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Peter Berrill¹ , Kenneth T Gillingham¹ and Edgar G Hertwich² ¹ Yale School of the Environment, New Haven, United States of America² Norwegian University of Science and Technology, Department of Energy and Process Engineering, Trondheim, NorwayE-mail: peter.berrill@yale.edu**Keywords:** residential GHG emissions, drivers, household size, demand-side solutions, electrification, decarbonization, residential floor areaSupplementary material for this article is available [online](#)**Abstract**

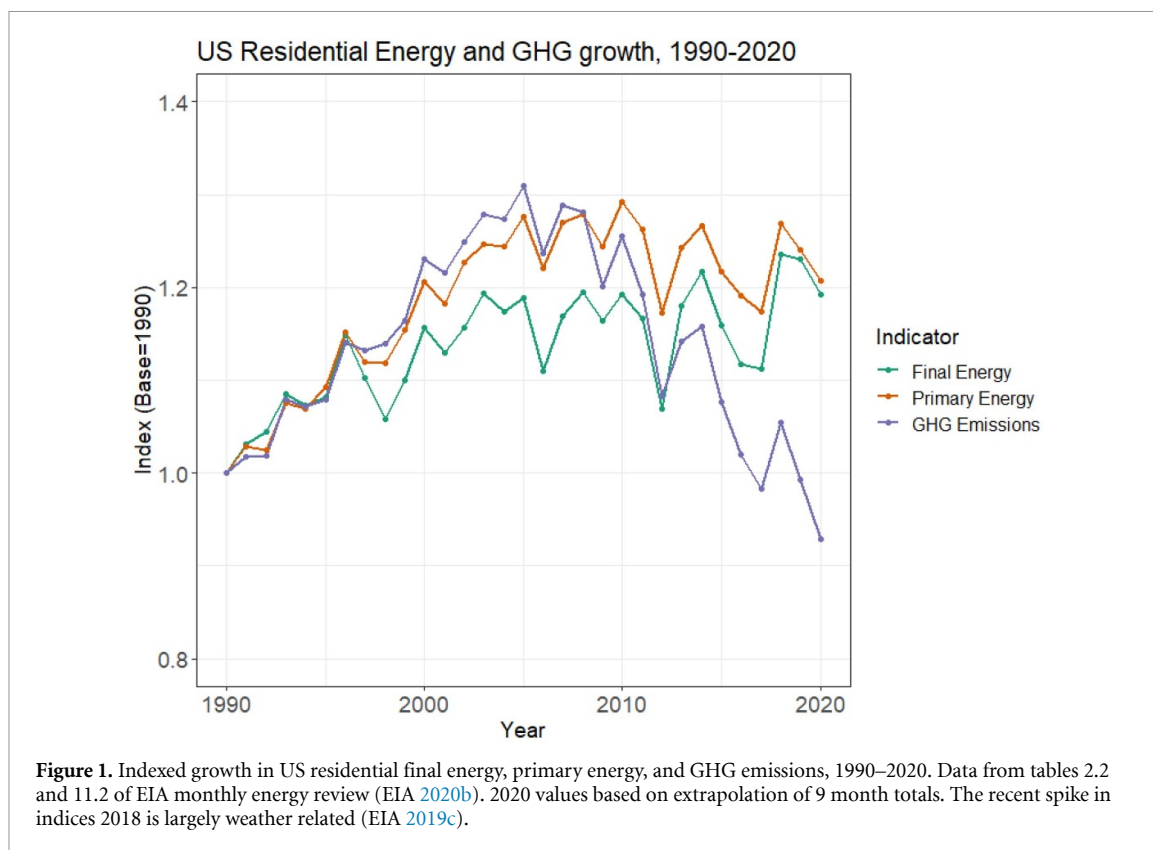
Annual greenhouse gas (GHG) emissions from residential energy use in the United States peaked in 2005 at 1.26 Gt CO_{2-eq} yr⁻¹, and have since decreased at an average annual rate of 2% yr⁻¹ to 0.96 Gt CO_{2-eq} yr⁻¹ in 2019. In this article we decompose changes in US residential energy supply and GHG emissions over the period 1990–2015 into relevant drivers for four end-use categories. The chosen drivers encompass changing demographics, housing characteristics, energy end-use intensities, and generation efficiency and GHG intensity of electricity. Reductions in household size, growth in heated floor area per house, and increased access to space cooling are the main drivers of increases in energy and GHG emissions after population growth. Growing shares of newer homes, and reductions in intensity of energy use per capita, household, or floor area have produced moderate primary energy and GHG emission reductions, but improved generation efficiency and decarbonization of electricity supply have brought about far bigger primary energy and GHG emission reductions. Continued decline of residential emissions from electrification of residential energy and decarbonization of electricity supply can be expected, but not fast enough to limit climate change to 1.5 °C warming. US residential final energy demand will therefore need to decline in absolute terms to meet such a target. However, without changes in the age distribution, type mix, or average size of housing, improvements in energy efficiency are unlikely to outweigh growth in the number of households from population growth and further household size reductions.

