average energy intensity (MJ/m^2) of housing stock segments, 2020-2060. Old = built before 2020; New = built from 2020 onwards; UnRen = unrenovated; Ren = Renovated

		Housing stock age, renovation status and renovation scenario					
Year	**New**	**Old, UnRen**	**Old, Ren**	**Old, UnRen**	**Old, Ren**	**Old, UnRen**	**Old, Ren**
		Reg Ren	**Reg Ren**	**Adv Ren**	**Adv Ren**	**Ext Ren**	**Ext Ren**
2020		508		508		508	
2025	251	465	539	463	489	454	466
2030	251	429	503	424	451	397	404
2035	242	396	475	403	418	365	352
2040	237	381	448	389	393	348	315
2045	230	367	428	390	373	359	293
2050	225	360	414	394	359	375	280
2055	219	359	401	416	347	407	270
2060	214	365	390	436	336	412	263

Supplementary Table 5 Average energy intensity (MJ/m^2) of housing by type and cohort, in 2020 (pre-renovation) and in 2060, for each renovation scenario. RR = regular renovation; AR = advanced renovation; ER = extensive renovation. SF = single-family, MF = multifamily, MH = manufacture home

	Vintage												
Type, Year, Ren	**<1940**	**‘40s**	**‘50s**	**‘60s**	**‘70s**	**‘80s**	**‘90s**	**2000s**	**‘10s**	**‘20s**	**‘30s**	**‘40s**	**‘50s**
SF, 2020	839	764	728	604	506	395	367	293	279				
SF, 2060 RR	582	530	516	433	399	327	311	256	259	229	201	180	163
SF, 2060 AR	474	442	430	364	340	284	275	227	228	229	201	180	163
SF, 2060 ER	318	317	315	271	263	226	221	187	189	229	201	180	163
MF, 2020	904	919	817	664	584	485	451	401	422				
MF, 2060 RR	759	780	694	585	530	462	433	386	412	341	309	290	273
MF, 2060 AR	692	706	626	517	476	414	394	356	386	341	309	290	273
MF, 2060 ER	563	591	506	431	404	356	347	315	346	341	309	290	273
MH, 2020	1,537	779	429	925	856	678	620	481	488				
MH, 2060 RR	1,118	567	344	725	718	595	554	444	485	399	359	324	299
MH, 2060 AR	991	545	335	626	627	525	496	393	431	399	359	324	299
MH, 2060 ER	483	335	357	484	480	426	415	345	391	399	359	324	299

Supplementary Table 6 Average reduction in household final energy (%) arising from replacements and renovations by house age and census region. MW = Midwest; NE = Northeast, S = South, W = West

Heating	*Regular Renovation*				*Advanced Renovation*				*Extensive Renovation*			
	MW	*NE*	*S*	*W*	*MW*	*NE*	*S*	*W*	*MW*	*NE*	*S*	*W*
<1940	8.8	8.5	8.2	6.9	14.6	13.9	14.4	10.6	21.1	22.8	21.0	19.0
1940-59	9.3	8.8	7.2	5.6	14.2	13.7	12.3	9.0	18.5	20.8	16.5	15.3
1960-79	7.5	7.0	5.6	5.2	13.1	12.1	10.3	8.7	18.4	19.6	13.2	14.5
1980-99	6.7	6.7	4.1	4.6	11.0	10.7	7.9	7.0	15.8	16.7	9.8	12.2
2000-09	6.8	7.1	4.2	4.9	10.0	10.1	7.3	6.7	13.2	15.0	8.9	11.4
2010s	5.8	6.6	4.5	5.5	9.2	9.5	7.7	7.5	15.8	18.6	11.6	14.7

Cooling	*Regular Renovation*				*Advanced Renovation*				*Extensive Renovation*			
	MW	*NE*	*S*	*W*	*MW*	*NE*	*S*	*W*	*MW*	*NE*	*S*	*W*
<1940	-0.6	-0.9	1.0	-4.3	-0.1	-0.5	0.8	-2.9	-0.2	-0.5	0.5	-2.2
1940-59	-0.2	-0.4	1.3	-3.5	0.1	-0.1	1.2	-2.1	-0.1	-0.2	0.8	-1.2
1960-79	-0.1	-0.3	1.7	-3.5	0.1	-0.1	1.4	-2.0	0.0	-0.2	1.1	-1.5
1980-99	0.1	0.1	1.9	-2.2	0.3	0.2	1.5	-1.2	0.1	-0.1	1.2	-0.8
2000-09	-0.1	0.1	0.9	-0.4	0.0	0.1	0.9	-0.3	-0.1	-0.1	0.9	0.2
2010s	0.1	0.4	1.2	0.5	0.3	0.5	1.1	0.4	0.2	0.2	1.2	0.9

Hot Water	*Regular Renovation*				*Advanced Renovation*				*Extensive Renovation*			
	MW	*NE*	*S*	*W*	*MW*	*NE*	*S*	*W*	*MW*	*NE*	*S*	*W*
<1940	3.2	3.7	3.5	4.2	4.2	4.4	4.6	6.2	5.9	6.4	6.1	9.4
1940-59	3.7	4.3	3.7	4.6	4.5	4.9	4.9	6.5	6.5	7.3	6.1	9.5
1960-79	3.1	4.0	2.3	4.1	4.6	4.7	4.6	6.5	6.7	7.5	5.8	9.4
1980-99	2.9	3.5	2.0	3.7	4.6	4.7	4.6	6.3	7.2	7.8	5.7	9.1
2000-09	2.8	3.5	2.2	3.7	4.5	5.0	4.5	5.7	6.8	8.0	5.6	8.5
2010s	1.9	4.6	2.2	3.7	4.7	5.9	4.7	5.9	7.1	9.5	6.0	8.9

Envelope	*Regular Renovation*				*Advanced Renovation*				*Extensive Renovation*			
	MW	*NE*	*S*	*W*	*MW*	*NE*	*S*	*W*	*MW*	*NE*	*S*	*W*
<1940	21.2	20.3	19.1	15.5	18.6	18.1	17.1	14.2	15.4	15.4	14.2	11.8
1940-59	22.5	21.6	19.1	16.1	18.7	18.0	16.6	14.5	15.6	15.2	13.8	11.3
1960-79	16.9	16.5	13.7	12.7	14.8	14.4	12.6	11.6	12.5	11.9	10.6	9.4
1980-99	10.8	10.1	7.8	7.2	9.4	8.7	7.1	6.4	7.9	7.1	5.9	5.1
2000-09	9.6	8.7	7.0	6.0	8.5	7.2	6.8	5.8	7.1	5.6	5.3	4.3
2010s	10.0	9.2	7.3	6.6	9.6	8.6	7.2	6.4	7.9	6.9	5.8	5.0

Supplementary Table 7 Average reduction in household final energy (%) arising from replacements and renovations by house type and age. NA's occur for Regular Renovation envelope renovations to 2010s multifamily homes because none of these homes are renovated in those scenarios, corresponding to the low envelope renovation rates for MF housing shown in Supplementary Table 1. Reductions for cooling renovations are minor and are excluded from this table

Regular Renovation – Heating	*<1940*	*1940-59*	*1960-79*	*1980-99*	*2000-09*	*2010s*
Mobile Home	8.4	3.3	6.9	5.9	3.8	5.5
Multi-Family 2 - 4 Units	7.3	7.1	4.6	4.1	3.8	4.5
Multi-Family 5+ Units	6.4	6.0	3.5	2.6	3.2	2.6
Single-Family Attached	8.4	7.0	5.3	5.2	5.9	5.7
Single-Family Detached	8.7	8.1	7.0	5.8	5.9	5.8

Advanced Renovation – Heating	*<1940*	*1940-59*	*1960-79*	*1980-99*	*2000-09*	*2010s*
Mobile Home	5.5	6.3	12.5	10.4	9.2	8.3
Multi-Family 2 - 4 Units	12.7	11.6	9.3	7.1	6.8	6.9
Multi-Family 5+ Units	10.9	10.0	8.3	6.1	5.4	5.2
Single-Family Attached	12.8	11.4	9.3	8.0	8.3	8.7
Single-Family Detached	14.4	12.8	11.7	9.4	8.4	9.4

Extensive Renovation – Heating	*<1940*	*1940-59*	*1960-79*	*1980-99*	*2000-09*	*2010s*
Mobile Home	56.5	5.5	20.8	15.6	13.7	14.6
Multi-Family 2 - 4 Units	24.6	20.9	15.7	12.2	12.2	13.0
Multi-Family 5+ Units	20.2	16.3	13.0	9.3	7.4	8.5
Single-Family Attached	19.9	16.1	12.6	11.4	10.3	14.4
Single-Family Detached	21.2	18.0	16.5	13.0	11.4	15.9

Regular Renovation – Hot Water	*<1940*	*1940-59*	*1960-79*	*1980-99*	*2000-09*	*2010s*
Mobile Home	1.6	5.5	2.1	1.3	1.1	0.3
Multi-Family 2 - 4 Units	3.6	4.0	3.3	2.5	2.1	2.7
Multi-Family 5+ Units	3.7	5.1	3.8	2.9	2.7	2.0
Single-Family Attached	5.4	6.7	4.5	4.4	4.7	4.3
Single-Family Detached	3.3	3.8	3.3	2.9	2.8	3.0

