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Working Paper

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Abstract

We estimate residential energy use and CO_2 emissions for single-family homes using administrative data from approximately 45 million property appraisals, or 1.8 billion property-month observations. First, we find that from 2013 to 2021, CO_2 emissions decreased by 8.8 percent in aggregate while single-family housing stock increased by 7.3 percent at the same time, suggesting decreasing carbon intensity of single-family homes. Emissions from electricity use decreased by 13.6 percent, while emissions from natural gas use for home heating increased by 3.6 percent. Second, we estimate that the majority of the decline in CO_2 emissions from properties in our sample can be attributed to changes in US electricity generation, rather than changes over time to property-level characteristics or growth in US housing stock. Third, we show that aggregate emissions estimates from the property-level data closely align with aggregate emissions estimates using publicly available state-level data in 2020 and 2021, providing validation of our approach using property-level data and demonstrating that for aggregate estimates, state-level data is sufficient.

Keywords: energy use · carbon emissions · housing stock

JEL Classification: Q54 · R11 · R30

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1. Introduction

The US Environmental Protection Agency (EPA) estimates that 30% of total US greenhouse gas emissions are from energy use in the commercial and residential sector (EPA 2023). Recently, there has been a push in the US to "green the grid" by encouraging energy generation to transition from relatively more carbon-intensive fuels to low- or no-carbon fuel sources such as natural gas and renewables. For example, as of November 2022, 36 states have set minimum requirements for energy generation using renewables.[1] At the same time, energy efficiency and home-electrification programs have become increasingly popular with expenditures on such programs in North America reaching 8.9 billion dollars in 2020.[2] For emissions from residential energy use, this opens the question of the relative importance of greening the grid versus changes in property-level characteristics, such as electrification.

From 2010 to 2020, the Energy Information Administration (EIA) estimates that CO_2 emissions from residential energy use have decreased by 26.5 percent (from 1210.145 MMT to 889.89 MMT) (Energy Information Administration 2023c). In this paper, we explore the drivers of that decrease in emissions from residential energy use. We do so by first estimating property-level energy use for a sample of single-family homes in the US by leveraging rich data on property-level characteristics. Second, we convert these property-level energy use estimates into expected CO_2 emissions. This exercise enables us to understand: (a) how much energy is used by single-family homes in our sample, (b) the associated CO_2 emissions at a finely disaggregated geographic level, and (c) how changes in electricity generation versus changes in property characteristics over time influence changes in CO_2 emissions. To answer this third question, we calculate counterfactual energy use and emissions under alternative electricity generation and property-characteristics scenarios. Last, we compare estimates of CO_2 emissions using the property-level data to estimates of CO_2 emissions using publicly available state-level data from the EIA.

We estimate property-level energy use and associated CO_2 emissions from approximately 45 million appraisal records from 2013 to 2022Q2 for single-family homes,[3] leading to a sample of around 1.8 billion property-month observations. The appraisal data includes a standard set of property attributes collected at the time a property is appraised in the mortgage

[1]EIA 2022
[2]CEE 2020
[3]We start with approximately 49 million appraisal records from the Uniform Appraisal Dataset.

origination or refinancing process. These property attributes include information on square feet, number of bedrooms, number of bathrooms, home heating fuel, and home heating and cooling equipment. We develop a simple model of energy use using data from the EIA's Residential Energy Consumption Survey (RECS) from 2015 and 2020. The RECS is a household survey administered by the EIA that collects data on property attributes as well as monthly electricity, natural gas, fuel oil, propane, and kerosene use. We use this detailed data to estimate the relationship between weather and property attributes and energy use. We apply these estimates to predict *expected* energy use for 1.8 billion property-month observations given local weather and individual property characteristics.

This property-level data enables us to take into account variation in sources used for electricity generation across the US as well as variation in property-level characteristics both across the US and over time. This allows us to capture changes in physical attributes of homes that change over time (for example, changing from a furnace to a heat pump) that drive end-use energy demand. The appraisal data contains newly built single-family homes, allowing us to capture how new construction affects the energy consumption and emissions of US single-family housing units over time. We conduct a similar exercise using publicly available, state-level, data from the EIA and the Census American Community Survey (ACS). However, this geographically aggregated data only enables us to take into account changes in the number and location of housing units over time, rather than the characteristics of those housing units.

We have three main findings. First, we show that CO_2 emissions from residential energy use in single-family homes decreased by 8.8 percent from 2013 to 2021 (from 654 MMT to 597 MMT). Emissions from electricity use make up the majority of emissions from residential energy use, at 65.1 percent in 2021, followed by emissions from natural gas at 28.3 percent, and emissions from other fossil fuel sources (fuel oil, kerosene, and propane) making up the remainder. Emissions from electricity use have decreased by 13.6 percent from 2013 to 2021 (from 450 MMT to 389 MMT), which represents a relative decrease given that the number of single-family homes grew by 5.6 percent over the same time period. In contrast to emissions from electricity use, emissions from natural gas use increased by 3.6 percent (163 MMT to 169 MMT) and emissions from other fossil fuel use are virtually unchanged (40.9 MMT to 39 MMT). Emissions from residential electricity use have decreased over time as the sources used for electricity generation have become less carbon intensive while the carbon intensity of natural gas, fuel oil, propane, and kerosene has remained relatively unchanged. These results show that much of the decrease in reducing carbon emissions result from changes in electricity generation. They also show that while emissions from electricity use are decreasing, emissions from natural gas used in homes have slightly increased.

Second, we complete two counterfactual estimation exercises to compare CO_2 emissions under alternative electricity generation and property-characteristics scenarios. In the first counterfactual, we hold grid-level electricity generation emissions factors constant to their 2010 levels. This exercise asks: what if there had been no changes to the fuel sources used for electricity generation since 2010? We find that had there been no changes to energy generation from 2010 to 2021, emissions would have been 1.28 times higher (764.56 MMT in the counterfactual versus 597 MMT in our estimation). This finding suggests that during this time period, switching from high carbon content fuel sources to relatively lower carbon content fuel sources contributed substantially to decreases in CO_2 emissions from residential energy use. In the second counterfactual, we hold property-level attributes fixed to the first time a property is appraised. This allows new appraisals to enter into the dataset, but each time a property is re-appraised if its attributes change, we do not update them. This exercise asks what would have happened to emissions had property-level characteristics been unchanged. In this case, we find that emissions would have been 0.99 times less than emissions were in reality (594 MMT versus 597 MMT). This finding suggests that changes in property-level attributes slightly increased emissions over the same time period.[4] Together, these results suggest that changes in the fuel sources generating electricity during this time period are driving the majority of the decrease in CO_2 emissions from residential energy use rather than changes in property attributes.

Third, we compare the findings under the property-level approach to estimates using publicly available, state-level data. We find that in 2021, the property-level estimates and the state-level estimates closely align. Using the publicly available data, we can calculate counterfactual emissions had the grid not changed, but we cannot calculate counterfactual emissions had property-level attributes not changed. We find a similar result that changes in fuel sources for electricity generation contribute substantially to decreases in CO_2 emissions during this time period. We also show that had there been no growth in the number of housing units during this time period, emissions would have decreased by even more than

[4]On average, houses are increasing in size over the sample.

they did in reality. However, this second approach only enables us to take into account aggregate changes in the number of housing units, rather than changes in underlying property characteristics.

This paper makes three contributions. First, it estimates property-level energy use and CO_2 emissions for single-family homes in the US. We decompose emissions into electricity and other fuels used for home heating. We find that emissions from electricity use decreased by more than emissions from fossil fuels used for home heating. National Renewable Energy Laboratory (NREL) has developed several estimates of property-level energy use using prototype housing and has leveraged these estimates to determine where energy efficiency upgrades or electrification may have the biggest impact on CO_2 emissions (Reyna et al. 2022). Goldstein, Gounaridis, and Newell (2020) estimates property-level emissions from residential energy use using data from Corelogic's tax assessor records. They also estimate correlations between demographic characteristics and expected energy use, finding that the highest income households tend to have the highest energy use, and thus emissions, per capita. However, they use a one-time snapshot of properties in 2015 which does not enable them to account for changes in housing characteristics over time in their sample. Estiri (2014) also uses RECS data from 2009 to estimate the effects of property characteristics versus household characteristics on energy use, finding that household characteristics matter little in comparison to property-level characteristics for end-use energy demand. However, the authors note that certain household types select into certain housing times, which is an important factor in driving energy use at the property level. Our paper focuses on property characteristics rather than household characteristics and focuses on a larger sample of properties over time.

Second, these results provide insight on the relative importance of changes in fuel sources for electricity generation over the last 10 years is an important driver of decreases in CO_2 emissions from residential energy use. We also show that changes in property-level attributes in our sample do not contribute meaningfully to decreases in emissions over time. But, as electricity generation becomes relatively less carbon intensive, it becomes important to electrify home heating given that emissions from home heating have been increasing. Goldstein, Gounaridis, and Newell (2020) also shows that for the US to meet its Paris Agreement targets, it must be the case that the US invests both in changes in energy generation sources as well as changes in property-level attributes. Berrill, Gillingham, and Hertwich (2021) estimates greenhouse gas emissions from primary energy demand leveraging RECS data from 1990 to 2015, finding that at the property-level, population growth, reductions in household size, and increases in conditioned space are the primary drivers of energy use and greenhouse gas emissions. They also find that the dominant drivers of primary energy and greenhouse gas emission reductions over time are improvements in the efficiency of electricity generation and reductions in the greenhouse gas intensity of electricity generation. However, given the relatively limited sample size of the RECS, the authors are not able to distinguish the importance of relative changes in property-level attributes within the US. Hojjati and Wade (2012) also decompose end-use energy using RECS data from 1990 to 2005, finding that aggregate energy intensity in the US declined over this time period, providing suggestive evidence that home energy-efficiency programs were beginning to reduce property-level energy demand.