1. Introduction

Residential buildings make a substantial contribution to global primary energy demand and greenhouse gas (GHG) emissions, and may be one of the easiest energy demand sectors to decarbonize (Lucon *et al* 2014). The primary energy required for residential energy services is determined by the *useful* energy demand (influenced by service level, occupant behavior and characteristics of the ‘passive device’, e.g. the building shell), *final* to useful energy efficiencies of conversion devices (such as space heaters), and *primary* to final energy efficiencies of final energy supply (e.g. fossil energy extraction and refining, electricity generation) (Cullen and Allwood 2010). GHG emissions associated with residential energy use are

determined by the primary energy demand, and the GHG intensity of each primary energy source.

There are various points along the energy supply chain where action may be taken to reduce primary energy requirements. Cullen and Allwood (2010) estimate that due to compounding of conversion efficiencies along energy supply chains, efficiency gains nearer the point of use have more potential for system-wide energy savings than efficiency gains further up the supply chain. To reduce GHG emissions from buildings, ‘electrify everything’ summarizes a strategy of electrification of energy services and simultaneous decarbonizing of electricity generation (Mai *et al* 2018, Miller 2018). The logic of this approach to reduce GHG emissions is clear. Studies estimating emission reductions from electrification



include scenario analyses in various regions including the US (Frisch *et al* 2018, Langevin *et al* 2019), China (Peng *et al* 2018), Chile (Verástegui *et al* 2020), and Europe (Manteuffel *et al* 2016, Heinen *et al* 2018). A common theme from such studies is the dependency of emission reductions on the rate of grid decarbonization, and on efficiency factors of alternative heating systems. Meanwhile, empirical studies of whether electrification has already reduced residential or building sector emissions are lacking.

In figure 1 we show changes in US residential final and primary energy, and GHG emissions, from 1990 to 2020. The relative decoupling of GHG emissions from primary energy since 2007 demonstrates decarbonization of electricity supply. Since peaking at 1.26 Gt CO_{2-eq} yr⁻¹ in 2005, residential GHG emissions have decreased at an average annual rate of around $-2\% \text{ yr}^{-1}$ –0.96 Gt CO_{2-eq} yr⁻¹ in 2019, with further reductions expected in 2020 (EIA 2020b). This downward trend, although encouraging, remains well below the -7% annual reductions needed to limit climate change to 1.5 °C warming (Höhne *et al* 2020).

This paper identifies the most prominent drivers of US residential energy and GHG emissions over the period 1990–2015. Our analyses test the hypotheses that reductions in GHG intensity and residential fuel switching drove energy and emissions down, while smaller households and larger houses drove energy and emissions up. We use index decomposition analysis (IDA) to decompose changes in US residential

final energy, primary energy, and GHG emissions into drivers covering demographics, housing characteristics, and the energy and GHG intensity of energy demand and supply. It is the first analysis to decompose U.S residential energy and emissions at the end-use level, and the first to consider changes in household size, housing age cohort distribution and fuel switching as drivers. In section 2 we present a brief review of literature examining drivers of residential energy and emissions. In section 3 we describe the materials and methods used for our analysis. In section 4 we present and describe the main results, and in the remaining sections we discuss and interpret the results before concluding the article.

2. Drivers of residential energy and GHG emissions

In table 1 we summarize a selection of IDA studies of residential energy or GHG by location, the outcome metric being decomposed, the activity variable, and the main drivers identified by each study. In IDA, ‘activity’ refers to a measure of the aggregate level of activity or service demand in a sector. It may be measured in economic output, or in physical units—for example passenger- or tonne-kilometers for passenger or freight transport sectors (Xu and Ang 2014). An important modeling choice in IDA models of residential energy is whether to define population or number of houses as the main activity variable (Xu and

Table 1. Features of selected IDA models of residential energy and/or GHG emissions, including study location, outcome metric being decomposed, choice of activity variable, and the main drivers identified.

Study	Location	Outcome metric	Activity	Upward drivers (excl. activity)	Downward drivers
Hojjati and Wade (2012)	USA	FE	House	FA/house	Intensity
Rogan <i>et al</i> (2012)	Ireland	FE (gas)	Pop.	Intensity	
Nie and Kemp (2014)	China	FE	Pop.	Appliances, FA/cap	
Xu and Ang (2014)	Singapore	FE (elec.)	Pop.	↓HHS	FA/house
EIA (2015)	USA	FE	House	FA/house	Intensity
Zang <i>et al</i> (2017)	China	GHG	House	Income/cap	↓HHS
Kurniawan <i>et al</i> (2018)	Indonesia	GHG	Pop.	GDP/cap	Intensity
Shigetomi <i>et al</i> (2018)	Japan	GHG	House	Intensity	↓HHS, cohort
Balezentis (2020)	Lithuania	FE, GHG	Pop.	↓HHS, FA/house	Intensity

Note: FE = final energy, elec. = electricity, Pop. = population, HHS = household size, FA = floor area. Intensity is defined as outcome metric divided by a scaling factor, e.g. household, population, floor area, or income. All studies except Balezentis (2020) report the activity variable as an upward driver. Upward drivers correlate with an increase in energy/emissions, while downward drivers correlate with a decrease.

Ang 2014). This choice can influence the modeled effects of changes in household size. If population is the activity variable, household size reductions will be identified as an upward driver of changes in the outcome, but if number of housing units is the activity variable, the same reduction in household size will be identified as a downward driver. We consider population a more appropriate choice of activity for residential IDA models than number of houses, as population growth is a more convincing exogenous variable (further discussion on this point is found in section S3 of the supplementary information (SI) (available online at stacks.iop.org/ERL/16/034045/mmedia)).