Advanced Renovation – Hot Water	*<1940*	*1940-59*	*1960-79*	*1980-99*	*2000-09*	*2010s*
Mobile Home	-1.5	1.2	3.9	3.6	3.8	3.6
Multi-Family 2 - 4 Units	4.4	5.0	5.2	5.6	5.8	6.0
Multi-Family 5+ Units	5.4	7.1	6.8	6.5	6.5	6.5
Single-Family Attached	6.1	6.6	6.0	6.0	5.9	5.7
Single-Family Detached	4.3	4.9	4.6	4.7	4.5	4.6

Extensive Renovation – Hot Water	*<1940*	*1940-59*	*1960-79*	*1980-99*	*2000-09*	*2010s*
Mobile Home	2.3	8.9	5.4	5.1	5.0	4.6
Multi-Family 2 - 4 Units	6.8	8.0	8.0	8.1	8.9	8.8
Multi-Family 5+ Units	8.3	10.1	9.6	9.7	9.1	9.8
Single-Family Attached	8.0	9.3	8.2	8.4	8.3	8.3
Single-Family Detached	6.1	6.9	6.5	6.5	6.2	6.3

Regular Renovation – Envelope	*<1940*	*1940-59*	*1960-79*	*1980-99*	*2000-09*	*2010s*
Mobile Home	19.9	15.0	12.3	7.7	7.8	8.7
Multi-Family 2 - 4 Units	18.9	17.4	11.6	6.6	5.9	NA
Multi-Family 5+ Units	12.5	12.3	9.3	5.9	5.8	NA
Single-Family Attached	19.1	18.0	13.5	9.4	8.1	8.6
Single-Family Detached	21.4	21.0	16.7	8.9	7.5	8.6

Advanced Renovation – Envelope	*<1940*	*1940-59*	*1960-79*	*1980-99*	*2000-09*	*2010s*
Mobile Home	10.9	12.7	11.8	7.7	7.2	6.9
Multi-Family 2 - 4 Units	19.7	18.7	12.2	6.0	5.4	8.9
Multi-Family 5+ Units	13.2	13.2	9.9	5.5	4.4	5.6
Single-Family Attached	16.2	15.4	12.0	8.3	7.5	7.7
Single-Family Detached	18.1	17.4	14.4	8.0	7.0	7.6

Extensive Renovation – Envelope	*<1940*	*1940-59*	*1960-79*	*1980-99*	*2000-09*	*2010s*
Mobile Home	11.2	11.4	10.4	6.7	6.1	6.8
Multi-Family 2 - 4 Units	18.0	17.2	10.4	5.2	4.0	3.8
Multi-Family 5+ Units	13.2	12.3	9.0	4.4	3.5	4.3
Single-Family Attached	13.2	12.1	9.7	6.6	5.6	6.1
Single-Family Detached	14.6	14.2	11.7	6.6	5.5	6.0

4 Characteristics of new construction

Characteristics of envelope systems and energy consuming appliances in new homes are informed by IECC building energy codes, currently planned updates to federal regulations on appliances, and assumptions of the characteristics and stringency of future codes and standards. We assume that IECC building codes apply to all types of buildings, although in reality different energy codes apply to multifamily homes of 5 stories and higher (ASHRAE 90.1) and manufactured housing (which are regulated by a federal standard). Adoption of energy codes is determined by state, and then average adoption rates are assumed by climate regions and ResStock custom regions, based on which states have plurality of the population in each climate region and ResStock region. The need for aggregating states to different regions is due to many of the code-dependent characteristics being defined in the ResStock database by ResStock custom region, which are state aggregations.

In Supplementary Tables 8-9 we show assumptions on how building energy code adoption will develop over the four future vintages, by ResStock custom region and IECC climate zone (CZ). These are based on current code adoptions by state, matching of states to custom regions and judging which code is most prevalent in each custom region, and matching of custom regions to climate zones and judging which climate zone is most prevalent in each custom region (for matching, see ResStock custom regions and IECC climate zones in in Figure 14 and Figure 12 of Wilson et al. 2017[11], and the status of residential energy code adoption by State as of September 2020[12]). These tables are used to define future housing characteristics that are influenced by building codes, such as infiltration, insulation, and windows. Non-code related housing characteristics, in particular the choice of heating distribution system, equipment, and fuel are determined considering recent trends by Census Region as outlined in the Characteristics of New Housing publications[13], and projected differences in gas and electricity prices by Census Region[14].

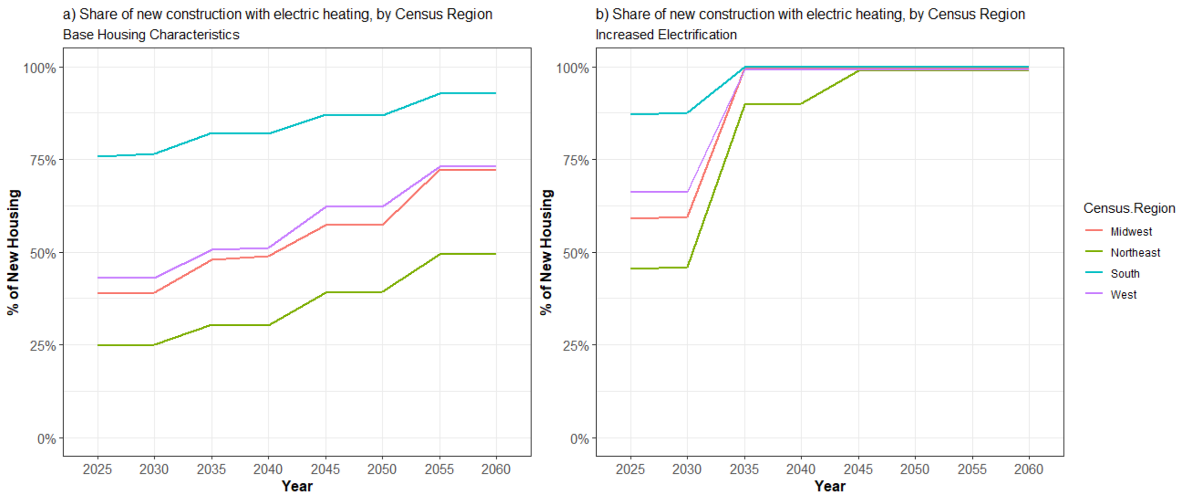
Supplementary Table 8 Assumption of representative climate zone and projection of representative IECC code adoption by Custom Regions (Location Region) and selected state groups

ResStock Custom Region	Main IECC-CZ	IECC Code Level by Vintage			
		2020s	2030s	2040s	2050s
2	6A	2009	2015	2018	2018
3	5A	2015	2018	2021	2021+
4	5A	2012	2015	2018	2021
5	5B	2009	2015	2018	2021
6	4C	2018	2021	2021+	2021+
7 (excl NY)	5A	2009	2015	2018	2021
8 (excl NE-DE-MD)	4A	2009	2012	2015	2018
9 (excl TX, FL)	3A	2009	2012	2018	2021
10	2A	2009	2012	2015	2021
11/CA	3C	2018	2021	2021+	2021+
TX-FL	2A	2018	2021	2021	2021+
NY	4A+	2018	2021	2021+	2021+
NE-DE-MD	4A	2018	2021	2021	2021+

Supplementary Table 9 Assumption of representative IECC code adoption by Climate Zone

IECC-CZ	IECC Code Level by Vintage			
	2020s	2030s	2040s	2050s
6A	2009	2015	2018	2018
5A	2012	2015	2018	2021
5B	2009	2015	2018	2021
4C	2018	2021	2021+	2021+
4A	2015	2018	2021	2021+
3A	2009	2012	2018	2021
2A	2015	2018	2021	2021+
3C	2018	2021	2021+	2021+

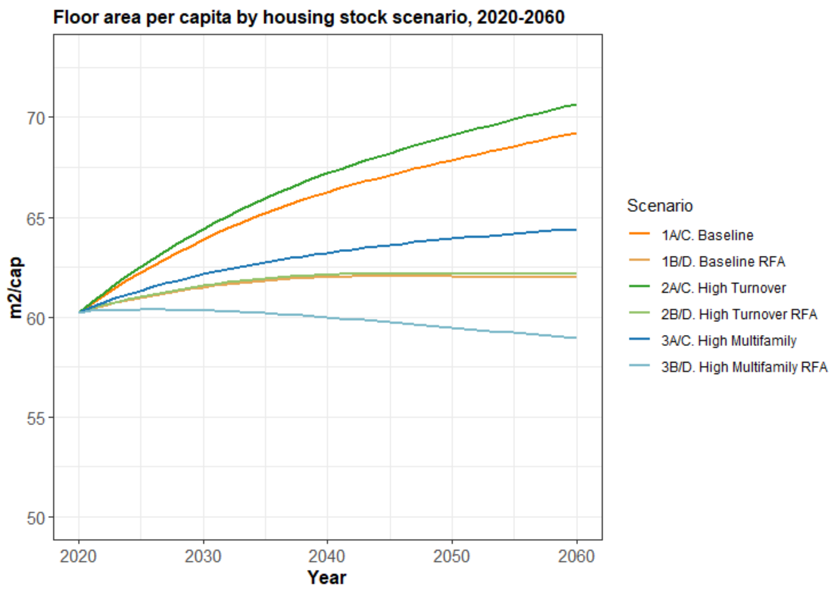
Increases in electrification of new housing is defined by Census Region, based on projected price differences between electricity and natural gas[5]. Price differences are largest (and electrification rates assumed to be lowest) in the Northeast, while price differences are smallest (and electrification 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 Public Use Microdata Area (PUMA)[15], 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 Supplementary Figure 22 we show increasing in the share of housing units using electricity for space heating in new construction, by Census Region, for Baseline and Increased Electrification new housing characteristics scenarios.