Third, we compare our results using publicly available, state-level, data versus, administrative, property-level data. We find that in 2021, there is only a 1.9 percent gap (608.76 MMT in the state-level estimates versus 597 MMT in the property-level estimates) in aggregate CO_2 emissions estimates between the property-level approach and the state-level approach. Using the state-level data, we also find decreases in property-level emissions over time. We find that the majority of these decreases are a result of the greening of the energy grid, qualitatively similar to the property-level results. However, using the aggregate, state-level, data we are unable to evaluate the importance of changes in characteristics of single-family homes.

The remainder of this paper is organized as follows. Section 2. details the property-level approach and the results of this analysis. Section 3. provides details regarding the state-level approach and the results of this analysis. Finally, Section 4. provides concluding remarks.

2. Property-Level Energy and CO_2 Estimates

The first approach we take estimates residential CO_2 emissions using property-level energy consumption data and characteristics to generate *predicted* energy use and CO_2 emissions for each property.

2.1 Property-Level Data

The property-level approach uses four sources of data. The first is data from the Energy Information Administration's Residential Energy Consumption Survey Data (RECS). The second is the Uniform Appraisal Dataset (UAD) from Fannie Mae and Freddie Mac's Uniform Mortgage Data Program (UMDP). The third is from NOAA's Global Historical Climatology Network Daily (GCHNd). The fourth is data on the total number of housing units and single family detached housing units from the five year ACS estimates at the county level from 2013 through 2021 (Census Bureau ACS 5-Year Estimates 2022).

The first data source is the RECS. The RECS is a survey dataset produced by the EIA. The survey is administered to "a nationally representative sample of housing units" and is produced every 4-5 years. The data used for the property-level approach represent the data collected in the 2015 and 2020 RECS. The RECS surveys households to collect information regarding the energy features of their home such as age, square footage, and appliance information. Next, the EIA contacts the households' utility companies to collect detailed monthly billing data for the households' electricity, fuel oil, kerosene, propane, and natural gas use. The version of the data we use includes both property-level characteristics as well as monthly energy use data.

The second source of data is the UAD. The UAD defines and collects all fields required for an appraisal submission for a property (Fannie Mae 2017). Appraisers fill out a form known by Fannie Mae as Form 1004 and Freddie Mac as Form 70. The forms are designed to collect data on one-unit properties or one-unit properties with accessory units.[5] The form collects detailed property-level characteristics such as location, square footage, number of bedrooms, number of bathrooms, air conditioning existence and type, and home heating equipment and fuel type. As we explain in more detail in the next subsection, we standardize this set of variables across the UAD and the RECS so that the variables of interest are comparable.

The third source of data is NOAA's Global Historical Climatology Network daily (GHCNd) data. This data includes daily maximum and minimum temperatures for a network of stations across the US. We aggregate the daily data to the monthly level and calculate heating degree days and cooling degree days by taking the average between daily maximum and minimum temperatures. We take the difference from 65 degrees to estimate the monthly heating degree days (HDD) and cooling degree days (CDD) experienced at each property in a month. We link data from the RECS and the UAD to NOAA's weather data by locating each property's nearest weather station. We assign each property in the RECS and the UAD

[5] See the form for Fannie Mae here and Freddie Mac here.

the monthly weather data of its nearest, active, weather station during the sample period.

The fourth source of data is from the census ACS data on the total number of housing units and single-family detached housing units at the census-tract level. We use this data to compare the number of housing units we have from appraisals to the number of housing units in the census data as well as to scale the per-residence emissions estimates to the aggregate level (Census Bureau ACS 5-Year Estimates 2022).

2.1.1 Cleaning and Combining the Data

The property-level dataset leverages information from three primary datsets: the 2015 RECS, the 2020 RECS, and the UAD. First, we describe the process of cleaning the RECS data and second the process of cleaning the UAD data.

The 2015 RECS data contains observations for 5,687 households and the 2020 RECS for 18,496 households. We link each household to its monthly billing data for electricity, natural gas, propane, fuel oil, and kerosene. Each household's billing cycle does not necessarily align with a calendar month.[6] For example, some billing cycles start on the 15th of the month and end on the 14th of the subsequent month. To prepare the RECS data for linking to monthly weather data from NOAA, we calendarize the data by redistributing energy use and bills to the calendar month.[7] Next, we link each household in the RECS to its nearest active weather station from NOAA's GHCNd dataset. For each household we observe property-level attributes, monthly energy billing data, and monthly weather data.

We limit the RECS sample to only single-family homes, both attached and detached, and drop observations in the top and bottom one percent of the distribution for electricity use and or natural gas use. This leads to a sample of 18,286 households and 349,580 observations. We then standardize variable definitions between the RECS and the UAD dataset. The common variables and our standardization process are described in Appendix Section A.2. These variables include physical attributes of the property such as square feet, number of bedrooms, number of bathrooms, and year built, as well as energy features of the home such as home heating fuel, home heating equipment, and home cooling equipment.

[6] The EIA has published statistics on the completeness of the monthly billing data in their 2015 Consumption and Expenditures Technical Documentation Summary (Energy Information Administration 2023b).

[7] In practice, this means calculating average daily energy use and bills within a billing cycle, and assigning the portion of that bill that falls within a month to that calendar month.

Table 1 reports summary statistics for the 2015 and 2020 RECS. The average single-family detached home sampled in the RECS in 2015 (2020) used 978 (921) kWh per month, used 63 (57) Therms of natural gas per month, used 7,182,700 (6,699,720) BTUs per month, and experienced 373 (347) HDD and 99 (124) CDD per month. The typical home was 2,470 (2,261) square feet and had 3.2 (3.2) bedrooms and 1.9 (2.0) bathrooms. Around 50 (59) percent of households use natural gas for heating and 34 (24) percent use electricity for home heating. The EIA notes that in the 2015 RECS, over 50 percent of residential energy consumption is for space heating and cooling (Energy Information Administration 2021). Important drivers of residential energy consumption are structure type, home size, and equipment and fuels used. For this reason, we focus on these physical attributes of the property in understanding the drivers of home energy consumption.

The UAD data contains approximately 49 million appraisals for single-family detached housing units from 2013 to 2022Q2. After data cleaning, we are left with about 45 million appraisals.[8] We link each appraisal record to its nearest active weather station from NOAA's GCHNd dataset using the same process as for the RECS data. We standardize all variables to the RECS data, described in Appendix Section A.2. This yields about 45 million unique appraisal records for single-family detached homes in the US, hereafter referred to as the property-level sample.[9] When we expand the dataset to include monthly weather data, this leads to 1.8 billion month-property observations.

Table 2 reports summary statistics for the property-level sample split between appraisals that occurred from 2013–2019 and 2020–2022Q2. We only include property-level characteristics here rather than the month-property data due to computing limitations. There are around 30 million appraisals before and including 2019 and around 16 million after 2019. The typical home in the first six years is 1990 square feet, has 3.3 bedrooms and 2.1 bathrooms, and was built in 1984. Almost 70 percent of records heat with natural gas and around 24 percent heat with electricity.

[8]We drop records without precise location information, without this information we cannot link a property to its nearest weather station. We further drop records that contains data anomalies such as missing appraisal values.

[9]Strictly speaking, if a property has been appraised multiple times during our study period 2013-2022, it will be included multiple times in the sample. Therefore, the observations are at the appraisal-level, rather than the property-level. However, for simplicity and to distinguish the property-level and the state-level approach we employ in this paper, we call this sample the property-level sample.

Table 1: Summary Statistics: 2015 and 2020 RECS

	RECS 2015	RECS 2020
Monthly kWh	977.51	921.42
	(634.63)	(641.34)
Monthly NG Therms	62.82	56.84
	(59.40)	(55.44)
Monthly Propane/Fuel Oil/Kerosene (gal.)	51.82	50.71
	(48.51)	(47.47)
Monthly Total BTU (1000s)	7182.70	6699.72
	(5586.49)	(5295.50)
Monthly HDD65	372.60	346.85
	(390.82)	(380.55)
Monthly CDD65	98.86	123.80
	(153.77)	(176.05)
Square Feet	2469.73	2260.53
	(1249.59)	(1141.48)
No. Bedrooms	3.20	3.22
	(0.91)	(0.92)
No. Bathrooms	1.89	1.96
	(0.76)	(0.76)
Year Built	1974.33	1974.78
	(28.80)	(32.09)
1[NG Heat]	0.50	0.59
	(0.50)	(0.49)
1[Propane Heat]	0.05	0.05
	(0.21)	(0.22)
1[Fuel Oil Heat]	0.05	0.06
	(0.21)	(0.25)
1[Elec. Heat]	0.34	0.24
	(0.47)	(0.43)
1[Steam Heat]	0.04	0.07
	(0.19)	(0.26)
1[Central Furnace]	0.65	0.69
	(0.48)	(0.46)
1[Heat Pump]	0.15	0.12
	(0.35)	(0.32)
1[Oth. Electric Heat]	0.06	0.03
	(0.23)	(0.16)
1[Oil Heat]	0.02	0.02
	(0.15)	(0.15)
1[Pellet Stove Heat]	0.03	0.02
	(0.17)	(0.14)
1[Fireplace Heat]	0.01	0.00
	(0.09)	(0.00)
1[Portable Heat]	0.02	0.01
	(0.13)	(0.11)
1[Other Heat]	0.00	0.01
	(0.07)	(0.08)
1[Central AC]	0.74	0.72
	(0.44)	(0.45)
1[Heat Pump AC]	0.22	0.12
	(0.41)	(0.32)
1[Window AC]	0.20	0.12
	(0.40)	(0.33)
1[Evap AC]	0.03	0.01
	(0.16)	(0.09)
N-Monthly	70168	278006
N-Property	3938	12943

Standard deviations are reported in parenthesis. Each column reports the average and the standard deviation in the 2015 and 2020 RECS.