Two decompositions of final energy in the US identified growth in the number of houses and average floor area per house as the main upward drivers of energy demand, and reductions in intensity (energy/floor area) as the main downward driver (Hojjati and Wade 2012, EIA 2015). Regression models of residential energy in the US largely agree on the importance of house type, size, and age in determining final energy demand or GHG emissions at the household level (Kaza 2010, Tso and Guan 2014, Goldstein *et al* 2020). Analyses at high spatial resolution report less energy consumption in urban areas with higher percentages of multifamily and smaller homes, more energy consumption in suburban, sprawling areas (Ewing and Rong 2008, Min *et al* 2010), and more energy consumption in states with lower average household size and higher proportions of older buildings (Salari and Javid 2016). The importance of household size as a determinant of aggregate residential demand has been long recognized (O'Neill and Chen 2002, Jiang and O'Neill 2007), and has been highlighted recently in the context of continued declining household sizes globally (Ellsworth-Krebs 2019, Ivanova and Büchs 2020), but the direction of this effect identified by IDA studies is mixed (table 1), as it depends on the choice of activity variable. On the role of building stock turnover, several studies using building stock based energy models (Fazeli *et al* 2016,

Reyna and Chester 2017, Breunig *et al* 2018) find that lower turnover rates impede energy demand reductions from more efficient new housing. No IDA model that we are aware of has considered the changing age profile of buildings as a driver of change in residential energy demand.

3. Data and methods

Final energy consumption and housing characteristics data are obtained from six Residential Energy Consumption Survey (RECS) from 1990 to the most recently published survey for 2015 (EIA 2019a). Choosing 1990 as our starting year allows us to track the evolution of households in housing built from 1990 onwards in our decomposition of housing cohorts described below. Primary energy consumption by residential end-use is calculated by combining RECS information with electricity generation efficiency by fuel from the State Energy Data System (SEDS) (EIA 2019b), and Monthly Energy Review (MER) (EIA 2020b). The supply-side (MER, SEDS) and demand-side (RECS) surveys from EIA differ in their estimates of total residential energy consumption. The supply side surveys produce better estimates of total demand, and are more comparable across years (EIA 2018), and so we scale RECS estimates to match supply-side estimates of total residential final energy consumption per fuel type and by census division. To calculate GHG emissions and primary energy, we use CO₂, CH₄, and N₂O emissions factors for fossil fuel combustion (EPA 2009), and calculate electricity GHG intensities and primary energy factors based on the generation fuel mix and electricity generation losses in each division and year (EIA 2019b). Aside from direct emissions from electricity generation, GHG emissions from energy supply chains are not included in the analysis. Primary energy for non-fossil electricity is calculated in SEDS using the physical energy content method for nuclear, and the substitution methods for renewables

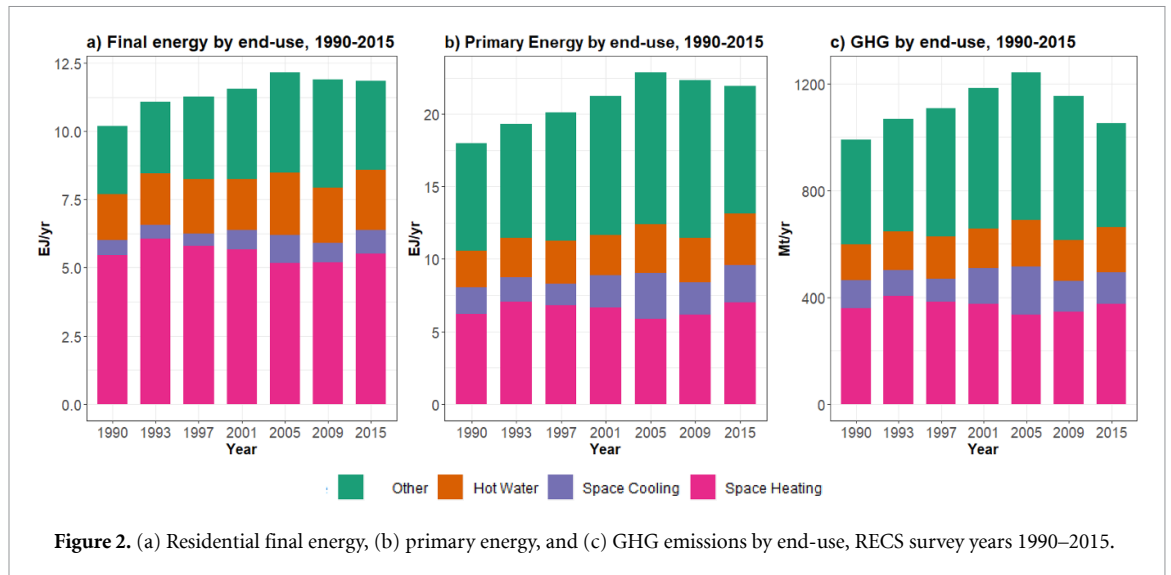


Figure 2. (a) Residential final energy, (b) primary energy, and (c) GHG emissions by end-use, RECS survey years 1990–2015.

(Grubler *et al* 2012, p 142). Our definition of primary energy demand in this context is thus primary energy use (or fossil heat equivalent) at the point of conversion. It is not a cumulative energy demand calculation, which would include energy for fuel extraction, refining, processing, and distribution (Arvesen and Hertwich 2015).

