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Linking Housing Policy, Housing Typology, and Residential Energy Demand in the United States

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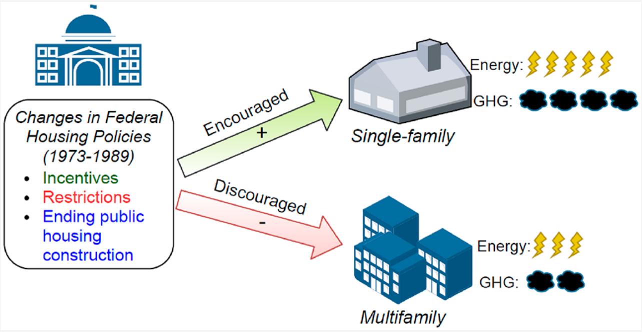
ABSTRACT: Residential energy demand can be greatly influenced by the types of housing structures that households live in, but few studies have assessed changes in the composition of housing stocks as a strategy for reducing residential energy demand or greenhouse gas (GHG) emissions. In this paper we examine the effects of three sequenced federal policies on the share of new housing construction by type in the U.S., and estimate the cumulative influence of those policies on the composition of the 2015 housing stock. In a counterfactual 2015 housing stock without the policy effects, 14 million housing units exist as multifamily rather than single-family, equal to 14.1% of urban housing. Accompanied by floor area reductions of 0−50%, the switch from single- to multifamily housing reduces energy demand by 27−47% per household, and total urban residential energy by 4.6−8.3%. This paper is the first to link federal policies to housing outcomes by type and estimate associated effects on residential energy and GHG emissions. Removing policy barriers and disincentives to multifamily housing can unlock a large potential for reducing residential energy demand and GHG emissions in the coming decades.



INTRODUCTION

Background. Energy efficiency is frequently recommended as a strategy for reducing primary energy demand and greenhouse gas (GHG) emissions, reducing the need for negative emissions technologies to achieve climate change mitigation targets.[1] Buildings in particular have been identified as a demand sector with high potential for energy efficiency,[2] a potential which is often underexploited.[3] Although structural characteristics such as building type (i.e., detached, attached, multiunit, etc.) are acknowledged to be important determinants of energy demand in residential buildings,[4,5] a change in the relative abundance of less energy intensive structural typologies in housing stocks is rarely considered as an energy efficiency or GHG mitigation strategy. Previous studies have evaluated a wide range of social benefits and costs of various housing policies, but there are exceedingly few assessments of the potential for housing policy to reduce residential energy or GHG emissions.

This study provides a novel perspective on the possibilities for energy and GHG reductions in the residential sector. Specifically, we measure the influence of three federal policies from the 1970s and 1980s on the single-family and multifamily share of new housing construction, estimate the cumulative effect of those policies on the type composition of urban housing stocks in 2015, and generate four scenarios of how this affected residential energy and emissions.

Policy Influence on Housing and Residential Energy. There is a broad literature assessing the influence of local housing and land-use restrictions on housing markets, estimating impacts on worker mobility and productivity, urban sprawl and segregation, and housing supply and affordability.[6−12] Some studies assessed the effects of local restrictions (including single-family/low-density zoning or minimum lot-size restrictions) on housing outcomes by type, finding that they disproportionally suppress multifamily construction,[13,14] and limit supply of multifamily and small-lot single family housing below what unrestricted housing markets would produce.[15−17] Local land-use restrictions can change over time and vary enormously across jurisdictions. In aggregate terms they appear relatively stable in recent years; two independent attempts at measuring the extent of such restrictions found that overall local regulatory intensity has not changed considerably since the 1990s.[18−20] Studies assessing federal policy impacts on housing and related outcomes are less common,[21,22] but because federal policies apply equally throughout the U.S. and change less frequently, their effects on national housing outcomes can be readily investigated.

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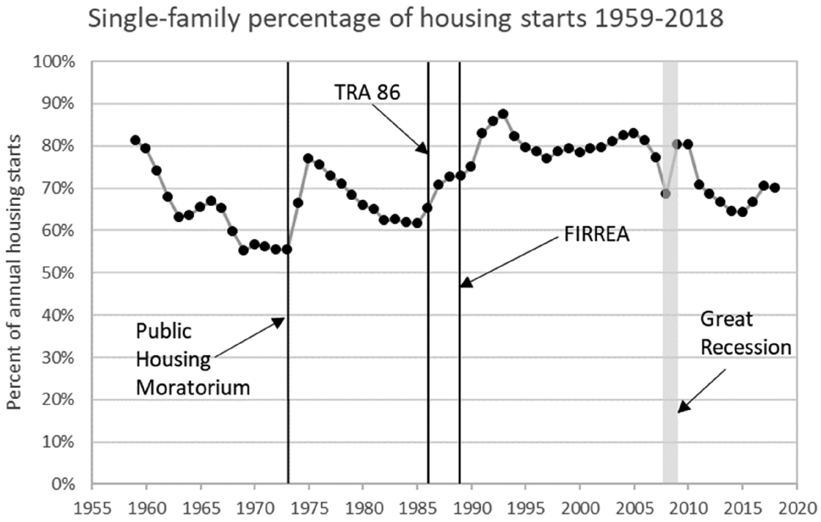

Figure 1. Annual single-family housing starts as a percentage of total starts, 1959−2018. Total starts refer to single-plus multifamily starts. Trend punctuated by major federal policies and the Great Recession. TRA 86 = Tax Reform Act 1986, FIRREA = Financial Institutions Reform Recovery and Enforcement Act. Data from USCB[32]