Table 2: Summary Statistics: UAD 2013 - 2022

	2013–2019	2020–2022
Square Feet	1990.54	2042.03
	(993.12)	(937.88)
No. Bedrooms	3.29	3.32
	(5.04)	(0.86)
No. Bathrooms	2.07	2.10
	(0.78)	(0.81)
Year Built	1983.62	1985.11
	(28.70)	(31.05)
1[NG Heat]	0.70	0.67
	(0.46)	(0.47)
1[Propane Heat]	0.03	0.03
	(0.17)	(0.17)
1[Fuel Oil Heat]	0.04	0.04
	(0.20)	(0.19)
1[Elec. Heat]	0.24	0.27
	(0.43)	(0.45)
1[Steam Heat]	0.08	0.08
	(0.28)	(0.27)
1[Central Furnace]	0.85	0.86
	(0.36)	(0.35)
1[Heat Pump]	0.05	0.04
	(0.21)	(0.21)
1[Oil Heat]	0.00	0.00
	(0.05)	(0.05)
1[Pellet Stove Heat]	0.00	0.00
	(0.04)	(0.04)
1[Fireplace Heat]	0.00	0.00
	(0.00)	(0.00)
1[Portable Heat]	0.00	0.00
	(0.00)	(0.00)
1[Other Heat]	0.01	0.01
	(0.09)	(0.10)
1[Central AC]	0.83	0.86
	(0.37)	(0.35)
1[Heat Pump AC]	0.05	0.04
	(0.21)	(0.21)
1[Window AC]	0.02	0.02
	(0.14)	(0.13)
1[Evap AC]	0.01	0.01
	(0.09)	(0.08)
N	29867403	15871090

Standard deviations are reported in parenthesis. Each column reports the average and the standard deviation in the UAD.

2.2 Estimating Property-Level Energy Use

Here, we estimate home energy consumption based on the features and local weather conditions of a given property. We first use the RECS data to develop a model of monthly energy consumption. Second, we use these coefficients to estimate predicted home energy consumption for each property in the main sample separately for the 2015 and 2020 RECS. We apply the estimates from the 2015 RECS to properties appraised from 2013 through the end of 2019 and the estimates from the 2020 RECS to properties appraised from 2020 through 2022Q2.

Figures 1 (a)–(c) show scatter plots of monthly BTUs relative to the home's decile of square feet, HDD, and CDD respectively pooled across the 2015 and 2020 waves. Panel (a) shows that there is a strong positive relationship between the decile of square footage of the home and the home's monthly energy consumption. Panel (b) shows the relationship between HDD and monthly energy consumption. As a home experiences more HDD, the home tends to use more total energy. Panel (c) shows the relationship between CDD and monthly energy consumption. This relationship exhibits a U-shape. For homes that experience CDD in the bottom and top decile use more energy that homes that experience the median amount of CDD. This is because homes in the most moderate weather require the least amount of cooling.

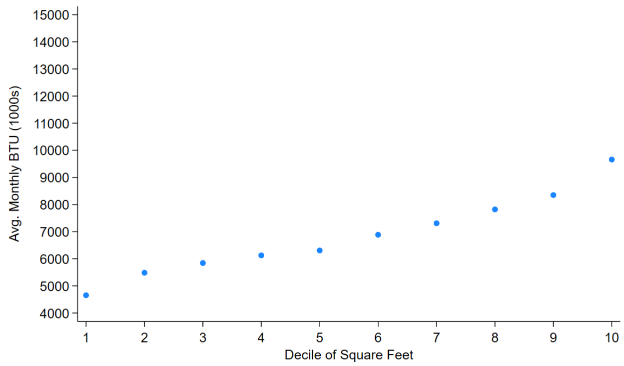
Weather, square footage, and home heating and cooling fuel type and equipment are all important drivers of home energy consumption and will be included in our residential energy demand model. We use a simple regression to estimate the relationship between weather, property-level characteristics, and monthly energy consumption separately for the 2015 and 2020 RECS:

$$E_{it} = \alpha_0 + \alpha_1 * HDD65_{it} + \alpha_2 * CDD65_{it} + X_i\beta + \tau_t + \delta_i + \epsilon_{it} \tag{1}$$

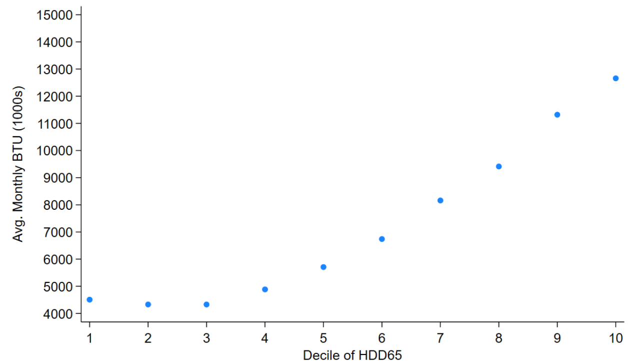
where E_{it} is the energy use of house i in month-of-sample t. We estimate the above specification for total BTUs, electricity, natural gas, propane, and fuel oil/kerosene. $HDD65$ represents heating degree days experienced by house i in month t; $CDD65$ represents cooling degree days experienced by house i in month t; X_i represents property-level characteristics such as square footage, number of bedrooms, number of bathrooms, home heating fuel type,

Figure 1: Deciles of Square Feet, HDD65, and CDD65 and Monthly Average Energy Use

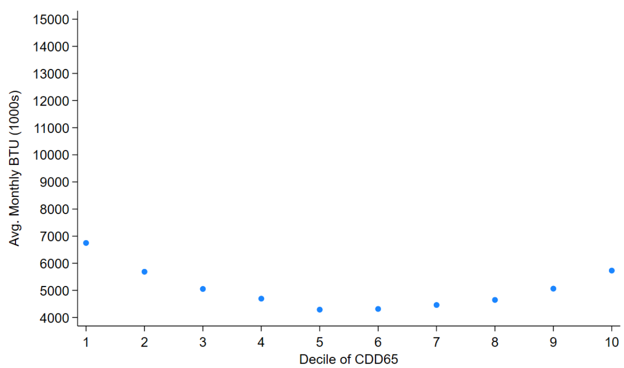
(a) Square Feet



(b) HDD



(c) CDD



Note: Each sub figure shows a scatter plot of the decile of the home's square footage, HDD, and CDD relative to average monthly BTUs (1000s). These figures pool data across the 2015 and 2020 RECS sample waves.

home heating equipment, and home cooling equipment. These variables have been selected both because of their importance in driving residential energy use as well as the overlap in variables between the RECS data and the appraisal data. τ_t is a month-of-sample fixed effect; δ_i represents IECC zone fixed effects, and ϵ_{it} is an error term with mean zero. All specifications are weighted by the inverse probability weights in the RECS.

The results from equation (1) are reported in Table 3 for BTUs, Table 4 for electricity, Table 5 for natural gas, and Table 6 for other fuel sources for the 2015 RECS. These same results for 2020 are reported in Appendix Tables A.5 through A.7. Column 1 in all tables shows the results from including only HDD, CDD, month-of-year fixed effects, and IECC zone fixed effects. Column 2 adds square feet, number of bedrooms, number of bathrooms; column 3 adds home heating fuel type, and column 4 adds in heating and cooling equipment. In Table 4, households with their fuel source as electricity and electric heat (not including heat pumps) are the baseline category. For natural gas, we limit the sample to only households that heat with natural gas and central furnaces are the baseline category. For fuel oil, kerosene, and propane again we limit the sample to only the households that heat with those fuels and the baseline category is households with central furnaces.

The regressions show that energy use is positively correlated with more square feet, number of bedrooms, number of bathrooms, HDD, CDD, as expected. The correlations between fuel type and heating and cooling equipment depend on the fuel used for home heating. Qualitatively, the 2015 and 2020 regressions show similar results.

2.3 Property-Level Energy Use and CO_2 Emissions

We predict property-level energy use for each property in the property-level sample using the 2015 estimates for properties appraised from 2013 through 2019 and using the 2020 estimates for properties appraised from 2020 through 2022Q2. We complete these predictions separately for BTUs, electricity, natural gas, and fuel oil/propane and kerosene using the estimates from column 4 in Tables 3, 4, 5, and 6. Figure 2 shows average annual energy consumption for the appraised single-family detached and attached properties in our data set. Our estimates show that total energy use is relatively constant, if not slightly increasing over time. The average SF detached home in our sample used 83.88 MMBtu per year per house in 2013 to 84.76 MMBtu per year per house in 2021.[10]

We take the estimates of energy consumption and multiply the predicted energy use of each property by the emissions factor for that energy source. For electricity, we use data from the EIA's state energy profiles (Energy Information Administration 2023a). These estimates represent the average CO_2 emissions per mWh of electricity consumed in that state, taking into account the grid mix and network. For all other fuels, we use emissions factors from the EPA's emissions factors hub (US EPA 2015).