In figure 2, we present final energy demand, primary energy, and GHG emissions by end-use for selected years 1990–2015. Weather adjusted versions of these figures are shown in SI figure S2. Space heating is the largest source of final energy demand, making up about 50% of the total each year. However, space and water heating become less important, and electricity dominated space cooling and other end-uses become more important when looking at primary energy and GHGs, due to the higher primary energy requirements and GHG intensity of electricity. In 2015, other end-uses accounted for around 28% of final energy and 37% of GHG, while space heating contributed 47% to final energy and 36% to GHG.

We use an additive log mean division index (LMDI)-I multilevel-parallel IDA model (Ang and Zhang 2000) to decompose changes in final energy, primary energy, and GHG emissions associated with four residential energy end-uses; space heating, space cooling, domestic hot water, and all other end-uses (see SI figure S6 for a disaggregation of energy and emissions from other end-uses in 2015). Our model is multi-level, meaning that we analyze changes within hierarchically disaggregated sub-groups of the data (SI figure S3). Multi-level models are useful for analyzing the effects of changes in distribution of population between different categories, such as geographic region, or age cohort of housing. Among the classes of IDA models, LMDI-I is better suited to multi-level models, as it produces estimates for sub-groups that can be aggregated in a consistent manner, while the

decompositions leave no residual term at the sub-category level (Ang and Liu 2001, Ang 2015). IDA models are informative in ranking the importance of different drivers over time and allocating changes in the outcome variable to coincident changes in the explanatory variables. Limitations of IDA include assumptions of unit proportionality between driver and outcome (York *et al* 2003), absence of measures of statistical significance, and assumptions of independence between drivers (O'Neill and Chen 2002). For an IDA model to produce meaningful results, two considerations are worthy of attention. First, it is crucial to define drivers that can be reasonably assumed to influence the outcome through some plausible mechanism. Second, where possible, defining drivers that are less likely to be interdependent should be best practice.

Decomposing individual end-uses allows flexibility in incorporating driving factors applicable to each end-use (Xu and Ang 2014). For instance, we incorporate changes in conditioned floor space as a driver of space heating and cooling, but disregard that driver when analyzing changes in domestic hot water or other end-uses. Avoiding incorporation of drivers that do not influence the outcome also avoids interdependence between drivers, as inclusion of such a driver can create two driving factors which are strongly inversely correlated. Equations (1)–(4) describe decompositions of final energy for each end-use, with all terms defined in table 2. For primary energy and GHG, we add an extra term (X_E and X_G respectively) to each equation, to enable decomposition of changes in total primary energy demand and GHG emissions for each end-use into changes in electricity generation efficiency and GHG intensity of electricity in each census division, in addition to other drivers (see equations (S1)–(S8)). The attribution of changes in energy and GHG by end-use into

Table 2. Indices and subscripts used in the IDA decomposition equations.

Symbol	Summary	Unit of measurement/example/description
P	Population	National household population.
N	Houses	Number of housing units.
A	Conditioned floor area	Heated square foot per house for space heating; number of houses with AC for space cooling.
E	Final energy consumption	MJ yr ⁻¹
E'	Weather-adjusted final energy	MJ yr ⁻¹
i	Subscript for census division (1–9)	P_5 is population in division 5 (South Atlantic).
j	Subscript for house type (1–5)	$P_{i,2}$ is population in single-family detached type.
k	Subscript for age cohort (1–6)	$P_{i,j,5}$ is population in houses built in 1980s.
l	Subscript for heating fuel (1–5)	$P_{i,j,k,2}$ is population using primarily natural gas for space heating.
R	Regional index	Distribution of national population among nine census divisions.
T	Type index	Distribution of census division population among house types.
C	Cohort index	Distribution of population among construction cohorts, for each division and house type.
F	Heating fuel index	Distribution of population by main fuel used for space/water heating, for each division, house type, and cohort.
H	Household size index	Average number of occupied houses per person for populations segments by division, house type and cohort, and main heating fuel (E^1 only).
S	Conditioned space index	Heated/cooled floorspace index for populations segments by division, house type and cohort, and main heating fuel (E^1 only), defined as: S_1 (heated m ² /house)—average heated floor area per house within population segment, S_2 (houses with AC/all houses)—portion of houses owning AC within a population segment.
I	End-use intensity index	Final energy end-use intensity index: I^1 (E^1 /heated m ²) for space heating, I^2 (E'^2 /house with AC) for space cooling, I^3 (E'^3 /person) for hot water I^4 (E^4 /house) for other end-uses.
W	Weather index	Ratio of actual final energy per end-use to weather adjusted final energy per end-use (i.e. an estimate of what final energy demand would have been with 30 year average weather).
X_E	Primary energy index	Ratio of primary energy calculated using current primary energy factors for electricity to primary energy calculated using 1990 primary energy factors for electricity.
X_G	GHG index	Ratio of GHG emissions calculated using current GHG intensity of electricity generation to GHG emissions calculated using 1990 GHG intensity of electricity generation.

the drivers is described further in the supplementary information and detailed in equations (S9)–(S31).