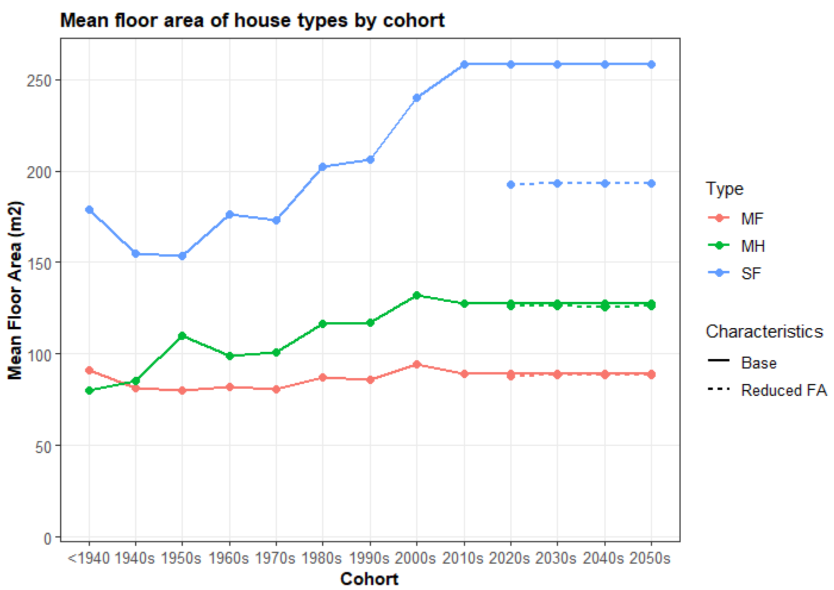
Supplementary Figure 22 Share of electric heating in new construction for base and IE new housing characteristics scenarios. Each year represents the sum of units built in the previous five years, i.e. 2025 refers to all units built 2021 to 2025.

Supplementary Figure 23 shows the development of floor area per capita in six of the twelve housing stock and characteristics scenarios. The Increased Electrification (C) scenarios have the same floor area projections as the Base (A) characteristics scenarios, while the Increased Electrification & Reduced Floor Area (D) scenarios have the same floor area projections as the Reduced Floor Area (B) scenarios. The Baseline (1) and High Turnover (2) stock scenarios depict strong growth in future floor area per capita, driven by differences in average size of new construction and old housing leaving the stock (Supplementary Figure 24), and to a lesser extent by reductions in average household size[1,16]. This growth is floor area per capita is greatly impeded by restricting the size of the largest new homes to less than 279 m^2 (3,000 ft^2) in the Reduced Floor Area (B) scenarios; but even in these scenarios (1B, 2B) there is a slight increase in floor area per capita which levels off at about 62.5 m^2/cap. The High Multifamily scenarios show much more gradual growth of floor area per capita (3A), or a slight decline when combined with Reduced Floor Area (3B). The evolution of floor area per capita has a great influence on emissions from both material production and construction[1], and energy use in new homes. Supplementary Figure 24 shows that the 279 m^2 limit primarily affects the size of new single-family homes, with mean size reducing from 258 m^2/house to 193 m^2/house in Reduced Floor Area scenarios, while multifamily and manufactured housing are essentially unaffected by Reduced Floor Area, as very few of those housing types exceed 279 m^2.

About half of households in houses of 279 m^2 or larger currently have two or fewer inhabitants[4], and if this continues to be the case most cases households affected by Reduced Floor Area would still have very large floor area consumption. For instance, reducing floor area from 325 m^2 (3,500 ft^2) to 232 m^2 (2,500 ft^2) for a two-person household would reduce per-capita floor area consumption from 163 m^2/cap to 116 m^2/cap, still far above a sufficiency upper limit of 40 m^2/cap. In fact, a household size of eight or more would be required to achieve sufficiency with a house larger than 279 m^2 (3,000 ft^2). One alternative approach to modelling scenarios of reduced floor area in new housing which we did not implement in this analysis would be to increase the share of homes built in the smallest size ranges, below 93 m^2 (1,000 ft^2), representing e.g. growth in accessory dwelling units currently seen in urban areas of the US with housing shortages[17].

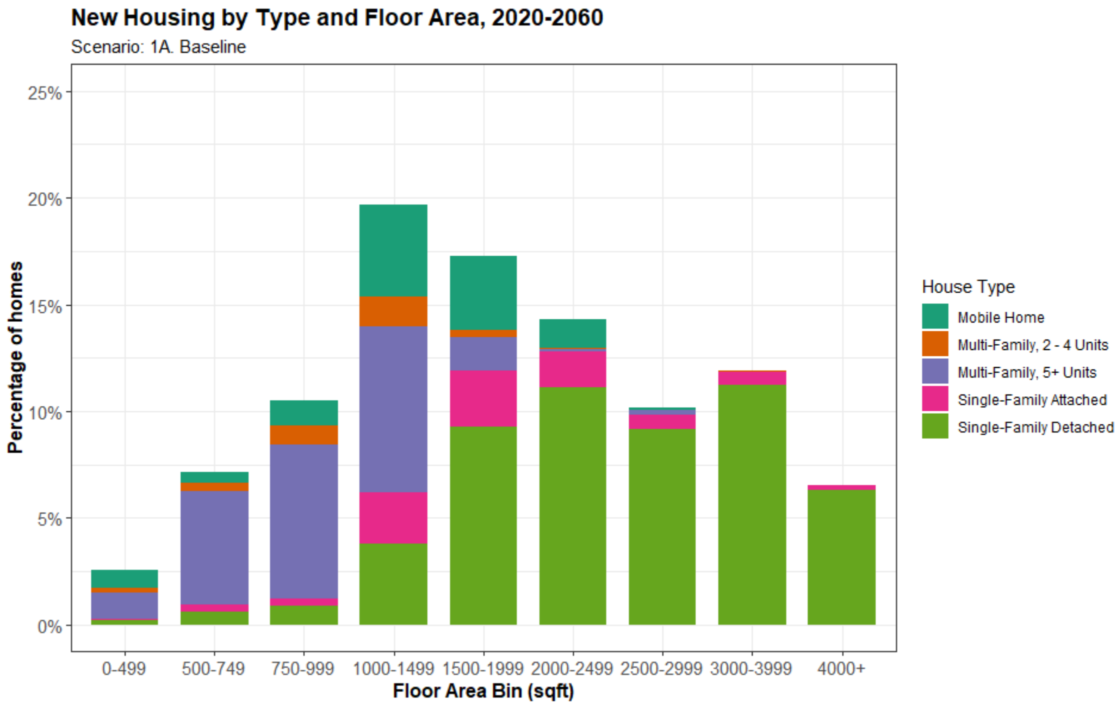


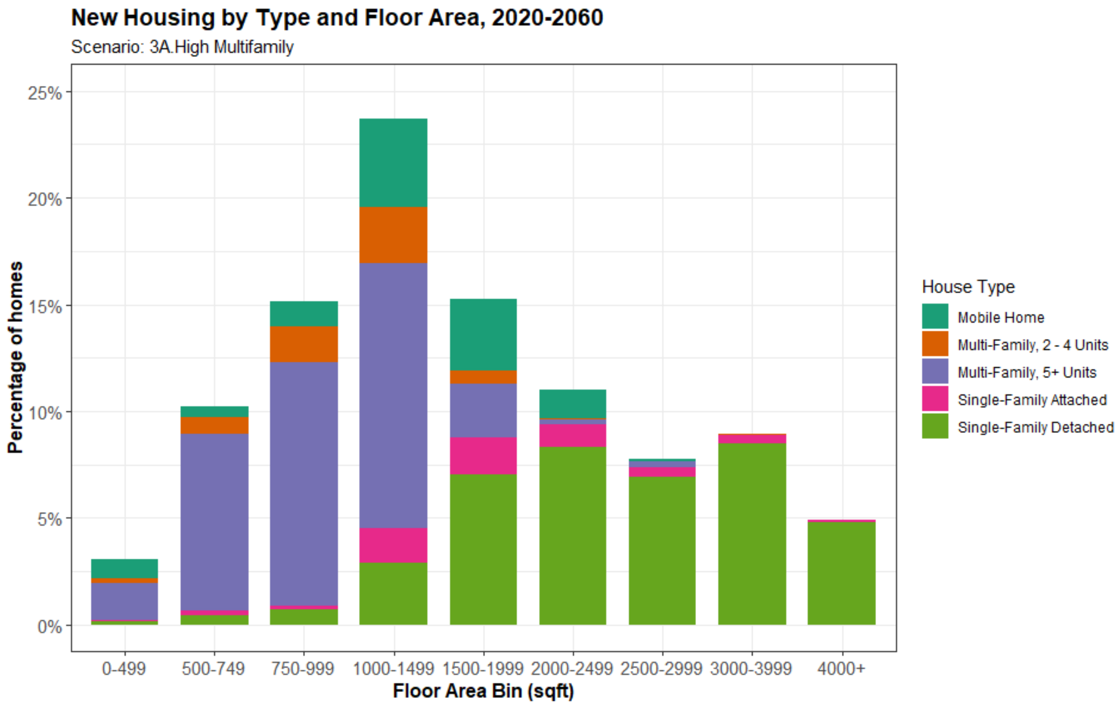
Supplementary Figure 23 Projections of floor area per capita by housing stock and characteristics scenarios.