Federal housing policies in the U.S. provide high levels of support for homeowners, and less support for renters.[23,24] This translates into greater support for single-family households, as most homeowners live in single-family homes and most renters live in multifamily homes.[25] The high fraction of homes that are single-family detached may help in understanding why U.S. residential energy use per capita (Figure S1) and floor space per capita is high by international standards.[26] Compared to the 62% of U.S. housing that is single-family detached,[27] Japanese housing is 55% single-family detached,[28] while EU27, German, and UK housing is 34%, 29%, and 25% single-family detached, respectively.[29]

If policy can influence housing outcomes by type, then there may be an indirect effect on residential energy consumption and GHG emissions, to the extent that housing typology influences energy demand. Analyses of household energy consumption in the U.S. consistently find that single-family detached houses consume more energy, after controlling for other variables including house size, climate, and income.[5,30] Estiri reports a large *indirect* effect of household size and income on residential energy, due to an increased propensity for households to choose larger and single-family detached housing as household size and income increase.[4] Ewing and Rong find more multifamily housing and lower household energy consumption in higher-density counties.[5] A scenario analysis by Goldstein and colleagues estimates that increased population density and a reduced share of single-family homes, on top of other energy saving and decarbonization measures, would be required for the U.S. residential sector to meet its 2050 Paris Agreement target.[31]

Federal Policies Affecting Housing Markets. Figure 1 charts the historical single-family share of annual total (single-family plus multifamily) housing starts from 1959 to 2018.[32] Three major federal policy events punctuate the figure, the Public Housing Moratorium (PHM) in 1973, the Tax Reform Act of 1986 (TRA 86), and the Financial Institutions Reform Recovery and Enforcement Act (FIRREA) in 1989. The PHM halted funding for all new public housing projects, excluding those devoted to elderly residency.[33] Public housing had been an important contributor to new housing construction in the U.S. since the Federal Housing Acts of 1949 and 1954. These Housing Acts also had other influences on housing stocks and markets, through large-scale demolition of buildings in city centers, and limiting access to mortgages in older and minority neighborhoods.[25] Although federal funding for low-income housing continued through rent vouchers and community development block grants,[25,34] after PHM the federal government would no longer directly build and own new public housing. TRA 86 curtailed the availability of depreciation losses to lower income taxes, eliminated accelerated depreciation allowances for multifamily housing, and lowered the highest tier tax rates, reducing the value of depreciation allowances.[25] Although the depreciation allowances had been made much more generous in the Economic Cost Recovery Tax Act of 1981, after TRA 86 depreciation terms became much less generous than what existed before 1981.[35] In summary, TRA 86 altered effective tax rates in a way that made multifamily homes less attractive investments than single-family homes. In 1989, FIRREA bailed out institutions affected by the savings and loans crisis, and imposed new restrictions on the types and terms of loans that could be made, making access to capital much more expensive for multifamily compared to single-family investments[21] (SI Note 1). Housing markets may also be influenced by transport policies and infrastructure. Federal Highway Acts in the 1920s and 1950s brought about the construction of highways connecting city centers to suburbs, which may have contributed to the population decline of city centers[36] where multifamily housing is more common.

In this article we estimate the effects of the sequential implementation of PHM, TRA 86, and FIRREA on new housing construction by type, and we illustrate the influence of house types and age cohort on energy end-uses in 2015, while controlling for other major determinants of residential energy demand. We create a counterfactual urban housing stock for 2015 by removing the effects of the federal policies and calculating the cumulative effect on the type composition of the housing stock. Our results suggest that policies affecting housing markets can support energy conservation and climate goals by removing disincentives and regulatory barriers to new and multifamily housing. This paper constitutes the first effort to link federal policies to residential energy demand and GHG