We define population as the activity variable, and the population effect describes changes in energy and GHG outcomes due to changes in total household population. Regional effects are calculated based on changes in the population distribution among the nine census divisions (New England, Mid Atlantic, East North Central, West North Central, South Atlantic, East South Central, West South Central, Mountain, and Pacific). Type effects are based changes in the population distribution among five types of housing within each division; single

family detached and attached, multifamily low-density (units in buildings with 2–4 units) and high-density (5+ units), and manufactured housing. Cohort effects are due to changes in population distribution (within each division-type segment) between housing of six age cohorts spanning houses built pre-1950 to houses built from the 1990s onwards. Fuel effects are due to changes in distribution of population by main fuel used for space/water heating (natural gas/liquefied petroleum gases, fuel oil/kerosene, electricity, or other), within each division-type-cohort subset. Household size effects are based on changes in the inverse of average household size

within each division-type-cohort-fuel subset. Conditioned space effects are due to changes in average household heated floor space for space heating ($m^2_{\text{heat}}/\text{house}$), and the percentage of houses owning air-conditioners for space cooling. End-use intensity effects are based on changes in the intensity index defined by the weather-adjusted outcome variable (final/primary energy, GHG) per heated floor area for space heating, per house with air-conditioning for space cooling, per person for domestic hot water, and per house for other energy.

Changes in the primary energy and GHG indices (X_E and X_G , included in the primary energy and GHG decomposition equations (S1)–(S8)) are used to calculate the electricity efficiency and GHG intensity effects. Weather effects capture differences in space conditioning and water heating due to difference in in heating degree days and cooling degree days in each census division from their 30 year average. This allows us to control for the influence of weather fluctuations, and thereby provide better estimates of the other driver effects. Changes in drivers over the study period are visualized in SI section 4. The data and code used to process the data and produced the results are available online (Berrill 2021).

Decomposition of final energy for space heating, end-use 1:

$$E^1 = \sum_i \sum_j \sum_k \sum_l P \frac{P_i}{P} \frac{P_{ij}}{P_i} \frac{P_{ijk}}{P_{ij}} \frac{P_{ijkl}}{P_{ijk}} \frac{N_{ijkl}}{P_{ijkl}} \frac{A_{ijkl}}{N_{ijkl}} \frac{E'^1_{ijkl}}{A_{ijkl}} \frac{E^1_{ijkl}}{E'^1_{ijkl}}$$

$$= P \times R \times T \times C \times F \times H \times S \times I^1 \times W. \quad (1)$$

Decomposition of final energy for space cooling:

$$E^2 = \sum_i \sum_j \sum_k P \frac{P_i}{P} \frac{P_{ij}}{P_i} \frac{P_{ijk}}{P_{ij}} \frac{N_{ijk}}{P_{ijk}} \frac{A_{ijk}}{N_{ijk}} \frac{E'^2_{ijk}}{A_{ijk}} \frac{E^2_{ijk}}{E'^2_{ijk}}$$

$$= P \times R \times T \times C \times F \times H \times S \times I^2 \times W. \quad (2)$$

Decomposition of final energy for domestic hot water:

$$E^3 = \sum_i \sum_j \sum_k \sum_l P \frac{P_i}{P} \frac{P_{ij}}{P_i} \frac{P_{ijk}}{P_{ij}} \frac{P_{ijkl}}{P_{ijk}} \frac{E'^3_{ijkl}}{P_{ijkl}} \frac{E^3_{ijkl}}{E'^3_{ijkl}}$$

$$= P \times R \times T \times C \times F \times I^3 \times W. \quad (3)$$

Decomposition of final energy for all other uses:

$$E^4 = \sum_i \sum_j \sum_k P \frac{P_i}{P} \frac{P_{ij}}{P_i} \frac{P_{ijk}}{P_{ij}} \frac{N_{ijk}}{P_{ijk}} \frac{E^4_{ijk}}{N_{ijk}}$$

$$= P \times R \times T \times C \times H \times I^4. \quad (4)$$

4. Results

In figure 3 we show changes in final and primary energy and GHG emissions decomposed into their relevant drivers. After population growth, the two most important upward drivers are reductions in household size and increases in conditioned space. Reductions in end-use intensity and cohort

changes are the dominant sources of reductions in final energy. Reductions in end-use intensity reflect changes in energy or emissions per floor area/person/house (depending on the end-use), and may result from appliance and envelope efficiency improvements, or behavioral change. Cohort effects are due to changes in the distribution of population between housing of different age cohorts, and reflect lower energy consumption in newer houses.

The dominant drivers of primary energy and GHG emissions reductions are improvements in the efficiency of electricity generation, and reductions in the GHG intensity of electricity generation, respectively. Compared to these supply side effects, demand side reductions from cohort changes and changes in end-use intensity are relatively minor. Additional smaller reductions in final energy are driven by changes in population distribution between house types and census divisions. Direct reductions from fuel switching are non-existent for primary energy, and small for GHG, despite substantial final energy reductions from fuel switching. This is likely due to electricity being more (primary energy and GHG) intensive than fossil alternatives at the time of switching (see SI figures S24 and S25).

To demonstrate how drivers differ between end-uses and over subperiods, in figure 4 we decompose changes in GHG emissions by end-use for 1990–2001 and 2001–2015. Reductions in household size drove substantial increases in GHG from other end-uses, space heating, and cooling. Increases in conditioned space was a prominent upward driver for both space heating and cooling, especially before 2001. Cohort changes are a prominent and consistent driver of energy and GHG reductions from space heating, suggesting that newer houses require much less energy to heat. Cohort changes interestingly do not drive GHG reductions for any of the other end-uses. Reductions in electricity GHG intensity are the second biggest driver of reductions in space heating GHG over the full period, and the dominant source of GHG reductions for all other end-uses. This effect is most impressive for other end-uses (incorporating lighting, refrigeration, appliances and cooking, etc., SI figure S6), and has clearly been concentrated in the latter years of the study, with almost no effect before 2001.