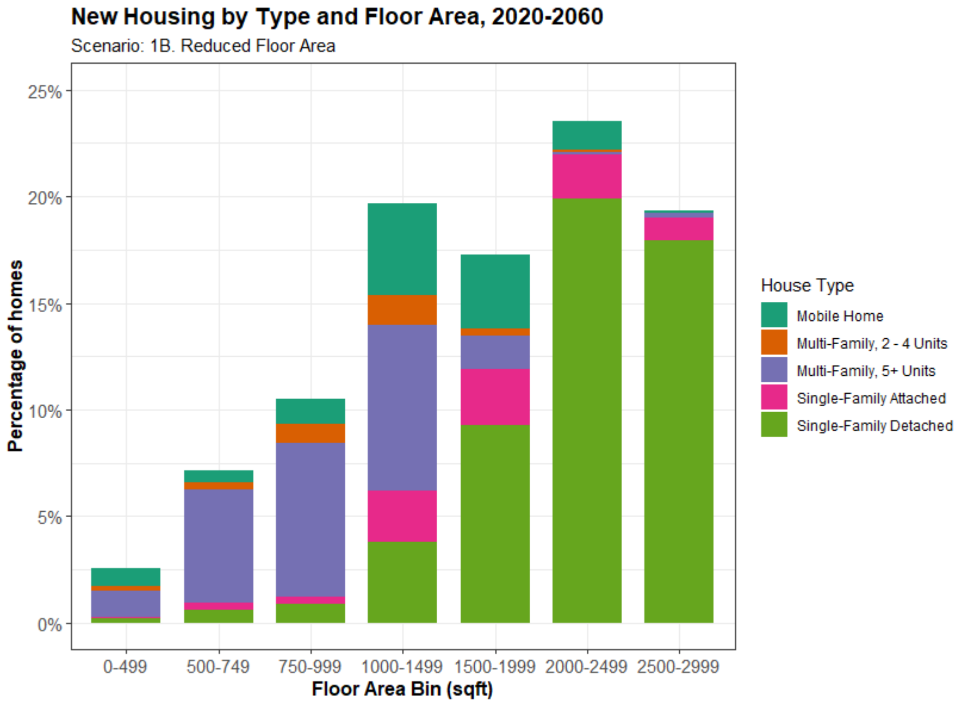


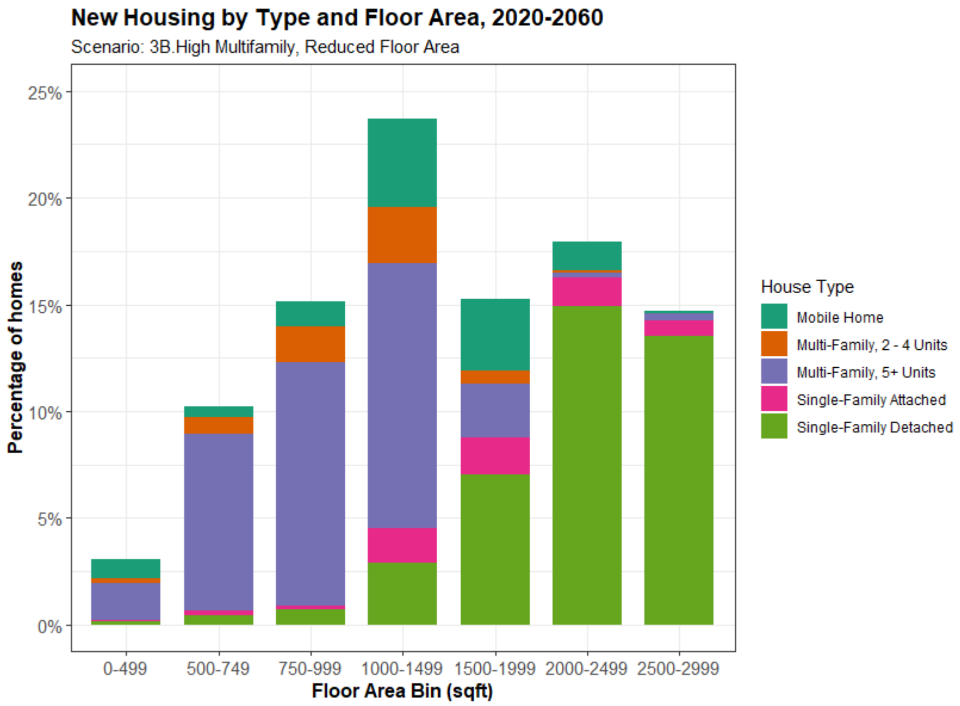
Supplementary Figure 24 Growth in average floor area of new housing over time, and in housing stock scenarios

Supplementary Figure 25 demonstrates the outcomes of combined housing stock (Baseline and High Multifamily) and characteristics (Base and Reduced Floor Area) scenarios on distributions of new construction by house type and size, which determine the average size of new construction (Supplementary Figure 24), and influence the growth in floor area per capita (Supplementary Figure 23).









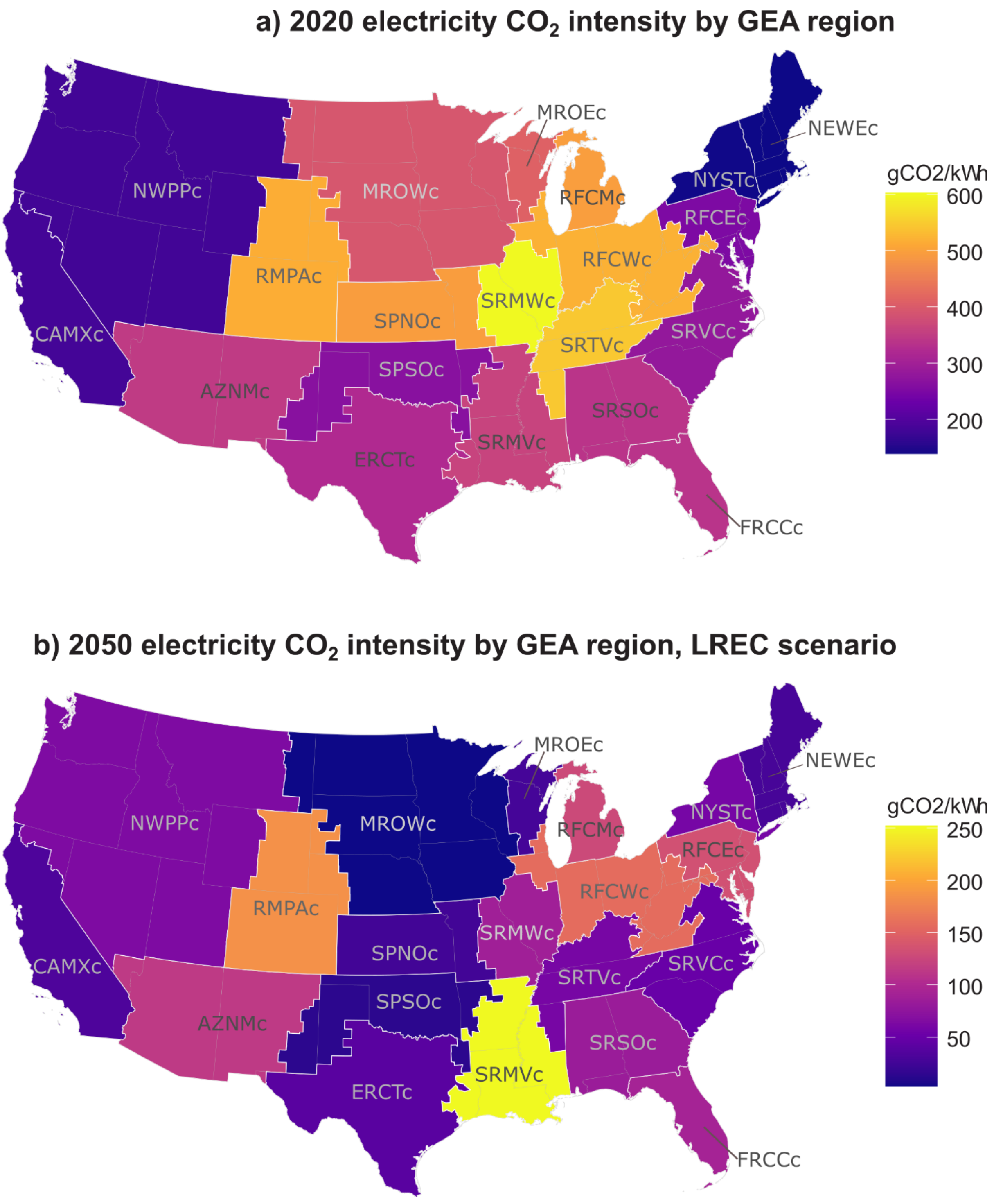
Supplementary Figure 25 Distributions of new construction by size and type for housing stock and characteristic scenarios