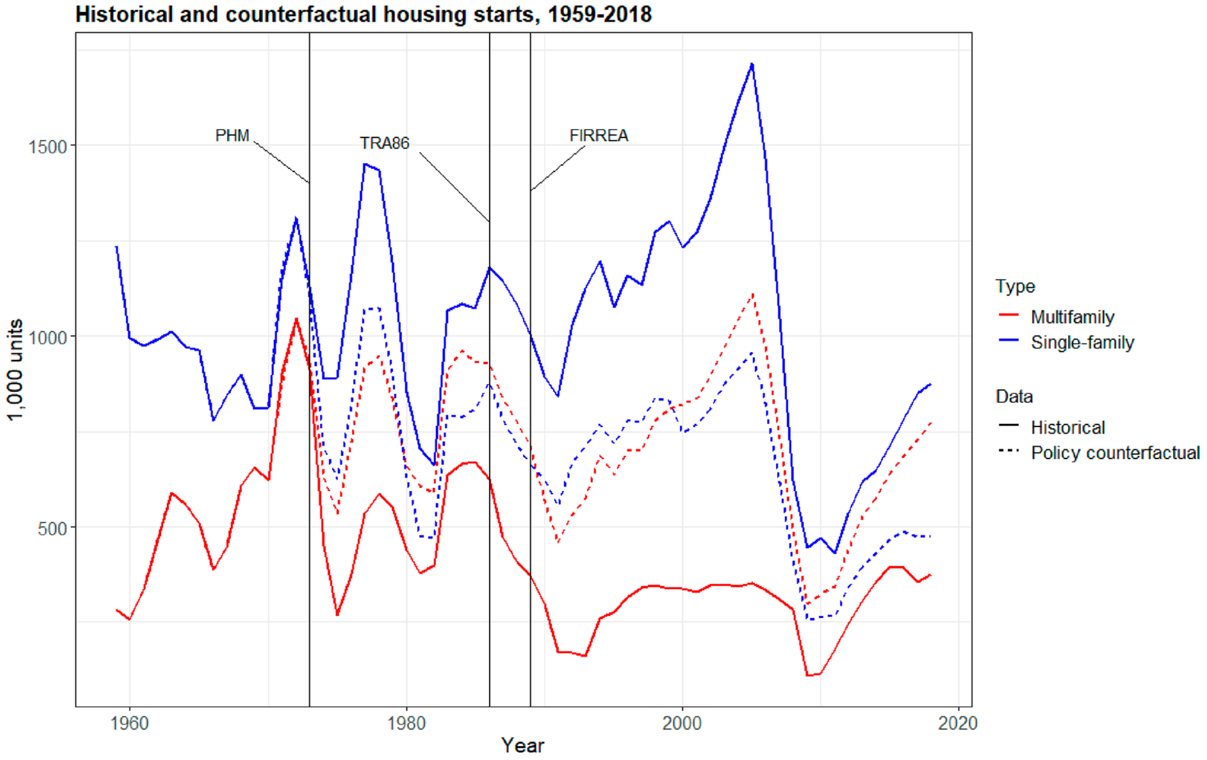

Figure 2. 1959−2018 historical single- and multifamily starts, and modeled starts without federal policies PHM, TRA 86, and FIRREA.

emissions, and to estimate aggregate effects of house typology on residential energy demand and emissions at a national scale.

■ METHODS AND DATA

Housing Starts Model. We develop a linear model of the single-family share of quarterly total housing starts (houses for which construction was started in each quarter) spanning 1971−2018. This model estimates the relationship between three federal policy changes, the PHM in 1973, TRA in 1986, and FIRREA in 1989, and the quarterly single-family share of housing starts, controlling for population growth, real GDP, 30-year mortgages rates, and seasonal effects. We use these results to estimate the share of housing starts by type in the absence of PHM, TRA86, and FIRREA. As existing local regulation and housing starts data do not support a time-series analysis of effects of local housing or land use policies on housing starts, local regulations on housing construction are not considered. Urban highway mileage and vehicle ownership per capita were considered as additional controls, but omitted from the final model (for further discussion on model development, see SI Note 2). Equation 1 summarizes the model, with macroeconomic and demographic covariate coefficients denoted as β, federal policy dummy variable coefficients denoted as γ, and ν_q denoting quarter-of-the-year fixed effects to capture seasonality. An observation t in this analysis is a quarter.

$$\begin{aligned}\mathrm{SF{\cdot}share}_t = {}& \beta_1\mathrm{population{\cdot}change}_t + \beta_2\mathrm{real{\cdot}GDP}_t \\ & + \beta_3\mathrm{30yr{\cdot}mortgage}_t + \gamma_1\mathrm{public{\cdot}housing}_t \\ & + \gamma_2\mathrm{TRA86}_t + \gamma_3\mathrm{FIRREA}_t + \nu_q + \epsilon_t \end{aligned} \tag{1}$$

Thirty-year mortgage data are available starting in Q2 of 1971,[37] which defines the start date of our model. The PHM dummy is given the value of “0” until Q4 of 1973, and “1” from Q1 1974, as the public housing moratorium was announced in Q1 of 1973 and we assume that it took one year until new starts were affected by the moratorium, based on the likelihood that public housing starts in 1973 were funded by money committed before the moratorium was announced. TRA86, and FIRREA dummy variables are turned “on” in Q1 of 1987 and Q4 of 1989, respectively, one-quarter after they were signed into law. To the extent that the policy effects are independent of each other, our model estimates the independent effect of each policy. If the effectiveness of one policy is correlated with a previous policy, then our model estimates the effects of the second policy conditional on the first policy being implemented. The coefficient estimates for TRA86 and FIRREA should therefore be interpreted as the effects of those policies conditional on earlier policies being implemented. Historical population change data are calculated based on monthly total population estimates.[38] Data for single-family, multifamily, and total starts are taken from the USCB New Residential Construction publications.[32] Quarterly real GDP, is calculated by multiplying quarterly nominal GDP[39] by quarterly price indexes for GDP (indexed to 2012 USD).[40]

Development of Counterfactual Housing Stock. The difference between the counterfactual and actual starts of each housing type in each year was used to inform a counterfactual 2015 national housing stock by type and age cohort (Figure 2a, SI Figure S2). To reflect lower rates of completion of housing starts for multifamily than single-family, we adjusted the change in housing starts predicted by the housing starts model downward by 4.1%, the percentage difference in completion rates.[41] We assume that the counterfactual starts made no change to the number of houses demolished each year of each type (SI Note 3). The number of additional multifamily units (and corresponding reduction in single-family houses) adds up to a total alteration to the 2015 stock of 13.96 million homes.

We assume that type changes are restricted to urban areas, as this seems more realistic.

The housing starts data are distinguished as single-family and multifamily,[32] while the energy consumption data described below splits single-family into attached and detached, and multifamily into units in buildings with 2−4 units and 5+ units. We convert the single-family/multifamily starts data into alterations of the stock by keeping the same ratio of more detailed housing types within single-family and multifamily.

Modeling of Energy End-Uses. We specify a linear model of urban household energy end-use consumption in 2015, drawing on data from the 2015 Residential Energy Consumption Survey (RECS).[27] The four end-uses considered are space heating, space cooling, domestic hot water, and all other uses. Equation 2 summarizes the general formulation for end-use i:

$$\text{energy use}_i = X_i\beta + \varphi_i + \epsilon_i \tag{2}$$

Covariates included in X are household income (all end-uses), heating degree days (HDD, space heating and domestic hot water), household size (all end-uses), cooling degree days (CDD, space cooling only), heated floor area (space heating only), cooled floor area (space cooling only), and total floor area (domestic hot water and other end-uses). The φ parameter contains house type-cohort fixed effects. Fixed effects are defined with 23 levels, based on combinations of building type (four levels: single-family detached, single-family attached, multifamily low, and multifamily high), and construction age cohort (six levels: < 1950, 1950−69, 1970s, 1980s, 1990s, 2000+) with "multifamily high 2000+" homes serving as the reference level. Multifamily low refers to units in buildings with 2−4 units, and multifamily high refers to units in buildings with 5+ units. We adopt these terms for brevity, but note that much of multifamily high is not necessarily high-density or high-rise; 27% of multifamily high units are in buildings with 5−9 units, and a further 25% are in buildings with 10−19 units.[42] One possible concern with our specification of energy end-use models is selection of housing types based on preferences for certain characteristics. Households may choose to live in single-family homes due to preferences for larger space or other type-related characteristics. This could reduce the energy savings potential of a type switch if the characteristics of counterfactual multifamily homes (such as size) closely resembled single-family homes which they replaced.