Fuel switching for space and water heating differed by region, with displacement of fuel oily by natural gas in North-Eastern divisions (New England and Mid Atlantic), and displacement of natural gas by electricity in southern divisions (East and West South Central, South Atlantic). These fuel switches have on the whole reduced GHG emissions from space heating, but increased GHG emissions from water heating. The region effect shows that higher population growth in warmer regions reduced GHG from space heating, but increased GHG from space cooling. Changes in the population distribution among housing types have been too small to cause large changes

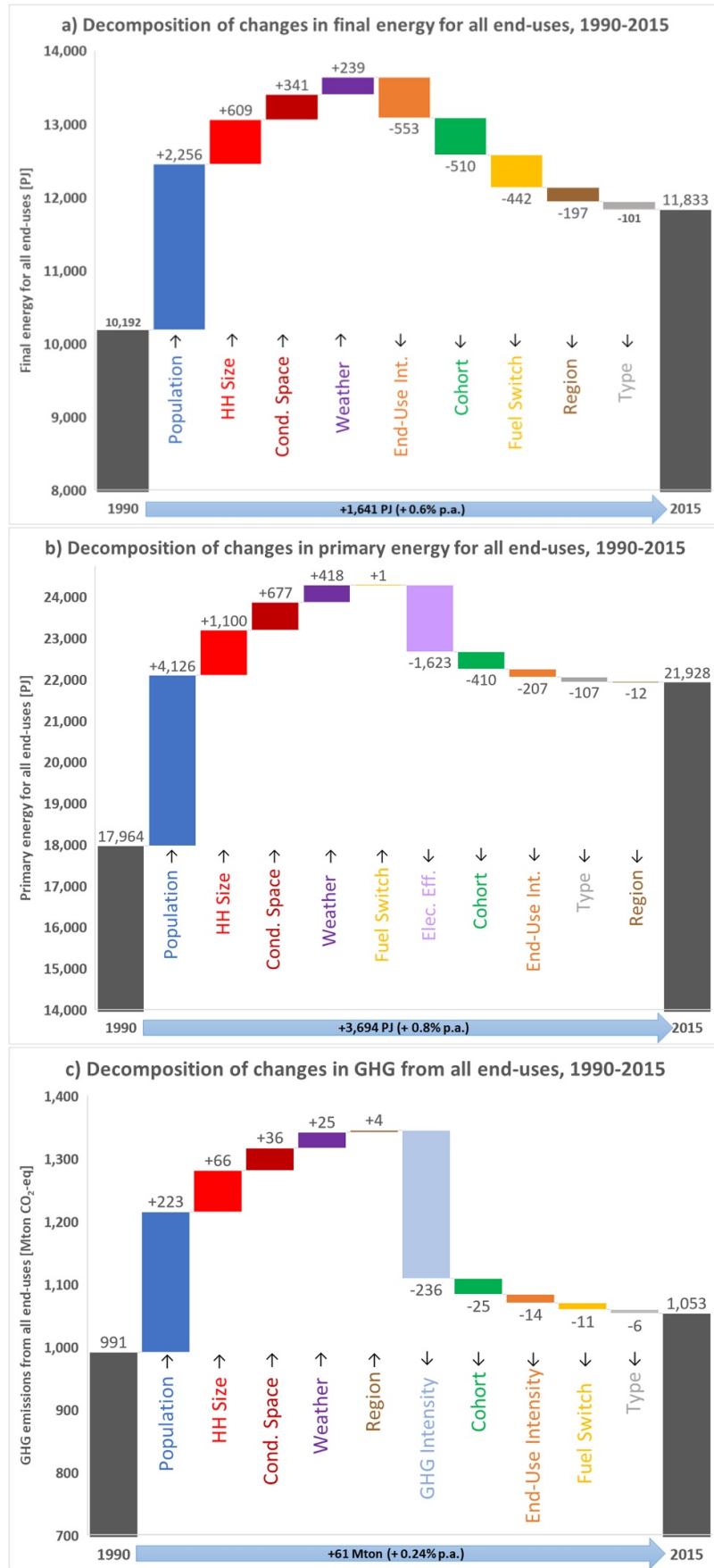


Figure 3. Decomposition of changes in (a) residential final energy, (b) primary energy, and (c) GHG emissions, 1990–2015. ‘Elec Eff.’ refers to the electricity efficiency effect based on changes in the primary energy index X_E .