[10]We complete the same calculation for electricity, natural gas, and other fuels. The average household used 10,615 kWh in 2013 and 10,892 kWh in 2021. The average household with natural gas heating used 620 therms in 2013 and 645 in 2021. Similarly, the average household with fuel oil, propane, or kerosene heat used 537 gallons in 2013 and 557 in 2021.

Table 3: 2015: Monthly BTUs (1000s) Use

	(1) Monthly BTU (1000s)	(2) Monthly BTU (1000s)	(3) Monthly BTU (1000s)	(4) Monthly BTU (1000s)
Monthly HDD65	7.925**	7.671**	7.660**	7.655**
	(0.256)	(0.249)	(0.221)	(0.219)
Monthly CDD65	5.303**	6.059**	6.304**	6.214**
	(0.397)	(0.387)	(0.386)	(0.389)
Square Feet		0.530**	0.564**	0.562**
		(0.072)	(0.058)	(0.058)
No. Bedrooms		837.657**	749.781**	720.216**
		(93.920)	(79.323)	(78.276)
No. Bathrooms		457.264**	434.037**	449.595**
		(123.334)	(110.874)	(110.159)
Year Built		−10.377**	−12.699**	−11.474**
		(3.498)	(2.184)	(2.226)
1[NG Heat]			2447.846**	2244.821**
			(127.846)	(158.158)
1[Propane Heat]			−509.223	−616.261
			(306.636)	(332.981)
1[Fuel Oil Heat]			−424.774	−682.699
			(333.302)	(351.231)
1[Wood Heat]			−2425.023**	−2075.799*
			(291.400)	(815.951)
1[Other Heat]			−5006.132**	−4888.178**
			(342.078)	(978.599)
1[Steam Heat]				962.764*
				(463.244)
1[Central Furnace]				106.967
				(197.665)
1[Heat Pump]				−370.840
				(236.829)
1[Oil Heat]				−611.980
				(416.521)
1[Pellet Stove Heat]				−438.607
				(870.716)
1[Fireplace Heat]				−259.834
				(683.089)
1[Portable Heat]				393.511
				(327.813)
1[Other Heat]				−86.713
				(1053.617)
1[Central AC]				722.110**
				(185.373)
1[Heat Pump AC]				−85.523
				(186.477)
1[Window AC]				859.044**
				(176.603)
1[Evap AC]				356.534
				(297.108)
Constant	3961.877**	19503.547**	23120.444**	20154.075**
	(86.432)	(6781.886)	(4267.110)	(4348.839)
Month-of-Year FE	Y	Y	Y	Y
IECC Zone	Y	Y	Y	Y
N	65234	65234	65234	65234
Adj. R-Squared	0.35	0.41	0.47	0.47

* $p<0.05$ ** $p<0.01$. The standard errors reported in parenthesis have been clustered at the individual level. Weighted by RECS sampling weights.

Table 4: 2015: Monthly Electricity Use

	(1) Monthly kWh	(2) Monthly kWh	(3) Monthly kWh	(4) Monthly kWh
Monthly HDD65	0.179*	0.158*	0.202*	0.213*
	(0.026)	(0.024)	(0.023)	(0.023)
Monthly CDD65	1.116*	1.181*	1.074*	1.047*
	(0.070)	(0.066)	(0.064)	(0.065)
Square Feet		0.045*	0.050*	0.047*
		(0.008)	(0.007)	(0.007)
No. Bedrooms		72.628*	84.930*	81.749*
		(11.529)	(10.926)	(10.693)
No. Bathrooms		100.811*	101.775*	99.452*
		(16.538)	(14.941)	(14.899)
Year Built		0.042	−0.449	−0.292
		(0.382)	(0.322)	(0.317)
1[NG Heat]			−381.378*	−312.392*
			(20.146)	(24.405)
1[Propane Heat]			−174.103*	−98.780*
			(37.256)	(40.231)
1[Fuel Oil Heat]			−304.376*	−215.788*
			(43.318)	(45.680)
1[Wood Heat]			−166.816*	−40.602
			(42.719)	(86.796)
1[Other Heat]			119.852	374.588*
			(85.652)	(130.829)
1[Steam Heat]				−164.734*
				(50.988)
1[Central Furnace]				−26.681
				(34.264)
1[Heat Pump]				49.027
				(42.065)
1[Oil Heat]				−34.194
				(53.074)
1[Pellet Stove Heat]				−96.614
				(99.380)
1[Fireplace Heat]				−52.916
				(91.696)
1[Portable Heat]				71.891
				(77.327)
1[Other Heat]				−213.954*
				(106.356)
1[Central AC]				113.501*
				(24.416)
1[Heat Pump AC]				99.986*
				(27.160)
1[Window AC]				184.324*
				(25.149)
1[Evap AC]				−12.419
				(40.049)
Constant	793.073*	170.740	1311.609*	851.520
	(11.282)	(742.886)	(627.904)	(619.504)
Month-of-Year FE	Y	Y	Y	Y
IECC Zone	Y	Y	Y	Y
N	65234	65234	65234	65234

* $p<0.05$ ** $p<0.01$. The standard errors reported in parenthesis have been clustered at the individual level. Weighted by RECS sampling weights.

Table 5: 2015: Monthly Natural Gas Use (Therms)

	(1) Monthly NG Therms	(2) Monthly NG Therms	(3) Monthly NG Therms
Monthly HDD65	0.093*	0.092*	0.092*
	(0.003)	(0.002)	(0.001)
Monthly CDD65	−0.003	0.001	0.001
	(0.005)	(0.005)	(0.002)
Square Feet		0.005*	0.005*
		(0.001)	(0.000)
No. Bedrooms		5.779*	5.382*
		(0.959)	(0.334)
No. Bathrooms		2.964*	3.534*
		(1.103)	(0.392)
Year Built		−0.164*	−0.135*
		(0.027)	(0.010)
1[Steam Heat]			19.253*
			(1.361)
1[Heat Pump]			−8.321*
			(1.215)
1[Oil Heat]			−5.368*
			(1.277)
1[Fireplace Heat]			−16.319*
			(2.863)
1[Other Heat]			−12.013*
			(3.160)
1[Central AC]			0.529
			(0.727)
1[Heat Pump AC]			2.871*
			(0.754)
1[Window AC]			3.066*
			(0.766)
1[Evap AC]			1.574
			(1.006)
Constant	29.795*	313.300*	256.218*
	(1.074)	(51.703)	(18.850)
Month-of-Year FE	Y	Y	Y
IECC Zone	Y	Y	Y
N	30310	30310	30310

* $p<0.05$ ** $p<0.01$. The standard errors reported in parenthesis have been clustered at the individual level. Weighted by RECS sampling weights.

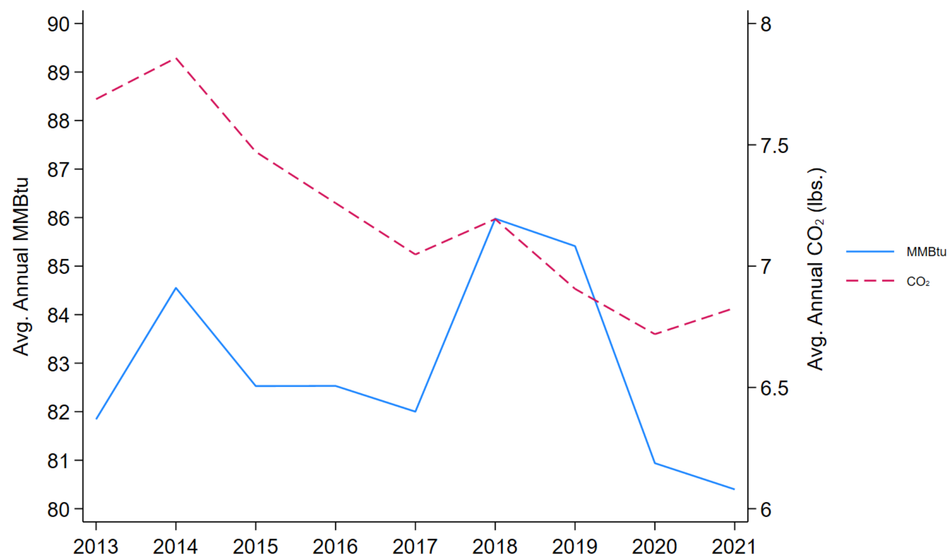
Table 6: 2015: Monthly Propane/Fuel Oil/Kerosene (gal.)