To provide insight into how selection in housing type choice and housing characteristics could affect the results, we explored selection based on household income in one of our energy demand scenarios (CF1). Further, a range of changes in floor area associated with type switch are represented in the scenarios. In CF1, we model changes in energy end-use consumption separately for three income groups. Specifically, we specified a variant of our end-use model where income was removed from X and included in an expanded φ' parameter describing type-cohort fixed effects for low (annual income < \$40,000), mid (\$40,000 to \$100,000), and high (>\$100,000) income households. The fixed effects in this case are defined with 71 levels, based on combinations of four building type, six age cohorts, and three income groups. Further information about model development is found in SI Note 4.

Energy and GHG Emissions in Housing Stock Counterfactuals. We calculate four scenarios of urban residential energy demand in 2015, reflecting different assumptions of how selection effects influence which households may move to multifamily, and how the average floor area of affected multifamily units may change. As mentioned above, one way selection could play a role is if households of different incomes demand both different housing types and characteristics. In the first counterfactual (CF1) we represent the possibility of substantial selection by income: we assume that 65% and 35% of the households exchanging single-family for multifamily are low-income and mid-income, respectively. Energy demand is calculated by applying income-group-specific type-cohort effects φ' to the changes in housing stock by cohort and type. This representation of selection is motivated by empirical analysis[4] and RECS data (SI Figure S7, Table S9) suggesting a strong role for household income in determining house type and floor area. CF1 also incorporates floor area preferences of single-family households, by assuming that households that moving to multifamily consume the same floor area as they consumed in a single-family house.

In the second scenario (CF2) we do not specify the income groups of households who move; the energy demand reductions are instead based on type-cohort effects for *average* households φ, after controlling for income. We again assume that households moving to multifamily consume the same floor area as they consumed in a single-family house, and household income remains unchanged.

In counterfactuals CF3 and CF4, we model the effect of the type switch for average households as in CF2, but relax the assumption of constant floor area. Instead, we estimate that moving from single- to multifamily housing is accompanied by a floor area reduction of 30% (of average single-family floor area) in CF3, and 50% in CF4. In these scenarios, the appropriate floor area regression coefficient for each end use (Table 2) is multiplied by the floor area reduction and applied to the multifamily houses added in the stock counterfactual. A complete description of the scenario energy calculations is provided in SI Note 5.

To calculate GHG emissions associated with final energy demand for each end-use and house type, we use direct emissions factors for fuel combustion,[43] and calculate electricity GHG intensities based on electricity fuel mix and generation losses, aggregating state data[44] to Census Divisions (SI Table S7). Calculating GHG intensities by Division is a simplification, as electricity grid regions do not follow Division boundaries, and there is much trading of electricity between grid regions. However, RECS data do not indicate locations of households at greater resolution than Census Division, so we could not use GHG intensities for specific grid regions. End-use GHG intensities differ by house type due to different energy carrier shares (e.g., electricity delivers a higher share of space heating in multifamily homes), and differences between electricity GHG intensities between regions where single-family and multifamily homes are more prominent. To calculate reductions in GHG emissions associated with counterfactual housing stocks, we multiply the final energy reduction per end-use and house type by the corresponding end-use GHG intensity.

RESULTS

Housing Stock and Construction under Counterfactual Federal Policy. Our housing starts model estimates indicate that all of the federal policies considered are associated with increases in the single-family share of housing starts

(Table 1) after controlling for demographic and macroeconomic factors. While recognizing that the effects of subsequent policies may depend on earlier ones, the PHM has the largest policy effect, and is associated with increasing the single-family share of quarterly starts by 18 percentage points, while TRA86 and FIRREA are associated with increases of the single-family share by 5–6 percentage points. Higher mortgage rates correlate with lower single-family shares, suggesting a stronger incentive to purchase a home with lower interest rates. Higher population growth is associated with a greater share of single-family homes. Higher GDP is associated with lower shares of single-family housing, contradicting positive correlations between GDP per capita and floor space per capita.[45] While the identified GDP effect might be consistent with positive associations of GDP and urbanization,[46] and more multifamily housing in urban areas,[27] GDP is included simply as a control for macroeconomic activity in our model, and we do not interpret this coefficient as a causal effect (SI Note 3).

Figure 2 shows historical single- and multifamily housing starts, and predictions of housing starts in the absence of PHM, TRA86, and FIRREA. To generate our predictions, we assumed that housing starts would follow the trend estimated by the model without the effects of those policies. The counterfactual quarterly single-family shares were multiplied by quarterly starts for all housing. The model suggests that housing starts would have followed a trend of decreasing single-family share without the influence of the three policies considered (SI Figure S3), producing 13.96 million more multifamily units since 1974, exerting a sizable influence on the current makeup of U.S. housing.