5 Electricity supply scenarios

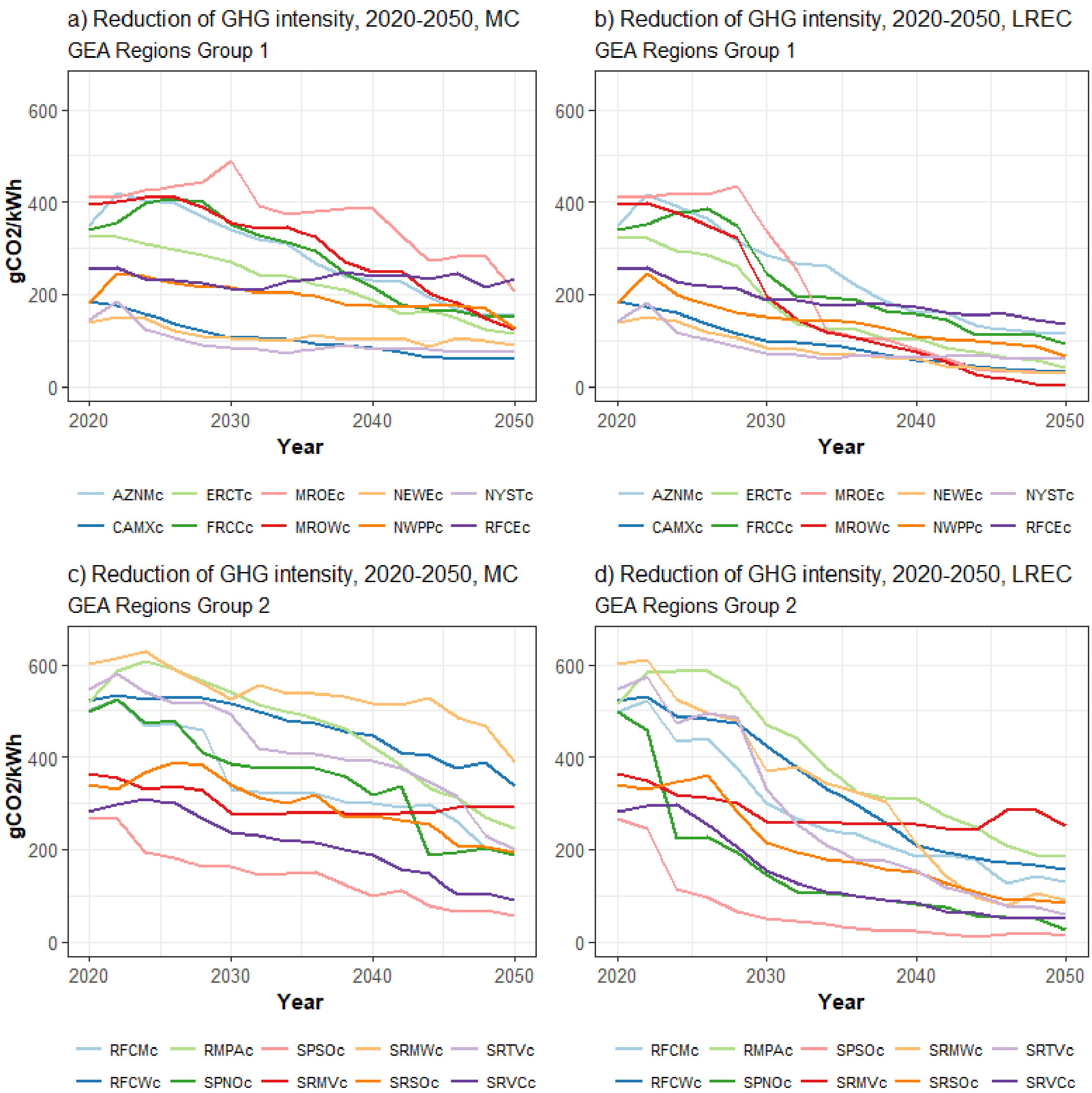
Supplementary Fig. 26 shows the change of GHG intensity of electricity supply by Cambium GEA region[18] between 2020 and 2050, for the LREC electricity supply scenario. Time-series of reductions in electricity GHG intensity by GEA region in shown in Supplementary Fig. 27 for both Mid-Case and LREC electricity supply scenarios[19,20]. Some regions experience much greater decarbonization than others. In LREC for instance, the SRMVc region incorporating the states of Louisiana, Mississippi and

Arkansas achieves quite modest reductions in GHG intensity of electricity supply, while the MROWc region (North and South Dakota, Nebraska, Minnesota, Iowa and part of Wisconsin) goes from having one of the highest electricity GHG intensities, to the lowest, with especially large growth of onshore wind generation. The NREL scenarios are estimated until 2050. In the Mid-Case scenario, combined electricity generation by coal and gas declines to 34% total generation in 2050, from 56% in 2020, while in the Low Renewable Energy Cost scenario combined coal and gas generation declines to 19% by 2050. For both scenarios, we assumed further decarbonization of electricity for the period 2051-2060 In the Mid-Case scenario we assumed intensity reductions of 5% every five years, while for LREC we assumed intensity reduction of 7% between 2051-2055, and 10% between 2056-2060. For Carbon Free Electricity (CFE) by 2035, 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.

The electricity supply distinguish between utility-scale PV (UPV) and distributed PV (DPV), which includes rooftop solar on residential buildings. As growth of DPV is already reflected in the electricity supply scenarios, we do not consider it as a residential renovation measure, to avoid double-counting. Both UPV and DPV capacity grow substantially in all supply scenarios, especially in LREC and CFE, but in absolute terms the majority of the growth of solar electricity is from UPV. Geographically, the growth of DPV is greatest in Texas, California, and Florida in absolute terms, but large growth is seen throughout the country. Growth is especially large in relative terms in Mississippi, Oklahoma, Michigan, Alabama and Arkansas[20].



Supplementary Figure 26 GHG intensity of electricity supply in Cambium GEA regions (approximately equivalent to EPA eGrid regions) a) in 2020 and b) in 2050 according to the LREC scenario. Data from NREL Cambium[20]



Supplementary Figure 27 Reduction of GHG intensity of electricity supply by GEA regions (a,c) in the MC supply scenario and (b,d) in the LREC supply scenario. Data from NREL Cambium[20]

6 Additional figures and tables

6.1 Housing stock evolution by type and size

In this section we compile additional figures and tables which are used to support analyses made in the main manuscript. Cumulative emission reductions of mitigation strategy combinations

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 Supp. Fig. 28), our baseline scenario (dotted black line in Fig. 28) generates substantial emission reductions. Beyond this baseline, mitigation actions are ordered in Supp. Fig 28a 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. 28b) 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.