	(1) Monthly P/FO/K (gal.)	(2) Monthly P/FO/K (gal.)	(3) Monthly P/FO/K (gal.)
Monthly HDD65	0.042*	0.039*	0.040*
	(0.011)	(0.010)	(0.010)
Monthly CDD65	−0.040*	−0.031*	−0.027
	(0.016)	(0.015)	(0.016)
Square Feet		0.002	0.003
		(0.002)	(0.002)
No. Bedrooms		7.588*	6.675*
		(2.534)	(2.361)
No. Bathrooms		1.300	1.075
		(4.428)	(4.355)
Year Built		0.113	0.074
		(0.073)	(0.062)
1[Steam Heat]			6.670
			(6.011)
1[Heat Pump]			17.772*
			(8.730)
1[Oil Heat]			−0.383
			(4.707)
1[Fireplace Heat]			−25.517*
			(7.188)
1[Other Heat]			−19.251
			(14.697)
1[Central AC]			1.529
			(6.543)
1[Heat Pump AC]			−17.267*
			(6.174)
1[Window AC]			2.739
			(5.682)
1[Evap AC]			24.192
			(19.535)
Constant	40.428*	−214.962	−141.160
	(5.534)	(141.370)	(118.285)
Month-of-Year FE	Y	Y	Y
IECC Zone	Y	Y	Y
N	3367	3367	3367

* $p<0.05$ ** $p<0.01$. The standard errors reported in parenthesis have been clustered at the individual level. Weighted by RECS sampling weights

Figure 2's second y-axis shows average annual household CO_2 emissions from all energy consumed at the property. The figure shows that on average, over time, per property CO_2 emissions have decreased from around 7.7 metric tons per house per year in 2013 to 6.8 metric tons per house per year in 2021.

Figure 2: Average Residential Energy Use and CO_2 Emissions

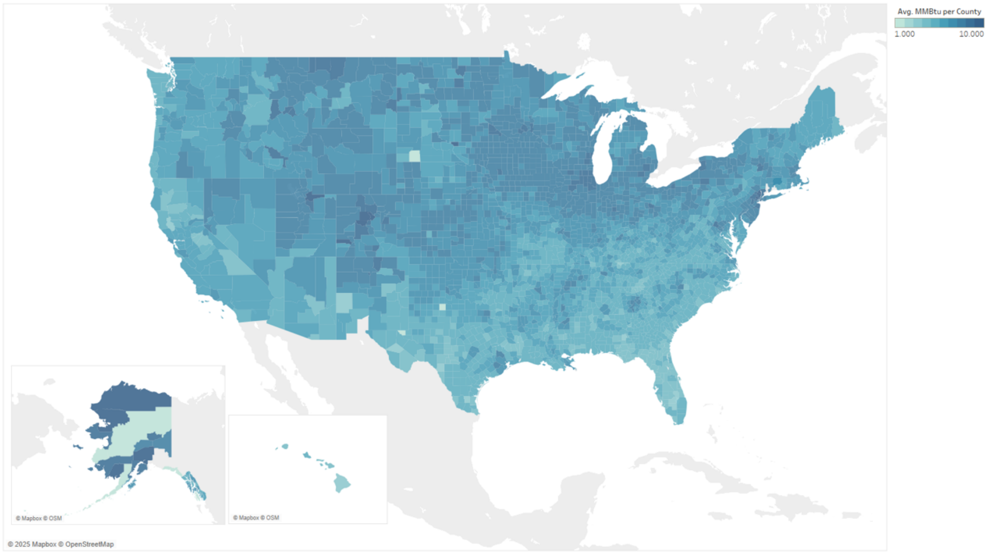


Note: This figure was generated using data from the EIA RECS, UAD, EIA, and EPA emissions factors. Source: Authors' calculations.

These estimates demonstrate that average energy use has remained relatively constant during this time period but that CO_2 emissions per house are decreasing over time. There is also substantial geographic heterogeneity in both residential energy use and CO_2 emissions per household. Figures 3, 4, and 5 show predicted property-level monthly energy use in 2021 for MMBtus, electricity (kWh) and natural gas (therms), respectively. These county-level estimates were generated by taking within-county property-level averages. The figure for total energy in MMBtus shows that the Upper Midwest uses the most energy, on average, per month. The figure for electricity shows that on average, the southeastern US tends to use the most electricity. The reverse is true for natural gas. The figure shows average natural gas use only for homes that heat with natural gas. Homes in the North East, Upper Midwest, Appalachia, and the Mountain West tend to use the most natural gas, on average.

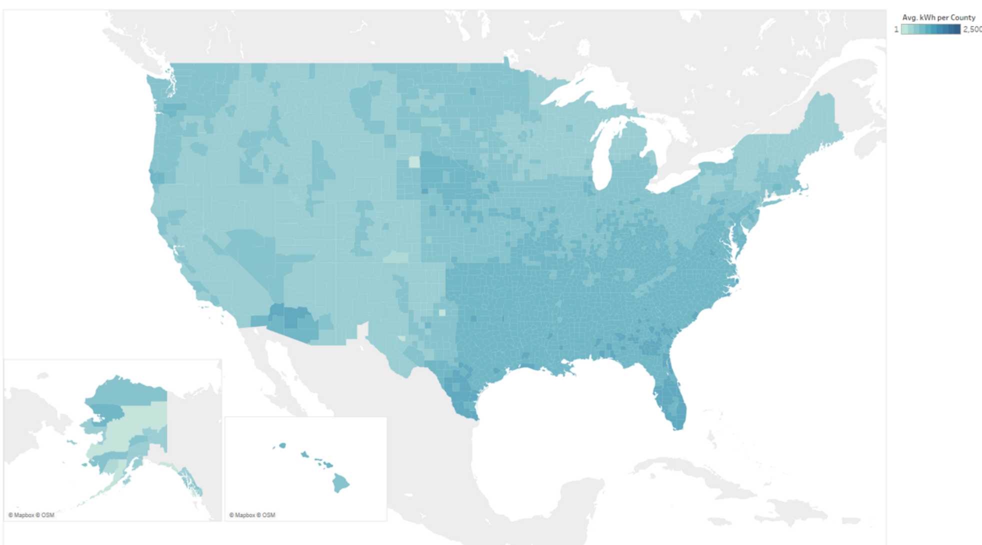
Of course, fuels used for energy generation across the US vary widely, so high average elec-

Figure 3: Average Monthly MMBtu per County (2021)



Note: This figure was generated using data from the EIA RECS, UAD, EIA, and EPA emissions factors. Source: Authors' calculations.

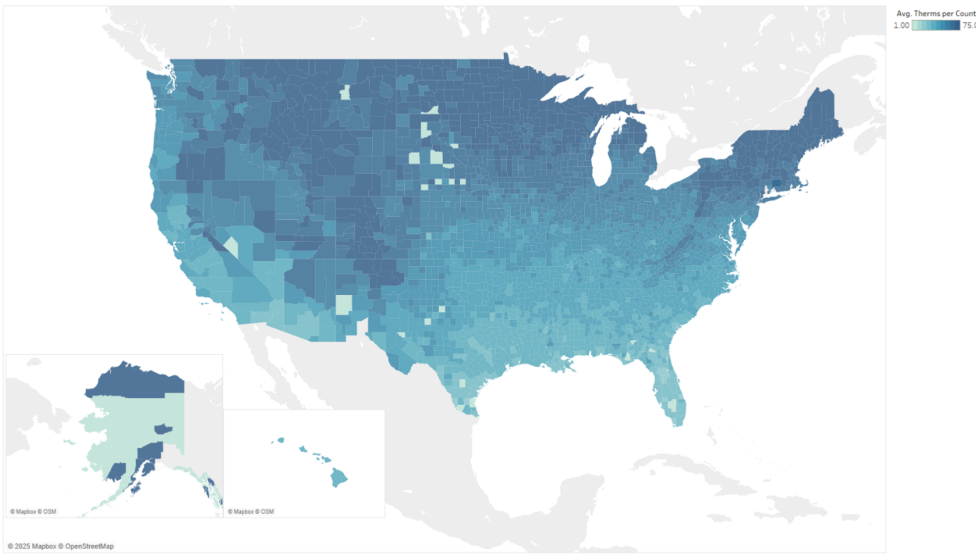
Figure 4: Average Monthly kWh per County (2021)



Note: This figure was generated using data from the EIA RECS, UAD, EIA, and EPA emissions factors. Source: Authors' calculations.

tricity use does not necessarily correspond to high CO_2 emissions. The emissions factor is the same for fossil fuels burned at home for home heating no matter where the household is

Figure 5: Average Monthly Therms per County (2021)

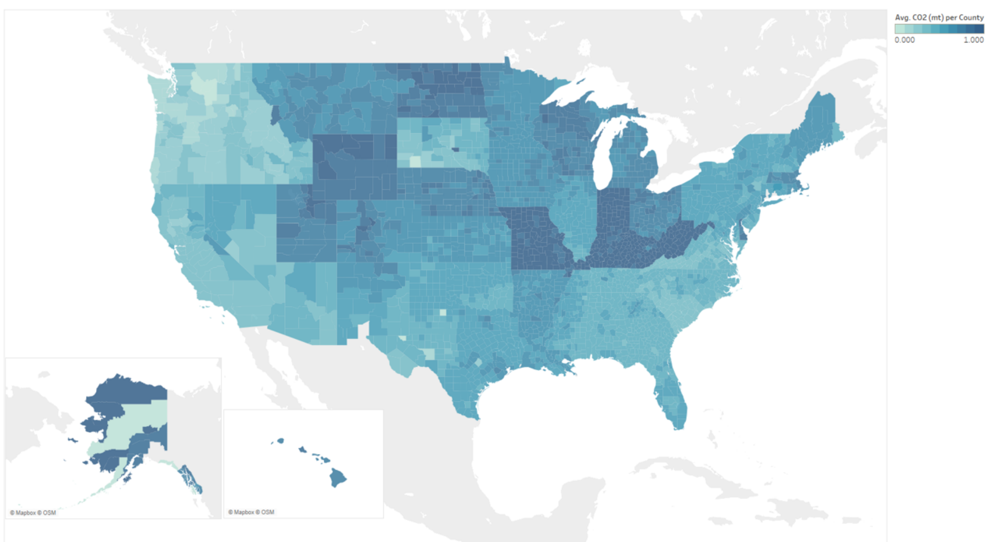


Note: This figure was generated using data from the EIA RECS, UAD, EIA, and EPA emissions factors. Source: Authors' calculations.