Table 1. Coefficient Estimates from Linear Regression Models of Single-Family Share (%) of Total Housing Starts Newey-West Robust Standard Errors Are Shown in Parentheses

	percent single-family	
PHM	18.06^{d}	(2.36)
TRA 86	5.84^{d}	(1.19)
FIRREA	5.18^{a}	(2.96)
Δpopulation	0.022^{b}	(0.009)
real GDP	−0.006^{d}	(0.002)
30 yr mortgage rate	−1.11^{d}	(0.27)
seasonal fixed effects	Y	
observations	191	
R^2	0.737	

$^{a}p < 0.10$. $^{b}p < 0.05$, $^{c}p < 0.01$. $^{d}p < 0.001$.

Housing Type and Cohort Influence on Residential Energy End-Uses. Results of our household energy end-use models are shown in Table 2. Space heating is strongly correlated with heating degree days (HDD), heated floor area, and income. Higher space cooling use is associated with higher cooling degree days (CDD), cooled floor area, and income, but effects are weaker than for space heating. Unlike space heating, the coefficient for household size is significant and positive, although small. Domestic hot water demand is strongly correlated with household size; significant coefficients also exist for income, climate, and house size, but are of smaller magnitude. Other energy end-uses are correlated with household size, income and house size, with income having stronger effects on "other" end-uses than on any other end-use.

Dependent variables are annual final energy consumption for the four energy end-uses. Coefficients reflect the modeled effects of each variable on each energy end-use, measured in MJ. Income is measured in thousand 2015 USD, household size in number of householders, HDD and CDD in °F-day, and floor area in square-foot. HH = household, HDD = heating degree day. CDD = cooling degree day. FE = fixed effects. Type-Cohort FE are show in SI Table S2 and displayed in Figure 3.

The fixed effect coefficients for the house type and age-cohort combinations are shown in Figure 3. These coefficients clearly demonstrate that single-family houses use far more energy for space heating. This is especially the case for older single-family homes. Within each cohort, single-family detached houses require 13–39 GJ more space heating annually than multifamily high units. Energy for space cooling follows the same pattern, higher in single-family and older houses, but the magnitude is much smaller, with single family homes requiring 3–4 GJ more space cooling within each cohort.

Single-family houses also use more energy for hot water, but the differences are relatively small, and there is no clear age-cohort trend, reinforcing the importance of household size above other characteristics in determining demand for hot water. Single-family detached homes use 5–10 GJ more energy for other end-uses, compared to multifamily high homes of the same cohort. The cohort effect is reversed in this case for single-family detached homes; greater energy use for other end-uses in *newer* homes is likely due to trends in appliance use and ownership. Newer single-family detached homes tend to

Table 2. Coefficient Estimates from Linear Regression Models of Energy End-Uses in Urban Homes in 2015 (MJ)

	space heating		space cooling		water heating		other	
HH income	51.25^{c}	(9.57)	5.46^{b}	(2.10)	13.48^{c}	(2.60)	56.37^{c}	(5.78)
HH size	−518	(281)	152^{a}	(61)	4,265^{c}	(76)	1,980^{c}	(170)
HDD	7.66^{c}	(0.19)			0.90^{c}	(0.05)		
CDD			4.21^{c}	(0.07)				
heated area	10.01^{c}	(0.43)						
cooled area			2.12^{c}	(0.08)				
total area					0.21	(0.11)	3.61^{c}	(0.24)
type-cohort FE	Y		Y		Y		Y	
observations	4,393		4,393		4,393		4,393	
R^2	0.549		0.570		0.496		0.284	

$^{a}p < 0.05$, $^{b}p < 0.01$. $^{c}p < 0.001$.