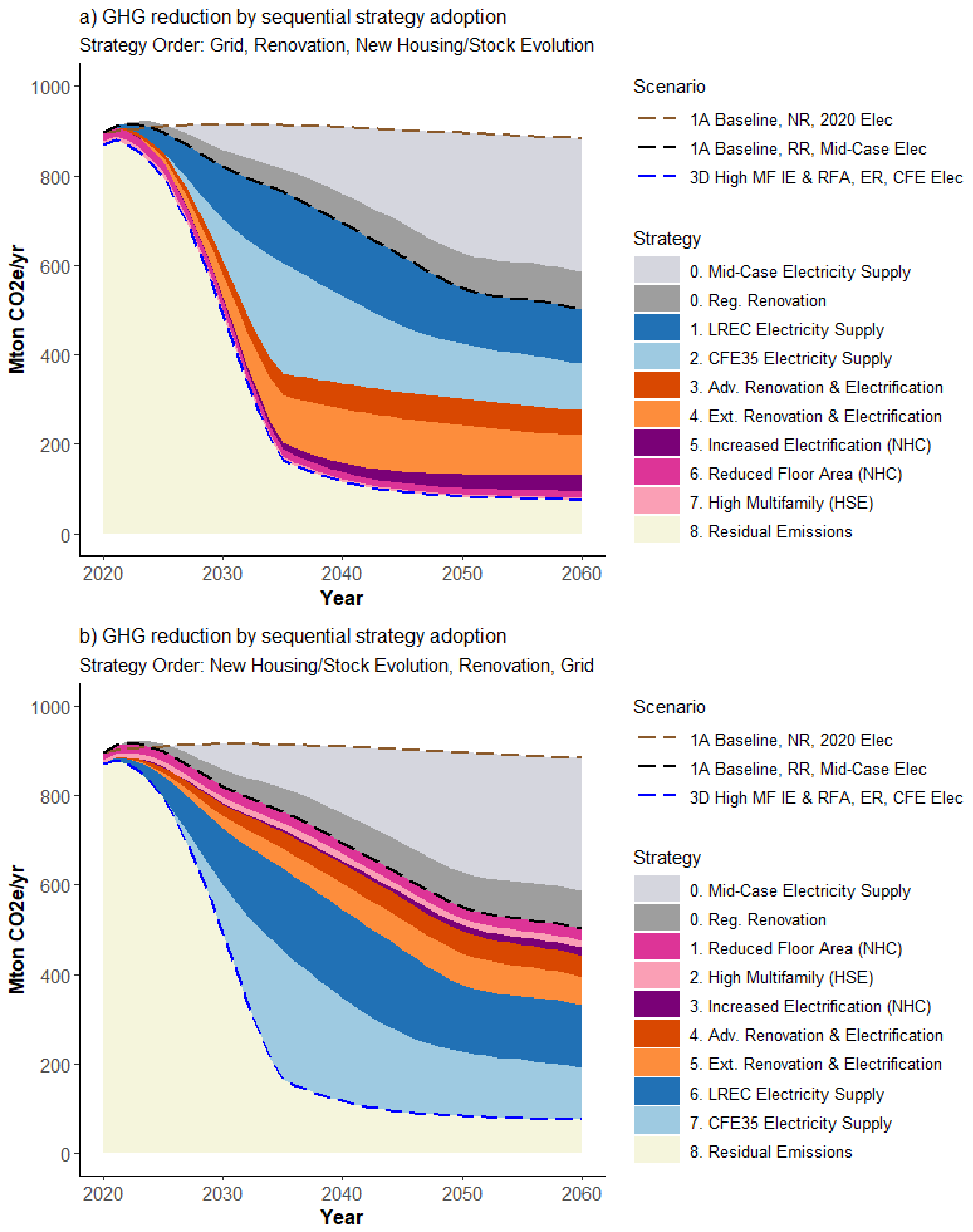
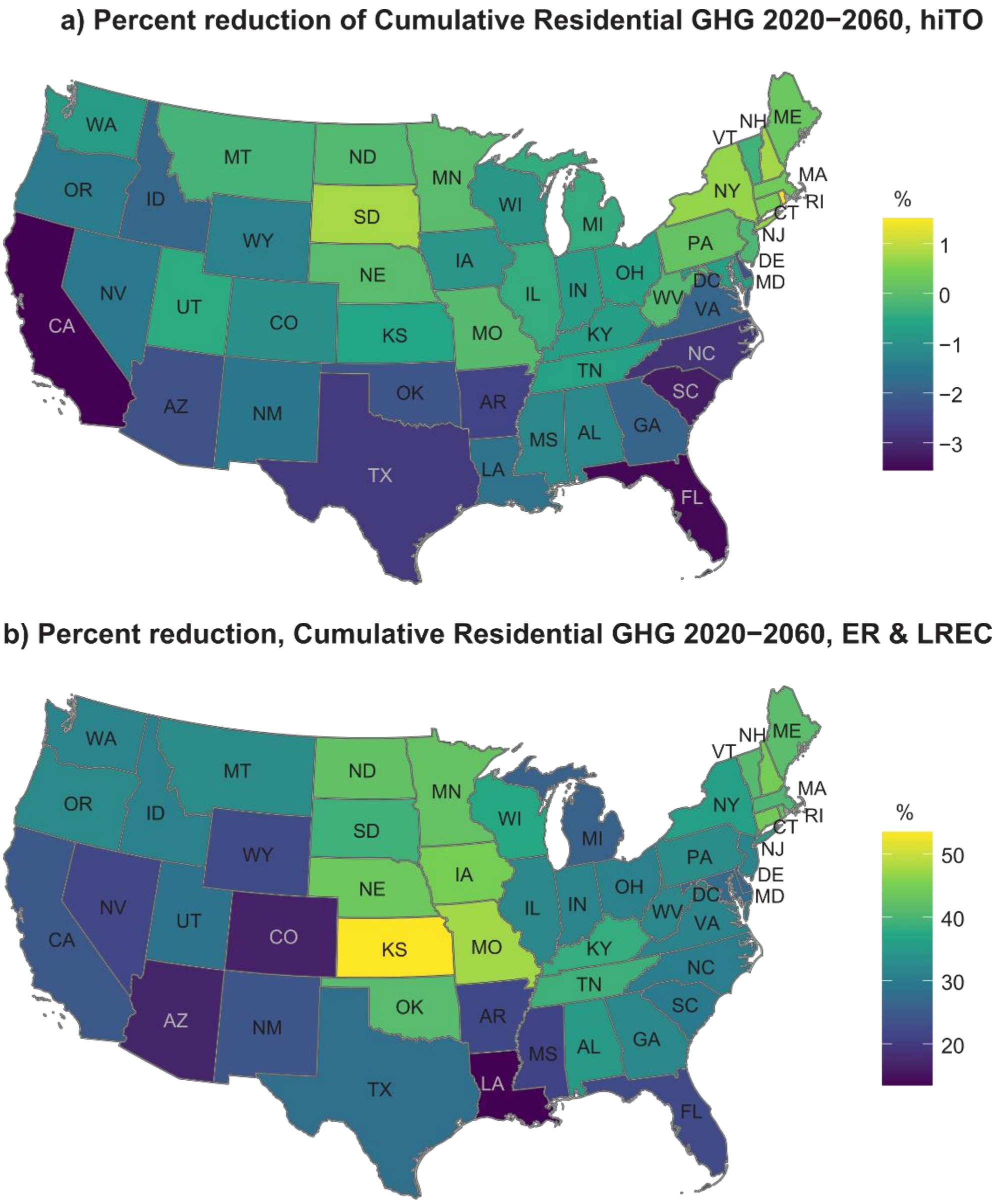


Figure 28 Emission reduction potential of individual strategies sequenced by a) their total reduction potential, relative to emissions in the Baseline stock, Base Housing Characteristics, Regular Renovation, and Mid-Case electricity GHG scenario and b) in reverse order. Strategies are grouped by those 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. High Stock Turnover is not considered as it leads to higher emissions than the baseline. NR = No Renovation

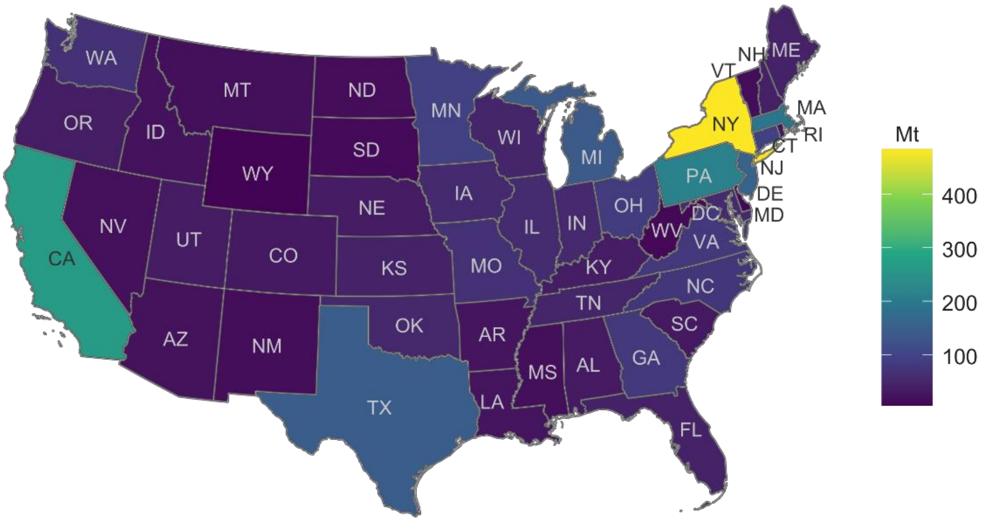
6.2 Spatial analysis of decarbonization strategies

Supplementary Fig. 29 shows relative reductions in cumulative GHG emissions by state for High Turnover and the combination of ER renovation and LREC electricity, similar to Fig. 4 in the main text. High Turnover only reduces emissions in a handful of states which tend to be cold climates with higher shares of old homes, fuel oil heating, or low population growth. The combination of ER and LREC is particularly high in states with high GHG intensity in 2020, low shares of electric heating, high shares of older homes, and colder climates. Supplementary Figure 30 shows absolute reductions in cumulative emissions for five individual strategies and for the combination of ER renovation and LREC electricity supply.

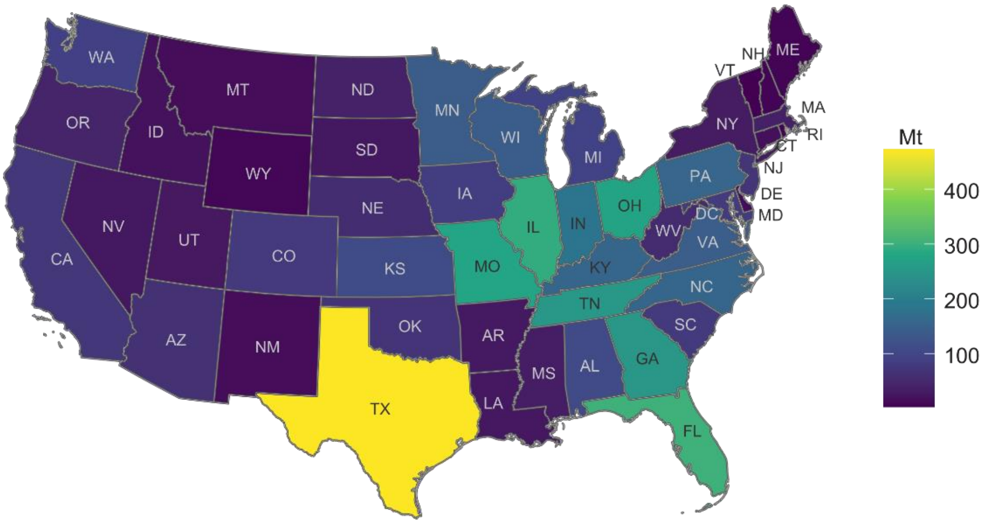


Supplementary Figure 29 Assessment of percentage reductions in 2020-2060 cumulative emissions by state from (a) High Stock Turnover (hiTO) and (b) combined Extensive Renovation and LREC electricity (ER & LREC).