located. Thus, the penetration and use of fossil fuels for home heating influences emissions from residential energy use. Figure 6 shows average property-level monthly metric tons of CO_2 emissions for energy consumed. Properties located in states with more dependence on coal for energy generation tend to have more CO_2 emissions per house than properties located in states with other, less carbon intensive, sources of electricity generation. And last, these figures show *average* emissions per house, however, they do not show total emissions. While states with carbon intensive energy sources tend to have high energy emissions per house, these states have relatively fewer homes. Aggregate emissions per county will depend on: property-level energy use, generation mix, penetration of fossil fuels for home heating, and the number of housing units in a given location. Figure 7 shows average CO_2 emissions per property multiplied by the number of single-family detached units in that county in the ACS 5-year estimates. This figure shows much more geographic heterogeneity in total county-level CO_2 emissions. Emissions from residential energy use are concentrated in places that tend to have larger populations and/or a more emissions intensive generation mix. For example, San Bernardino county in California has relatively high aggregate emissions at 2.14 MMT per month, while California has a relatively clean energy generation mix, San Bernardino has a relatively large concentration of single-family detached homes, leading to a large population and relatively large aggregate emissions. Population centers across the country tend to have higher aggregate emissions such as South Florida, Houston, Chicago, Detroit, and the tri-state area around New York City, for example.

Figure 8 shows aggregate emissions from single-family homes, decomposed into emissions from electricity use, natural gas use, and fuel oil, propane, and kerosene use. We generated these estimates using average annual county-level emissions (as shown in Figure 6) and multiply by the county-level ACS 5-year estimates of total single-family detached homes. Figure 8 shows that aggregate emissions from single-family detached homes decreased by 8.8 percent from 2013 to 2021 (from 654 MMT in 2013 to 597 in 2021). Emissions from electricity use have decreased by 13.6 percent from 2013 to 2021 (from 450 MMT to 389 MMT). Whereas emissions from natural gas have increased by 3.6 percent (163 MMT to 169 MMT) and emissions from other fossil fuels are virtually unchanged (40.9 MMT to 39 MMT). This finding demonstrates decreases in emissions from residential energy use are primarily driven by decreases in emissions from electricity generation. And, in fact, emissions from natural gas have increased over the same time period.

Figure 6: Average Monthly CO_2 (mt) per County (2021)

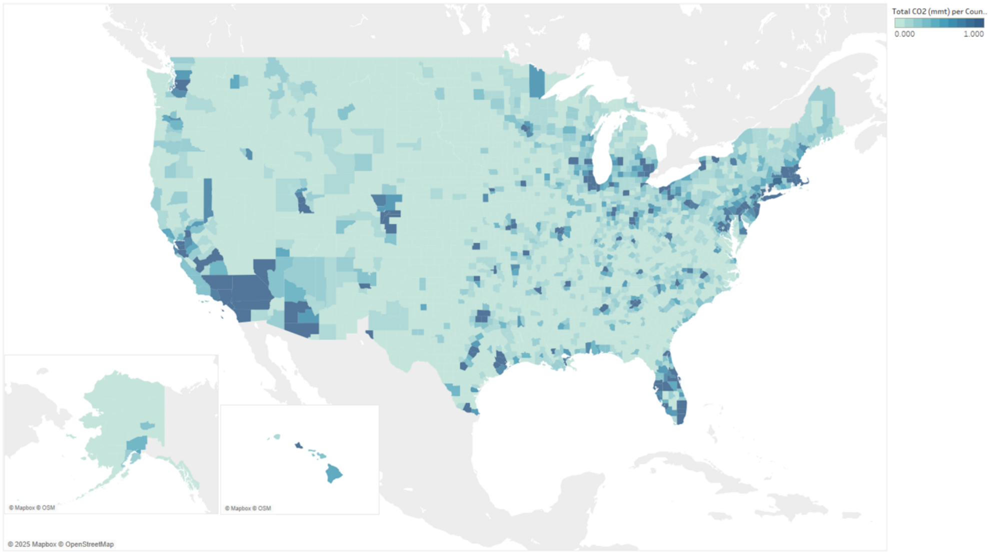


Note: This figure was generated using data from the EIA RECS, UAD, EIA, and EPA emissions factors. Source: Authors' calculations.

2.4 Housing Stock or Changes in the Grid

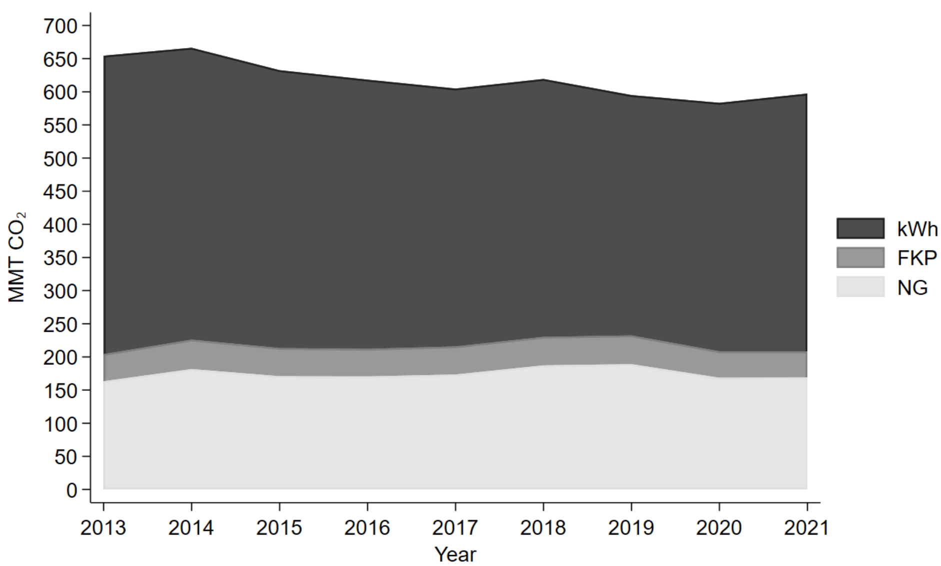
In this section, we estimate two counterfactual scenarios for aggregate emissions. We investigate the relative importance of the greening of the US energy grid versus changes in

Figure 7: Total Monthly CO_2 (mmt) per County (2021)



Note: This figure was generated using data from the EIA RECS, UAD, EIA, ACS, and EPA emissions factors. Source: Authors' calculations.

Figure 8: Total CO_2 Emissions by Fuel Source

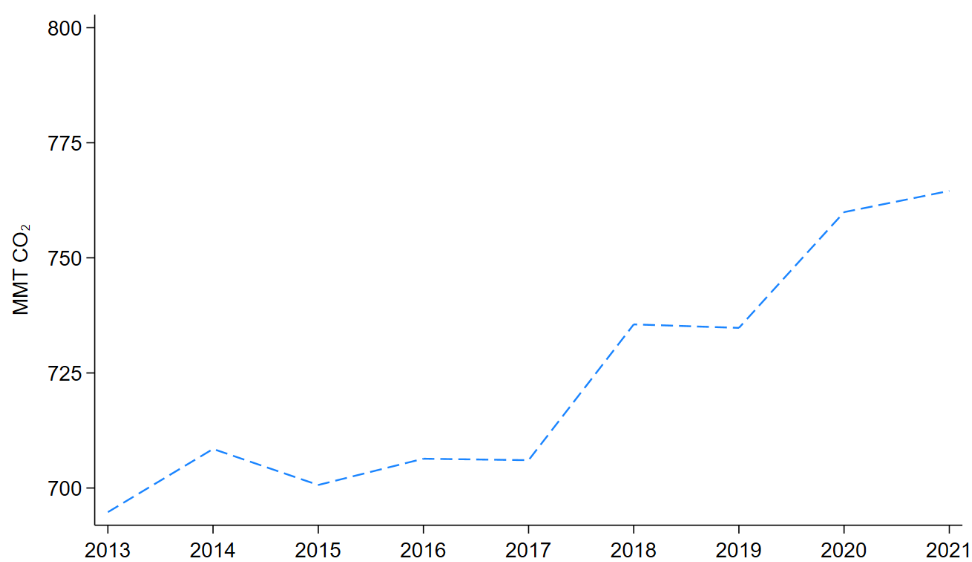


Note: This figure was generated using data from the EIA RECS, UAD, EIA, ACS, and EPA emissions factors. Source: Authors' calculations.

property-level attributes. First, we will hold emissions rates constant to their 2010 levels and allow for changes in housing characteristics. Second, we will allow for changes in the grid, but hold property characteristics fixed to the first appraisal that we observe in the appraisal data.