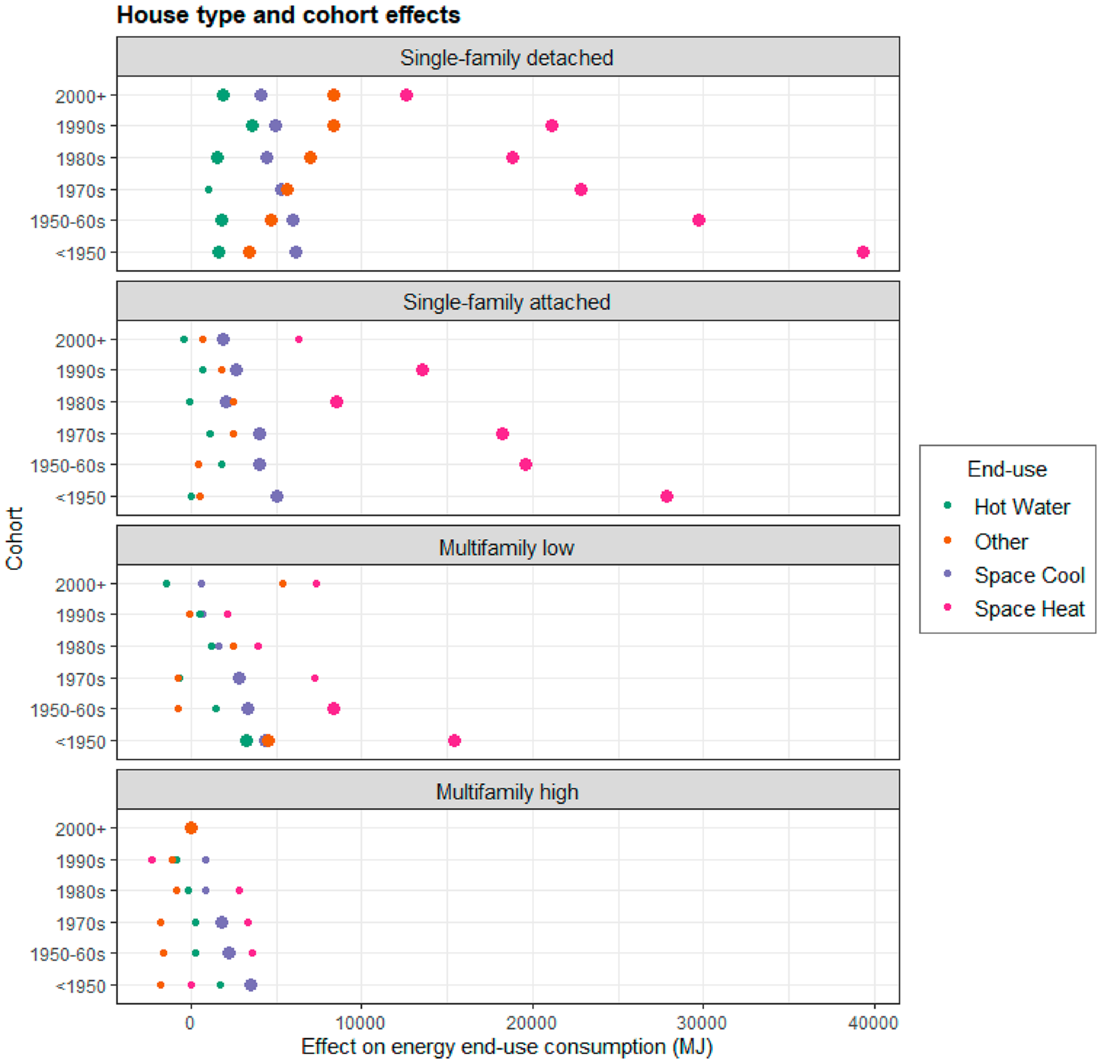

Figure 3. Effects of house type and cohort on urban residential energy end-uses in 2015. Effects are coefficient offsets by type-cohort to the reference of Multifamily high-density homes built 2000+, and are estimated by the linear models summarized in Table 2. Heavier markers are used for effects which are significant at $p < 0.05$

have more TVs, refrigerators, lights, and appliances, particularly homes built in 1990s and 2000s (SI Tables S3 and S4).

In summary, single-family detached houses use more energy than multifamily homes for all end-uses, but especially space heating. Newer single-family detached homes are characterized by greater appliance ownership and greater other energy use, while for heating and to a lesser extent cooling, older homes require considerably more energy. Increasing floor area correlates with increased energy consumption for all end-uses, most notably space heating. Increases in income also correlate with higher energy use, especially for other end-uses and space heating.

Residential Energy Demand in Counterfactual Housing Stocks. We now demonstrate scenarios of reductions in residential energy use under a housing stock counterfactual resulting from removing the cumulative effects of three federal policies, PHM TRA 86, and FIRREA from new housing construction. Figure 4(a) shows the actual and counterfactual post-1970 urban housing stock by type in 2015. In the counterfactual stock, 13.96 million houses (14.1%) are multifamily rather than single family. Figure 4(b) shows four scenarios of energy consumption in the counterfactual stock, compared to actual consumption. The increase in multifamily housing reduces total urban residential energy by 356 PJ (4.6%) in CF1, 385 PJ (5.0%) in CF2, 514 PJ (7.0%) in CF3, and 645 PJ (8.3%) in CF4. Results per-household in Figure 5 show the lower and upper bounds of the percentage energy reduction from our scenarios for the average single-family household. Assuming no floor area reduction, energy is reduced by over one-quarter (27% in CF1, 28% in CF2), with the more substantial selection effect by income (CF1) having a minimal effect on energy reductions. Including floor area reductions of 30% and 50% brings the percentage energy reductions to 40% (CF3) and 47% (CF4) per household, respectively. Over half of the reductions are from space heating in every scenario. We compare the range of reductions from our scenarios with modeled energy savings from individual and combined energy efficiency measures in U.S. single-family detached housing,[47] and find reductions from the type switch to be considerably larger.

GHG emission reductions in each scenario by energy end-use are shown in SI Figure S4, and range from 1.9 tons $CO_{2\text{-eq}}$ (21.5%) reduction per affected house in CF1, to 3.8 tons $CO_{2\text{-eq}}$ (44%) in CF4. Due to the higher GHG intensity per