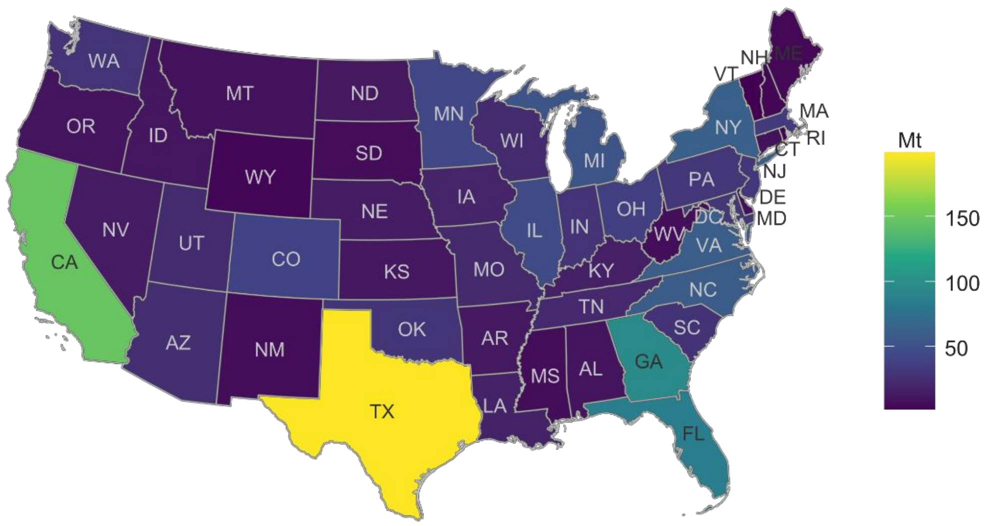
a) Absolute reduction, Cumulative Residential GHG 2020−2060, ER

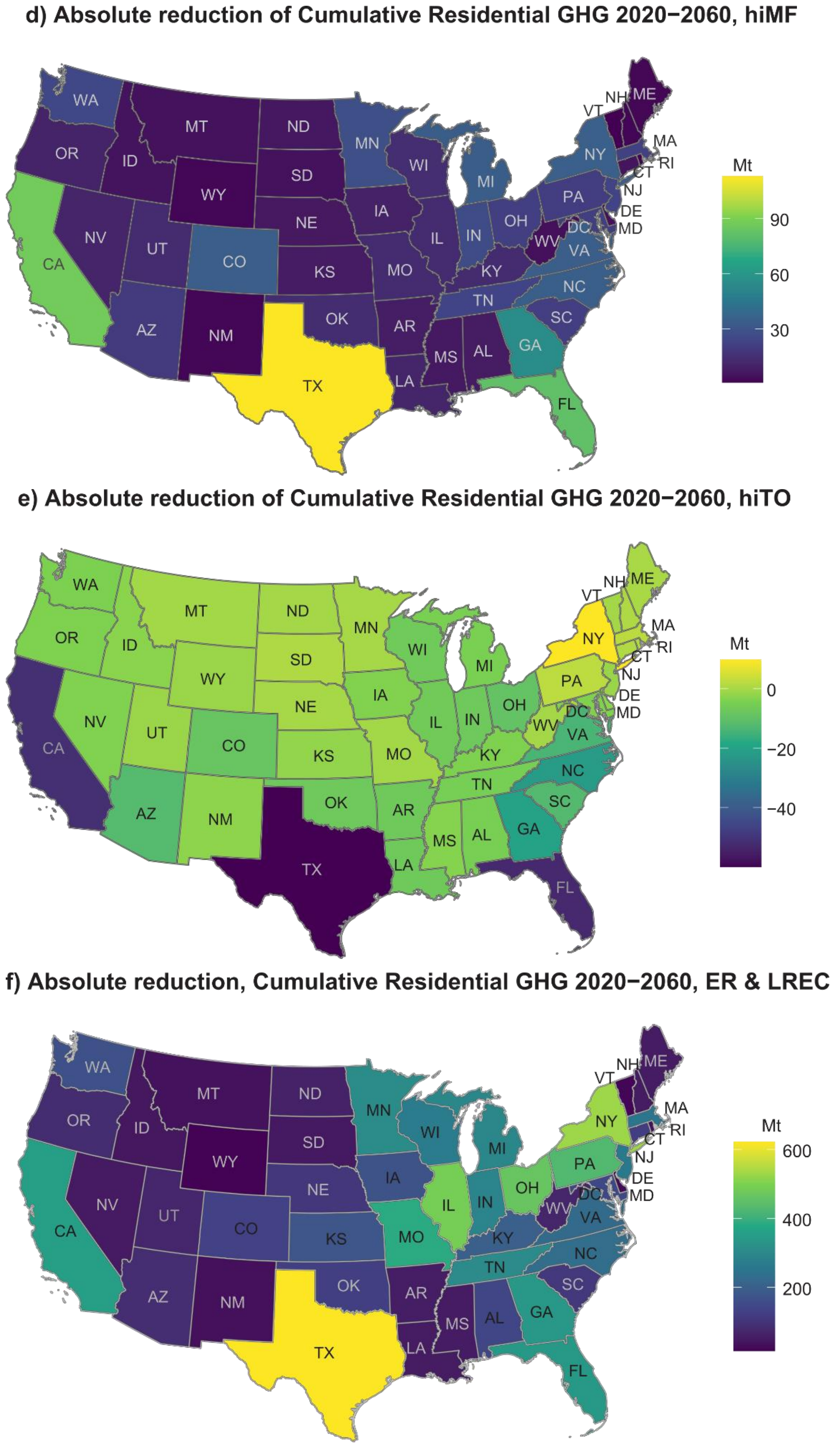


b) Absolute reduction of Cumulative Residential GHG 2020−2060, LREC



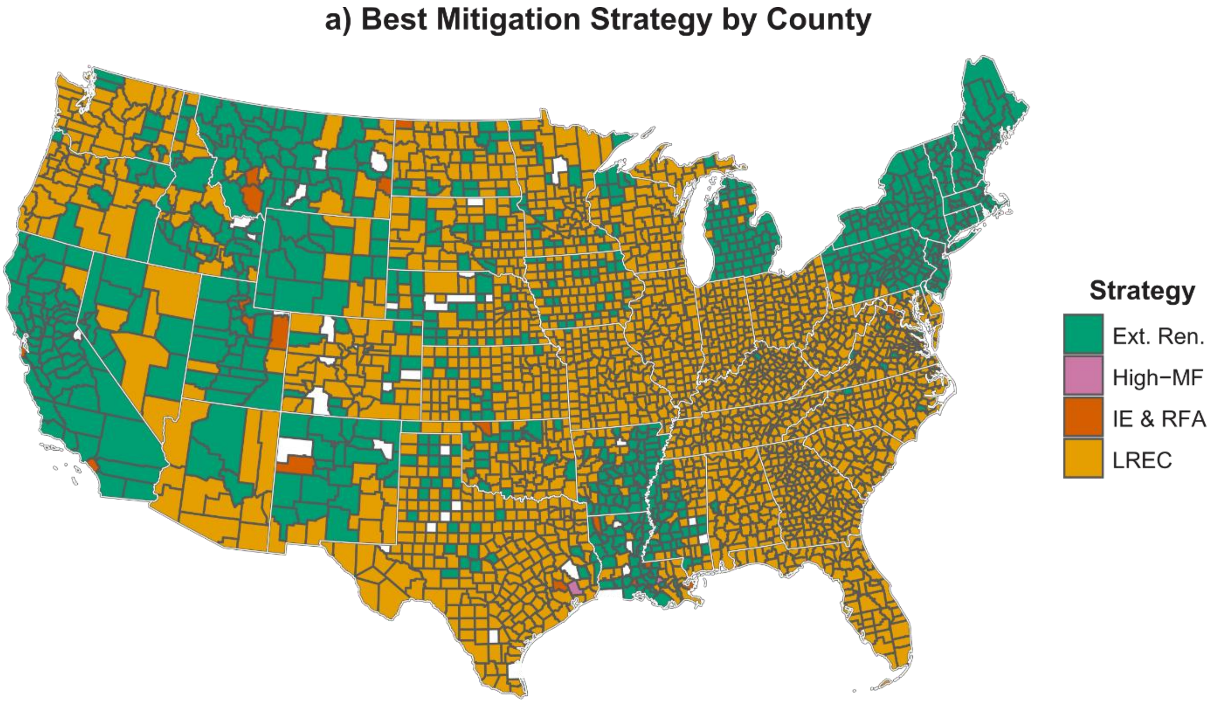
c) Absolute reduction of Cumulative Residential GHG 2020−2060, IE & RFA