First, we assume that state-level emissions factors have been constant since 2010. We use 2010 as the base year, rather than 2013, so that the results here are directly comparable to the results in Section 3.3.1. Figure 9 shows the outcome of this exercise. Had there been no changes to the grid from 2010, emissions would have increased by 10 percent from 2013 to 2021 (from 694.77 MMT to 764.56 MMT). In reality in 2021, emissions were 597 MMT. In other words, emissions would have been 1.28 times greater than they were had there been no changes to the grid.

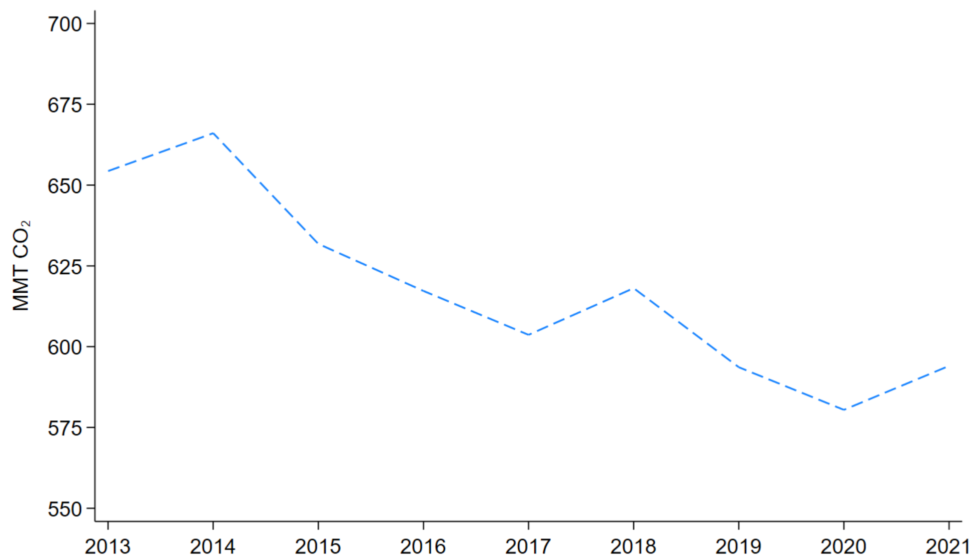
Figure 9: Total MMT CO_2 Holding Emissions Factors to 2010 Levels



Note: This figure was generated using data from the EIA RECS, UAD, EIA, ACS, and EPA emissions factors. Source: Authors' calculations.

Second, we assume that state-level emissions factors could change, but that property-level characteristics do not change over time. We allow new appraisals to enter into the sample over time, but for any property re-appraisals we keep the characteristics constant to the first time the property is appraised. Figure 10 shows the outcome of this exercise. If property characteristics had remained fixed during this time, emissions would have decreased by 9.1 percent from 2013 to 2021 (from 654 MMT to 594 MMT). These results suggest that emissions would have decreased by *slightly* more had property characteristics remained constant to the first appraisal. Over this time period, on average, properties are getting larger in the sample, these results show that had properties remained slightly smaller, emissions would have been slightly lower than they otherwise were. Taken together, these results suggest that the greening of the grid is primarily responsible for the decline in CO_2 emissions from residential housing stock in the US.

Figure 10: Total MMT CO_2 Holding Property Characteristics Fixed



Note: This figure was generated using data from the EIA RECS, UAD, EIA, and EPA emissions factors. Source: Authors' calculations.

3. State-Level Approach

The second approach we use in this paper uses state-level data to estimate "per-residence" CO_2 emissions from energy consumption for the average housing unit within a state.

3.1 State-Level Data

We combine several publicly available data sets from the Energy Information Administration to generate measures of the CO_2 emissions from residential energy consumption. The first source is the EIA's Annual Electric Power Industry Report, Form 861, data. The EIA-861 data provides annual information at the state level for total electricity sales (consumption), revenue, and prices to ultimate consumers from 1990–2021 (Energy Information Administration 2022a). The second source is the EIA's state-level estimates of CO_2 energy-related emissions for the residential sector from 1970–2021 (Energy Information Administration 2022b).[11] The third source is the EIA's state-level estimates of fuel-specific emissions by state from 1970–2021. This data provides information on the CO_2 emissions from energy consumed directly by residential consumers at home. For example, this includes estimates from fuels used directly by the household, typically for home heating, such as natural gas, distillate fuel oil, and propane (Energy Information Administration 2022b).[12]

The fourth source is state-level energy consumption data from the EIA's State Energy Data System (SEDS). The SEDS contains state-level energy consumption information by fuel type from 1960–2021 (Energy Information Administration 2022c). This additional information enables us to generate estimates of CO_2 emissions from fuel consumed at home to compare to those the EIA produces in the third data set described above. To do so, we download emissions rates by fuel type from 1973–2021 (Energy Information Administration 2022d).[13] The estimates of direct CO_2 emissions that we generate using this approach are equivalent to the residential estimates published by the EIA in the third dataset described above.

We also use information contained in the survey data produced by the EIA, the Residential Energy Consumption Survey (RECS). The RECS represents a series of nationally representative household surveys regarding energy consumption, energy bills, home energy characteristics, and demographic information. We use information from survey years 1990, 1993, 1997, 2001, 2005, 2009, 2015, and 2020. The finest level of geographic information for most survey years are the nine census divisions, and ten in some years when the mountain division is split between the north and the south.[14] However, in 1993, 1997, 2001, and 2005, the survey reports data for the four largest states: Florida, California, Texas, and New York. In 2009, the survey reports information for 27 "reportable domains" which represent individual states or groupings of states. And in 2020, the survey reports information at the state-level.

[11]This data was downloaded in October, 2024 from https://www.eia.gov/environment/emissions/state/ under the table "Electricity energy-related carbon dioxide emissions."

[12]This data was downloaded in October, 2024 from https://www.eia.gov/environment/emissions/state/ under the table "Residential energy-related carbon dioxide emissions".

[13]These data represent the detailed emissions factors developed by the Environmental Protection Agency *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021,* Tables A-22, A-27, A-34, and A-230

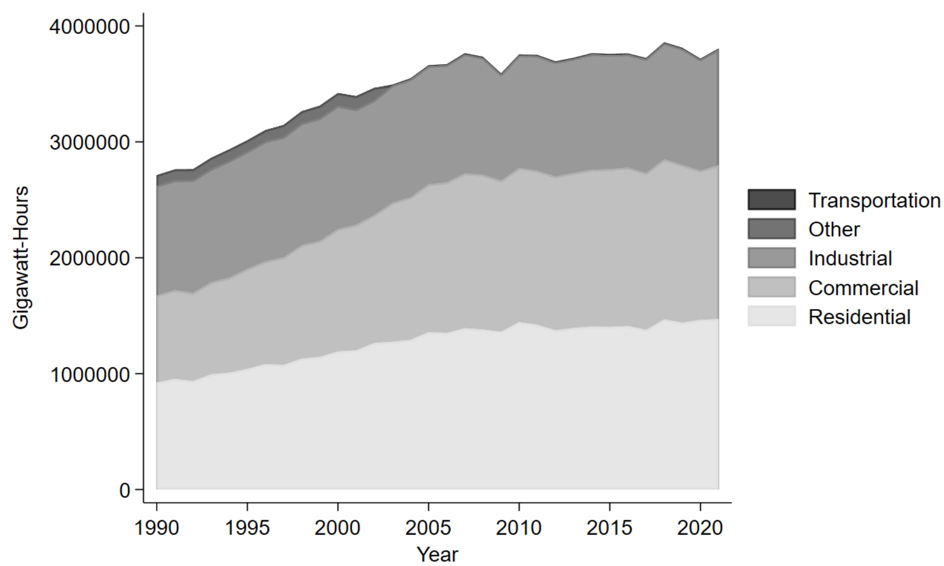
[14]New England Census Division (CT, MA, ME, NH, RI, VT); Middle Atlantic Census Division (NJ, NY, PA); East North Central Census Division (IL, IN, MI, OH, WI); West North Central Census Division (IA, KS, MN, MO, ND, NE, SD); South Atlantic Census Division (DC, DE, FL, GA, MD, NC, SC, VA, WV); East South Central Census Division (AL, KY, MS, TN); West South Central Census Division (AR, LA, OK, TX); Mountain North Sub-Division (CO, ID, MT, UT, WY); Mountain South Sub-Division (AZ, NM, NV); Pacific Census Division (AK, CA, HI, OR, WA)

We use this data to estimate the typical number of household members in owner-occupied housing.

3.2 State-Level Empirical Approach

We combine these data sets to generate an estimate of state-level CO_2 emissions from residential energy consumption from 1990–2021. Figure 11 below shows total electricity consumption across five sectors: residential, commercial, industrial, transportation, and other. The figure shows that on average, electricity consumption has increased over time until growth begins leveling off around 2005. From 1990 to 2020 the total share of electricity consumed by the residential sector increased from 34 percent to 39.4 percent.