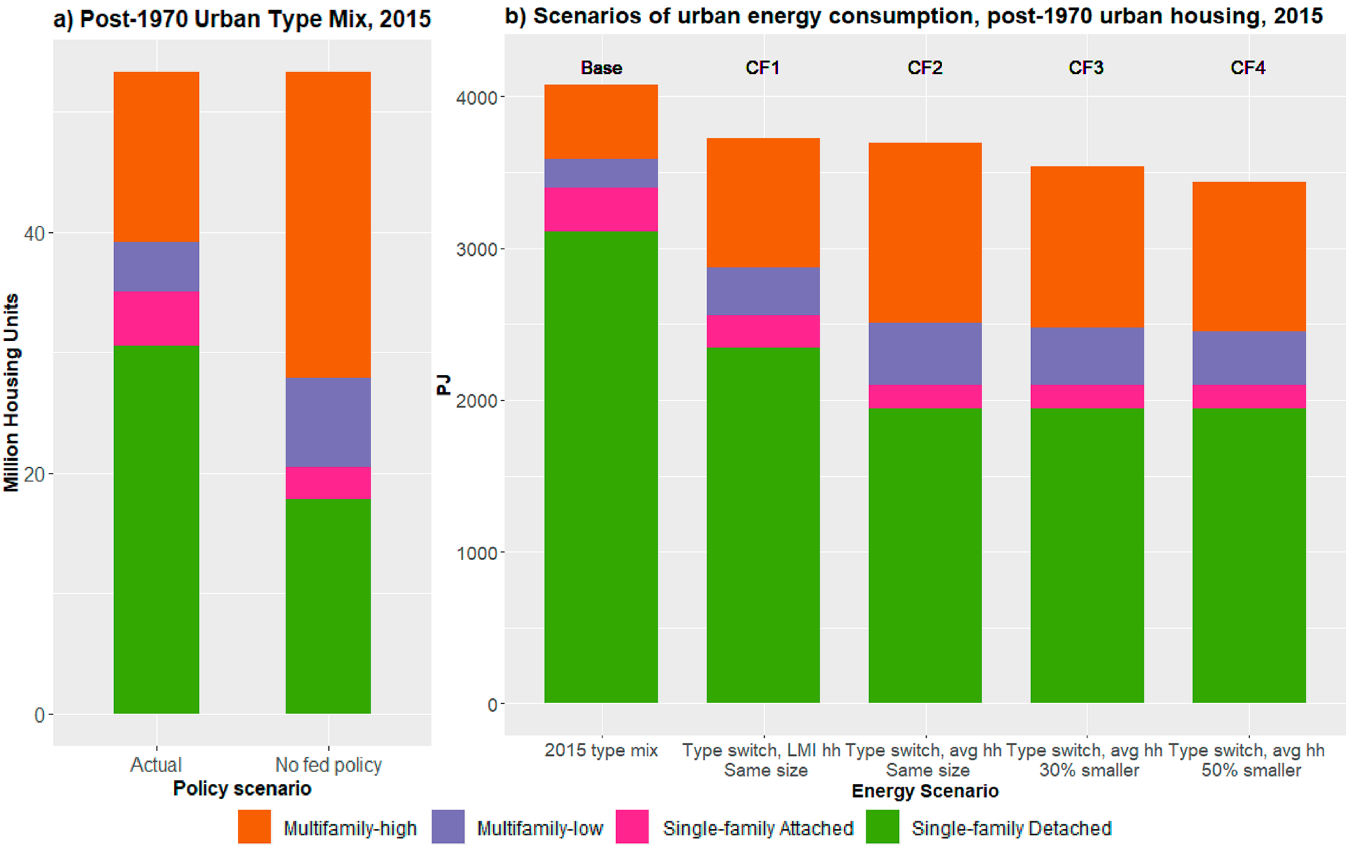

Figure 4. Counterfactual urban housing stock and energy consumption, 2015. (a) Actual and counterfactual 2015 urban housing by type. (b) Actual and counterfactual urban energy consumption in 2015 by type. CF1 assumes only low and midincome (LMI) households switch from single-family to multifamily. CF 2 assumes average households switch from single-family to multifamily, after controlling for income. CF1 and CF2 assume households switching to multifamily have no change in floor area. CF3 and CF4 assume floor area in counterfactual multifamily homes is reduced to 70%/50% of average single-family floor area. Cohorts before 1970 and manufactured homes are unaffected by the counterfactual, and omitted from the figure.

unit final energy, “other end-uses” figure more prominently in the GHG savings, with comparable reductions to those from space heating. Although the effects of typology changes take time to accrue, there is clearly substantial potential for energy and GHG reductions from a policy environment which encourages more multifamily housing.

■ SUMMARY AND DISCUSSION

Single-family homeownership is often described as part of the American Dream,[29] and this is reflected in policies at federal and local level that disproportionally assist home-owning single-family households. This policy preference is at odds with climate mitigation. Changing housing policy to be more encouraging of multifamily housing could support reaching GHG reduction targets, such as those set by the Paris Agreement. Our analysis finds substantially lower energy consumption in newer homes and multifamily homes. Lower energy consumption in newer homes is likely due to improved building standards and residential building energy codes, which were introduced in the 1980s and have steadily become more stringent over time.[48] Older homes tend to have higher air leakage,[49] and are more likely to have vented attics, less insulation, and less energy efficient windows.[47,50] Suspected mechanisms for lower energy requirements in multifamily homes include structural characteristics including less externally exposed area,[51] higher urban heat island effects,[5] and higher thermal mass. Multifamily homes are also more likely to have newer space and water heating equipment (SI Figure S8), and are far more likely to use electric-based heating (SI Figure S10), which is more efficient (in final to useful energy conversion) than natural gas heating[52] which is more common in single-family.

Moving beyond a comparison of physical characteristics and energy consumption of housing types as they currently exist, it is helpful to consider how housing markets, housing characteristics, and the share of housing types might evolve in a policy environment that was less focused on supporting home-ownership of mostly single-family homes. Based on current correlations of household income, house type choice, and floor area demand, it is likely that an increase in the share of multifamily households would increase the average income and floor area consumption of multifamily households. Energy efficiency adoption may also be affected by a higher share of multifamily homes, but the overall impact is unclear. Among home-owners, single-family and high-income households are more likely to invest in energy efficiency,[42] but this group of households also has the highest energy consumption (SI Note 7). Potential changes in the average floor area of multifamily will be more likely to determine the overall energy savings.

Concrete steps that can be taken at the federal level to support multifamily housing include equalizing federal taxes and subsidies for owned and rental housing, and equalizing access to finance for multifamily and single-family investors (SI Note 8). In addition to reducing the large difference in federal