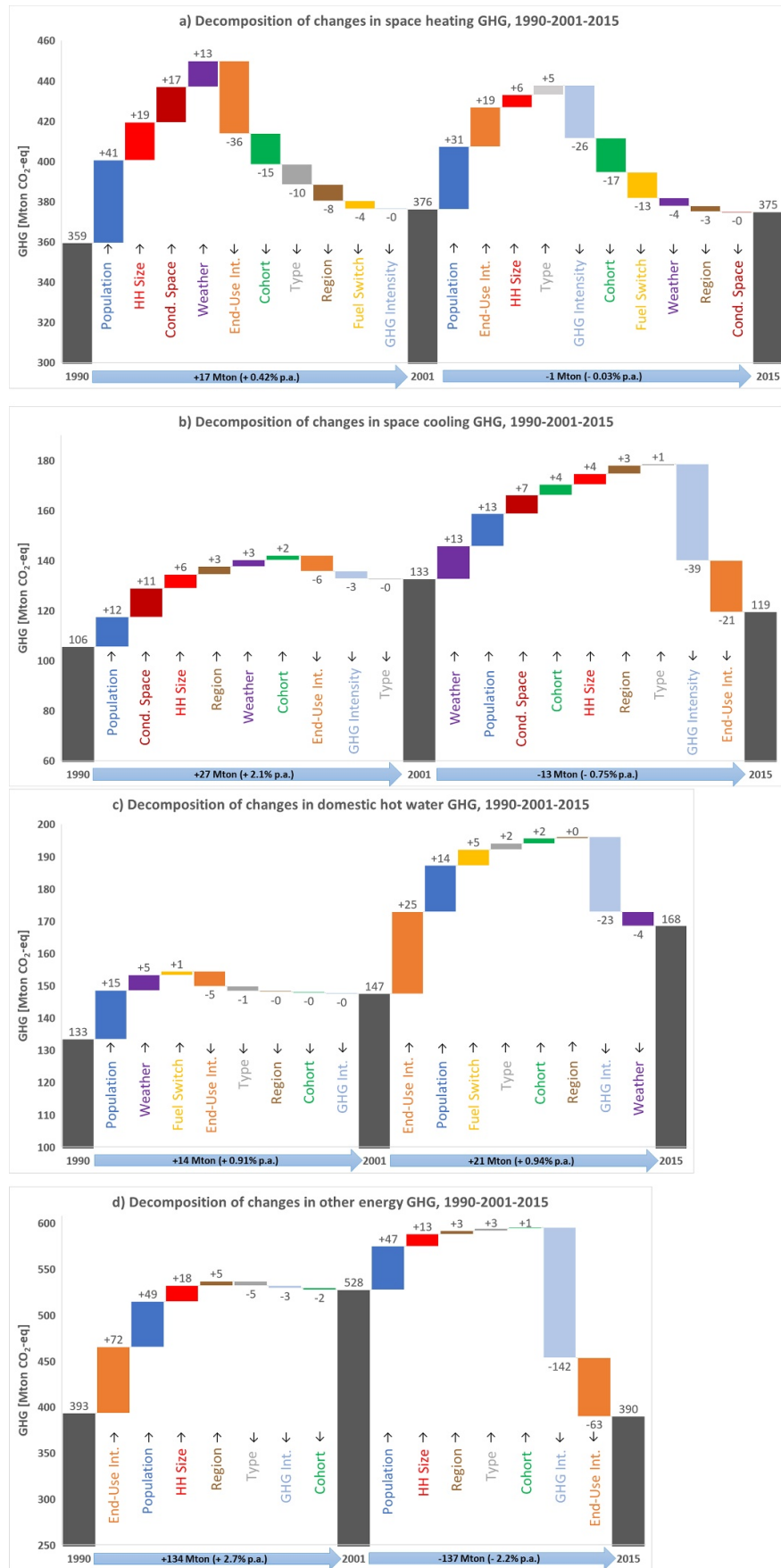


Figure 4. Decomposition of changes in residential GHG emissions 1990–2001–2015 from (a) space heating, (b) space cooling, (c) domestic hot water, and (d) other end uses.

in energy or GHG emissions. Due to a change in the allocation of electricity to different end-uses in RECS surveys between 2009 and 2015 (EIA 2018), 1990–2015 growth in energy/emissions from space and water heating are likely overestimated, and growth in energy/emissions from other end-uses underestimated. This should not influence the relative importance of drivers (further discussion in SI section S2).

5. Discussion

Our results confirm our hypotheses regarding the effects of reductions in household size, growth in conditioned floor area, and reductions in GHG intensity of electricity, while providing a mixed assessment of residential fuel switching. All else equal, changes in GHG intensity of electricity would have reduced annual GHG emissions by 24% of the 1990 level, 9–40 times more than any of the demand side measures investigated. We quantify for the first time changes in US residential energy and GHG emissions due to reductions in household size. The changes attributed to household size reductions equal 37% of the total increase in final energy, 28% of the total increase in primary energy, and 108% of the total increase in GHG. Our findings on the relationship between household size and residential energy and emissions concur with findings based on statistical modeling approaches (Fremstad *et al* 2018, Ivanova and Büchs 2020) and IDA studies which define population as the activity (Xu and Ang 2014, Balezentis 2020), but conflict with IDA studies which define housing as the activity variable (Zang *et al* 2017, Shigetomi *et al* 2018). Reductions in household size and increases in floorspace per house can explain the trends of growth in residential floor area per capita, recognized as a critical driver of increases in residential energy and GHG emissions (Ellsworth-Krebs 2019, Hertwich *et al* 2020). Growth in heated floor area per house in single-family and manufactured homes (figure S15), and growth in the percentage of households owning space cooling equipment have driven growth in energy and emissions from space heating and space cooling, respectively. The average size of new single-family homes may have peaked in 2015 (figure S23), but it is too early to say whether this reversal of the historic trend will be temporary or longer lasting. Increases in the percentage of houses using cooling equipment were stronger in the earlier years of our study period, and as access to cooling approaches saturation in most regions, this is expected to be a less important driver of increased energy and emissions in the future. However, larger houses, an increase in the percent of household floorspace that is cooled, and warmer weather could still drive future increases in cooling demand.