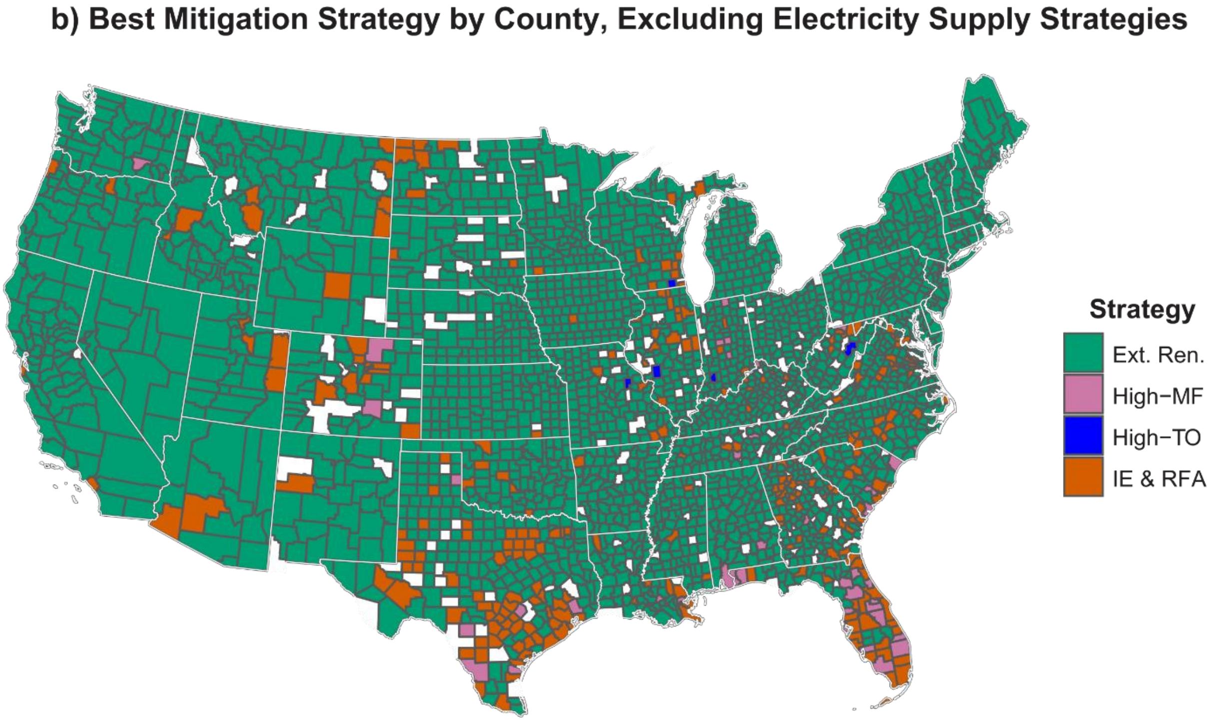




Supplementary Figure 30 Absolute reductions in 2020-2060 cumulative emissions by state from (a) Extensive Renovation (ER) (b) LREC electricity (c) Increased Electrification and Reduced Floor Area (IE&RFA) in new homes, (d) high Multifamily stock growth, (e) High Stock Turnover (hiTO) and (f) combined Extensive Renovation and LREC electricity (ER & LREC)

Supplementary Fig. 31 identifies the best individual strategy for all counties, both including (a) and excluding (b) LREC electricity supply. Blank counties signify that counties were removed due to insufficient sample points, or differences in sample sizes at the county level between stock (base, hiMF, hiTO) scenarios which prevented a direct comparison of stock strategies. When excluding electricity supply scenarios (Supp. Fig. 34b), Extensive Renovation is the highest potential strategy in most counties. However, in some counties experiencing high population growth, building smaller electrified new homes (IE-RFA), or prioritizing multifamily in housing stock growth (hiMF) has greater potential than Extensive Renovation.

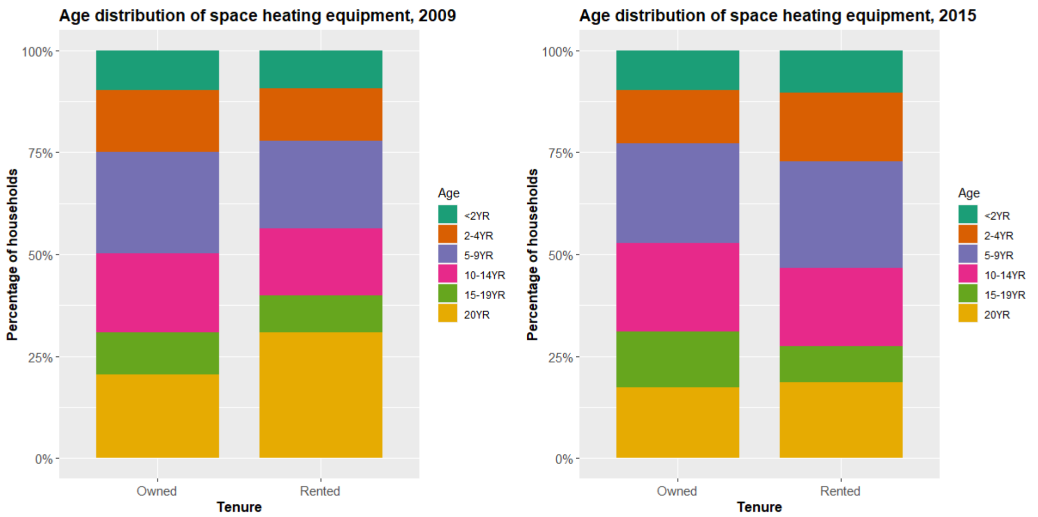




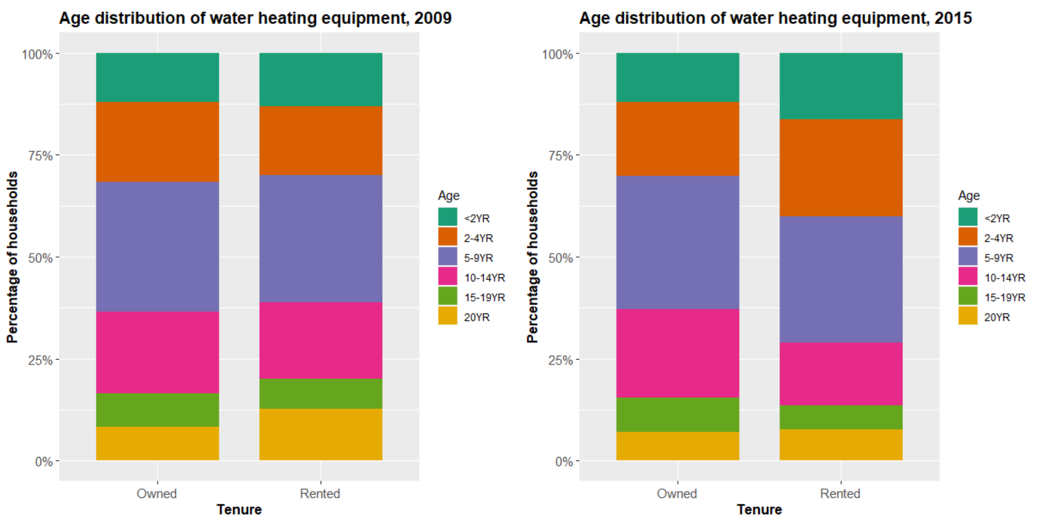
Supplementary Figure 31 Identification of decarbonization strategy with highest potential GHG reductions in each county, considering a) of Extensive Renovation (Ext. Ren), High Multifamily Stock Growth (High MF), Increased Electrification and Reduced Floor Area of new housing (IE & RFA), and LREC electricity supply, and b) with the same candidate strategies except for LREC electricity supply. Blank counties were removed due to insufficient sample points, or differences in sample sizes between stock scenarios which prevented a direct comparison of stock strategies.

6.3 Comparison of heating equipment age by tenure

Supplementary Figure 32 and 33 compare age distributions of space and water heating equipment from RECS 2009 and RECS 2015[21] in owned and rented housing, as a proxy for assessing differences in energy efficiency and for likelihood and frequency of renovation by housing tenure. The comparison is inconclusive, although RECS 2009 shows a notably higher share of old space heating equipment in rented housing units, RECS 2015 shows that owned and rented homes have very similar shares of old (20 years or higher) space heating equipment, while rented homes have higher shares of young (<5 years old) space heating equipment. For water heating, RECS 2009 again shows rented homes to have slightly higher shares of old equipment, but RECS 2015 suggest that rented homes have a notably higher share of young equipment. Different samples were drawn for RECS 2009 and 2015, and as the RECS 2009 sample was larger (12,083 observations vs 5,686), it probably gives a better representation of the housing stock at that time. Although empirical data demonstrating the extent of the differences in renovation rates and efficiency standards by tenure are sparse, several papers have investigated this issue, and estimate higher energy consumption and/or energy use intensity in rented vs owned housing units, after controlling for other variables[22,23].



Supplementary Figure 32 Comparison of age distribution of space heating equipment by housing tenure from RECS 2009 and 2015. Houses reporting no space heating equipment are omitted from the calculation.



Supplementary Figure 33 Comparison of age distribution of water heating equipment by housing tenure from RECS 2009 and 2015. Houses reporting no space heating equipment are omitted from the calculation.

References

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

2. 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).

3. Landis, J. & Reina, V. Eleven Ways Demographic and Economic Change Is Reframing American Housing Policy. *Hous. Policy Debate* **29**, 4–21 (2019).

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

5. EIA. Annual Energy Outloot 2021. https://www.eia.gov/outlooks/aeo/ (2021).

6. AHRI. Historical Data. *Statistical information on HVACR equipment* https://www.ahrinet.org/resources/statistics/historical-data (2022).

7. Shrestha, P. M. *et al.* Impact of Low-Income Home Energy-Efficiency Retrofits on Building Air Tightness and Healthy Home Indicators. *Sustainability* **11**, 1–22 (2019).

8. Schweitzer, M. *Estimating the national effects of the U.S. Department of Energy's weatherization assistance program with state-level data: A metaevaluation using studies from 1993 to 2005.* https://weatherization.ornl.gov/wp-content/uploads/pdf/2001_2005/ORNL_CON-493.pdf (2005).

9. Sherman, M. H. & Dickerhoff, D. Air-Tightness of U.S. Dwellings. *ASHRAE Trans.* (1998).

10. 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.

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

12. EIA. Status of State Energy Code Adoption - Residential. https://www.energycodes.gov/status/residential (2020).

13. US Census Bureau. Characteristics of New Housing. *Survey of Construction* https://www.census.gov/construction/chars/ (2020).

14. EIA. Annual Energy Outlook 2020. https://www.eia.gov/outlooks/aeo/ (2020).

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

16. McCue, D. *Updated Household Growth Projections: 2018-2028 and 2028-2038.* https://www.jchs.harvard.edu/sites/default/files/Harvard_JCHS_McCue_Household_Projections_Rev010319.pdf (2018).

17. 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).

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

19. 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).

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

21. EIA. Residential Energy Consumption Survey (RECS). https://www.eia.gov/consumption/residential/index.php (2019).

22. 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).

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