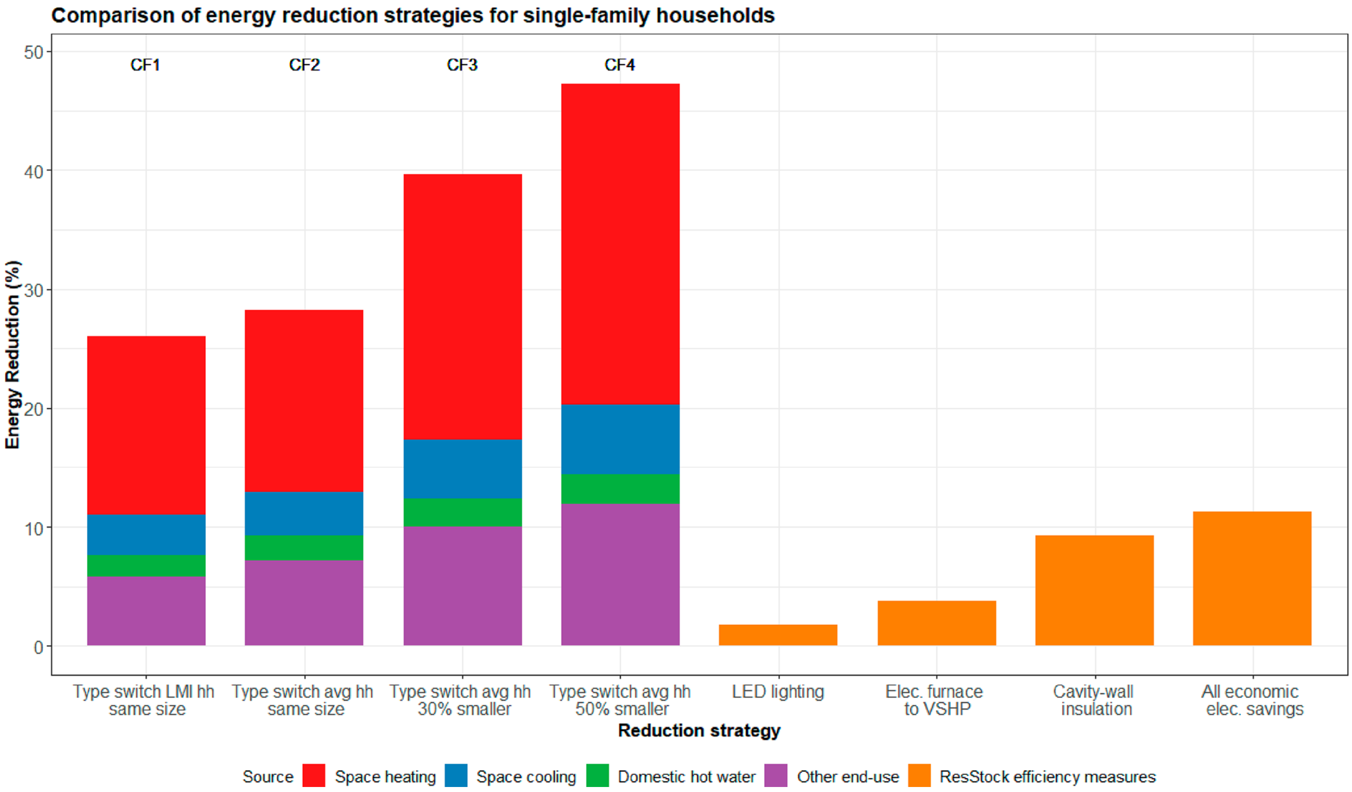

Figure 5. Comparison of residential energy reductions per household in average post-1970 single-family housing. CF1 shows reductions for low-mid income households, CF2−CF4 for average households controlling for income effects. CF1, CF2 assume no change in floor area when exchanging single-family for multifamily, CF3 and CF4 add floor area reductions of 35% amd 50%. Scenarios are compared with efficiency strategies in U.S. single-family detached homes modeled by Wilson et al.,[47] VSHP = variable speed heat pump, “economic elec. saving” refers to implementing all electricity efficiency upgrades with positive NPV. Basis for % reductions is average single-family home affected by the housing stock scenario.

subsidies for homeowners and renters, increased support for rental housing could help reduce the number of very low income households who need, but do not receive, rental housing assistance.[24] Many scholars question the benefits of home-ownership policy targets,[22,54] and alternative approaches exist. For example, Germany has less emphasis on home-ownership, rental contracts which allow for indefinite leases, and greater scope for recourse against unsatisfactory landlords, resulting in a higher fraction of multifamily housing and renter households, and long average leases.[55] Barriers to multifamily housing also exist at the local level, where multifamily properties are often subject to higher effective property taxes,[56] and numerous land-use regulations restrict supply of multifamily housing.[13−16] In addition to allowing increased supply of multifamily construction, relaxing local land-use regulations would also increase the rate of new housing construction generally,[6,7] which would aid in replacing or renewing the houses with highest potential for energy reduction—older single-family houses. Greater support for multifamily housing could complement approaches to pricing carbon, as carbon prices which raised gasoline prices would likely incentivize denser urban development.[57]

Our estimates of energy and GHG savings are based on a major alteration to the share of housing types in the 2015 urban housing stock. Other housing and demographic trends will have important influences on residential energy demand in coming decades. Growth in average floor area and reductions in household size have been important upward drivers of per capita residential energy demand since 1990.[53] Climate change, stronger population growth in warmer areas, and increasing adoption of air-conditioning (AC) have also increased demand for cooling. AC ownership is currently similar for housing types in the warmest regions, and slightly higher in single-family housing in cooler regions (SI Figure S11). Due to saturating AC ownership, current trends suggest the biggest societal driver of future cooling will be increases in cooled floor area per house, which would be smaller with greater shares of multifamily housing. The evolution of housing stocks by housing type and other characteristics (most notably age and size) will be of great relevance to future residential energy demand and GHG emissions in the U.S., and is a promising area for future work.

In this paper we provide evidence suggesting that U.S. federal housing policy changes have encouraged construction of single-family housing and suppressed multifamily housing, increasing residential energy demand and GHG emissions. Increasing the multifamily share of housing can be expected to produce energy large savings, even with no change of household income or floor area. Policies that suppress demand and restrict supply of multifamily housing thereby directly obstruct a large potential for residential GHG emission reductions. Housing policy can support climate policy by removing barriers and disincentives to multifamily housing.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c05696.

Supporting notes with additional details on methods and discussion points in the main text, supporting figures, and supporting tables (PDF)

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Notes

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