The effects of fuel switching were zero for primary energy and minor for GHG emissions. Considering

the effects of fuel switching on space heating emissions by region, switching to electricity resistance heating will in most cases create a short-term increase in emissions (until electricity decarbonizes further) while switching to electric heat pumps is much more likely to produce an immediate reduction in GHG emissions (see figures S24 and S25). Even if it results in a short-term increase in emissions, fuel switching to electricity increases the amount of energy which can be decarbonized in subsequent years through electricity decarbonization. The GHG benefits of ‘electrifying everything’ have therefore been minor up to 2015, but larger future reductions can be expected given the increased rate of electricity decarbonization, and increased market share of heat pumps. Prioritizing the adoption of heat pump water heaters can also be of great help in providing more immediate and cost effective GHG reductions through electrification (Langevin *et al* 2019). Most gas storage water heaters (which make up almost half of water heater sales) have a final-to-useful efficiency range of just 58%–66%, while instantaneous (tankless) gas water heaters achieve efficiencies of over 82%, electric resistance water heaters over 90%, and heat pump water heaters over 200% (EIA 2017).

Comparing emissions by end-use, ‘other’ energy end-uses make up the largest contribution to overall residential GHG emissions. This is important to remember when modeling and comparing strategies for reducing residential energy and emissions. Due to high electrification levels, future GHG from other end-uses will continue to decline in line with GHG intensity of electricity, but this decline may be outweighed by population/household growth, and growth in intensity of use. Newer appliances have become more efficient over time (EIA 2017), but newer homes also tend to have more and larger appliances that are used more often, which can outweigh the efficiency gains (SI tables S1 and S2). The multifunctionality of newer electronic devices has potential to reduce both total number of appliances and energy consumption by product communities, but this effect is not yet evident for personal electronics (Ryen *et al* 2014, 2015).

6. Implications for future residential energy use and emissions

In the introduction we note that there are multiple points along energy supply chains to reduce primary energy and/or GHG emissions. It is clear from figure 2 that efficiency gains and decarbonization of electricity supply have been the dominant factors limiting growth of residential primary energy and GHG emissions in the United States. While we may expect this to continue, limitations to the rate of further reductions in GHG intensity of electricity should be considered. Deep decarbonization of electricity in

the United States is not part of existing mid-range projections. EIA's Annual Energy Outlook baseline scenario projects that the combined share of US electricity generated by coal and gas will decrease from 61% in 2019 to 50% in 2050, with the national average carbon intensity of electricity decreasing from 0.39 to 0.25 kg CO₂ kWh⁻¹ (EIA 2020a). The Mid-Case scenario from NREL's 'standard scenarios' outlook is more optimistic, forecasting coal and gas to fall to 33% of total generation, and carbon intensity to become 0.18 kg CO₂ kWh⁻¹ by 2050 (Cole *et al* 2019). These developments are in the right direction, but insufficient and inconsistent with climate stabilization goals requiring halving of emissions between 2020 and 2030, and net-zero emissions by 2050 (Otto *et al* 2020). To meet more ambitious targets for emissions reductions, the US residential sector cannot rely so heavily on supply side electricity decarbonization; demand side solutions will need to play a larger role, through reducing residential final energy demand.

There is a large technical and economic potential for energy demand reduction through technology upgrading, with building envelope improvements and increases in electric heat pumps in particular having a large potential to reduce final energy demand for space and water heating (Wilson *et al* 2017, Langevin *et al* 2019). Substantial further reductions in final energy demand would result from decreasing the size of new housing, higher rates of stock turnover enabling more new housing, and increases in the portion of population living in multifamily house types (Berrill *et al* 2021). All of these changes could be encouraged by relaxing or removing the many regulatory deterrents to multifamily, smaller, and new housing which exist at federal (Schwartz 2015) and local (Gray and Furth 2019, Gyourko *et al* 2019) levels, allowing markets to respond to increased demand for house types consistent with smaller households. Household size will likely continue to decline for at least the next two decades (McCue 2018), causing household growth to outpace population growth. Increases in appliance efficiency can support demand side emission reductions from other energy use, but efficiency improvements are limited by the rate of appliance stock turnover (Ryen *et al* 2015), and could be counterbalanced by household growth, and greater overall appliance ownership and use. Behavioral change can contribute to reducing future energy demand, but is difficult to influence through policy (excepting incentives for efficient technology adoption) and may have to come about through greater cultural diffusion of efficiency and sufficiency attitudes towards energy use and conservation (Marghetis *et al* 2019, Wolske *et al* 2020).

Electrification of end-uses and decarbonization of electricity will help to reduce US residential sector GHG emissions, but to meet climate targets such as 1.5 °C of warming, greater energy demand reductions are needed. In existing houses, envelope retrofits and

increased uptake of efficient equipment and appliances will be required. For future changes to the housing stock, policies which remove regulatory barriers to new construction and especially multifamily housing could encourage faster replacement of older housing stock with more efficient housing typologies (Berrill *et al* 2021). Combining the potential of demand-side reductions with electrification and rapid decarbonization would bring more ambitious climate targets within reach.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://doi.org/10.5281/zenodo.4499100>.

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