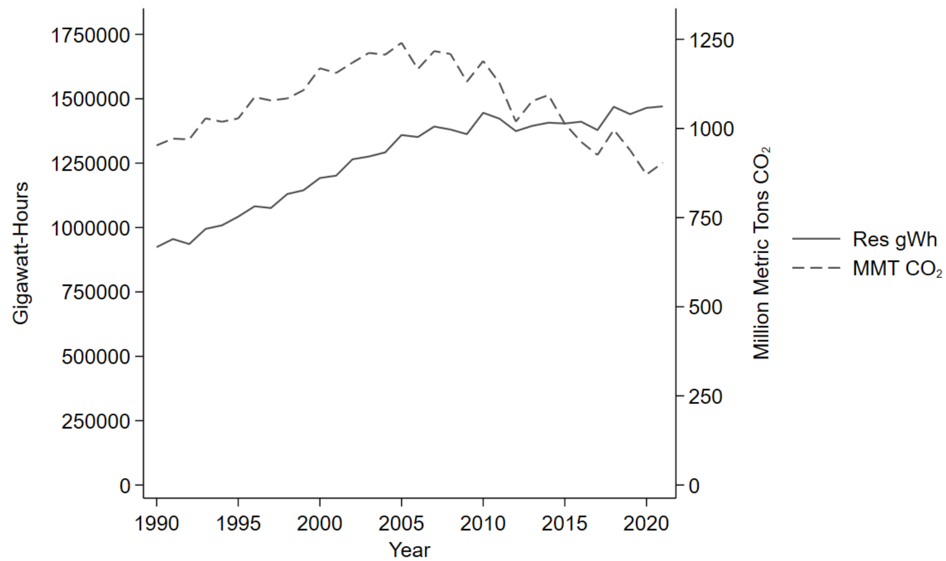
Figure 11: Total Electricity Use by Sector



Note: This figure was generated using data from EIA Form-861 on annual energy consumption by sector from 1990-2021. Source: Authors' calculations and EIA Form-861

Next, we generate state-level CO_2 emissions from residential energy consumption. We start with information on total state-level energy emissions. Then, multiply those state-level emissions by the share of energy within the state used by the residential sector, and add in emissions from energy used directly in the home. Figure 12 shows total residential energy consumed within the US from 1990–2021 and total CO_2 emissions associated with that energy consumption. Starting in 2007, the figure shows the relative decoupling of residential energy consumption from CO_2 emissions. Berrill, Gillingham, and Hertwich (2021) notes that this change is the result of the decarbonization of the electricity supply.

Figure 12: Total Electricity in Residential Sector and CO_2 Emissions



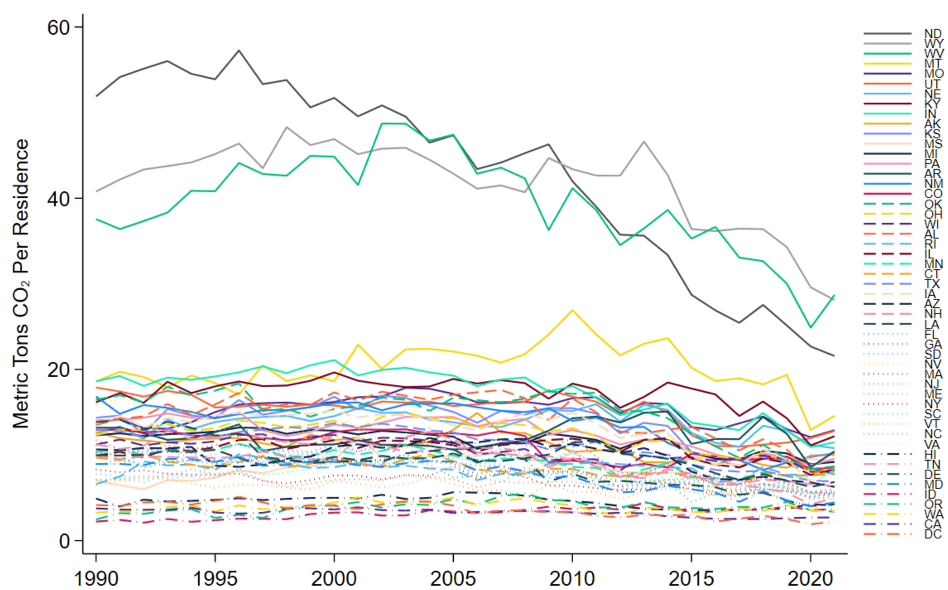
Note: This figure was generated using data from EIA Form-861 on annual energy consumption by sector from 1990-2020. Source: Authors' calculations and EIA Form-861

After generating state-level residential energy emissions, we scale these estimates by the population in each state. This yields a per-capita estimate of CO_2 emissions in each state. The total population estimates we use are those from the SEDS data for each state from 1990–2021. Berrill, Gillingham, and Hertwich (2021) notes there is an important difference between thinking about residential electricity use per *residence* versus per *resident*. For the purposes of this paper, we would generate a per *residence* estimate to understand CO_2 emissions for the typical residential property within a state.

To obtain a per *residence* estimate, the per capita estimates must be scaled by the typical number of householders within a given owner-occupied housing unit. To obtain the typical number of householders in an owner-occupied housing unit, we use data collected from the 1990, 1993, 1997, 2001, 2005, 2009, 2015, and 2020 RECS on the number of householders. We generate estimates for owner-occupied housing using the finest geographic level available in the given RECS survey year by applying the survey weights provided in the RECS. The resulting estimates are a weighted average representative of an owner occupied housing unit within a given geographic unit. Appendix Figure A.1 shows an example of the resulting estimates for four example states: California, Florida, New York, and Texas. The estimates update when new RECS years become available and show that for these states, the typical number of individuals within a home ranges from 2.4 up to almost 3 depending on the year and the state. We merge these at the state level to the per-capita emissions estimates and multiply by the number of householders to obtain a typical *per residence* estimate for each state from 1990 to 2021.

Figure 13 shows the outcome of this exercise: state-level per-residence estimates of metric tons of CO_2 emissions ordered from most to least based on 1990 emissions. The figure shows that on average, CO_2 emissions per residence are decreasing over time, especially for coal-heavy, and cold, states such as North Dakota, Wyoming, and West Virginia. Appendix Tables A.1 through A.4 show the average metric tons of CO_2 from energy consumption per residence from 1990–2021 by state. These tables show the estimates displayed in Figure 13.

Figure 13: CO_2 per Residence by State



Note: This figure shows metric tons of CO_2 per residence by state from 1990 – 2021. This figure was generated using data from EIA RECS, EIA SEDS, and EIA Form-861 on state-level emissions, total residential customers, and number of householders. Source: Authors' calculations, EIA RECS, SEDS, and Form-861.

Next, we use data on the total number of housing units and single-family detached housing units from the five-year ACS estimates at the county level from 2010 through 2020 (Census Bureau ACS 5-Year Estimates 2022). We multiply the state-level CO_2 emissions estimates by the total number of housing units in each county in each state to estimate aggregate emissions from single-family homes in the US.

Figure 14 below shows the single-family housing stock estimates from the ACS data. As we do not have precise estimates prior to 2010, all estimates for years before 2010 use the estimates of housing stock from 2010 (in other words, from 1990-2009, housing stock is held constant at 2010 levels). Total housing stock increased by 7.4 percent from 2010 to 2020 (from 130,038,080 units in 2010 to 139,647,020 in 2021).[15]

While single-family housing stock in the US increased from 2010 – 2021, total CO_2 from energy consumption at these units decreased. Figure 15 shows trends in aggregate CO_2 emissions for all US housing and single-family detached homes. Emissions from residential energy consumption have decreased by 27.8 percent (from 1334.19 MMT in 2010 to 963.09 MMT in 2021).[16]

3.3 Comparison to Property-Level Results

3.3.1 Housing Stock or Changes in the Grid

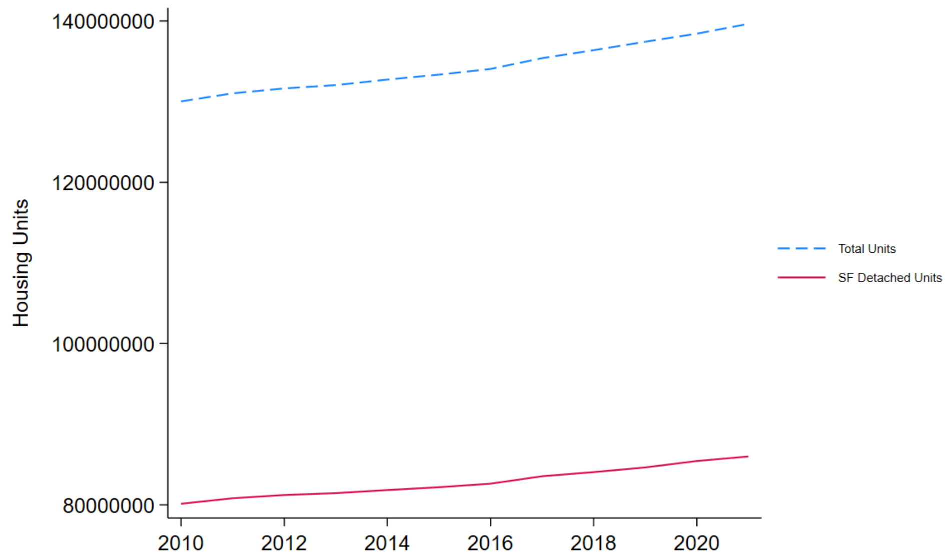
In this section, we investigate the relative importance of the greening of the US energy grid versus changes in US housing stock and energy consumption in driving the decrease in emissions from residential energy consumption. We do so by first holding state-level emissions and energy consumption patterns constant at their 2010 levels, and allowing for changes in housing stock. Second, we do the opposite and hold housing stock constant at its 2010 levels and allow for changes in state-level emissions rates and energy use patterns.

For the first case, we assume that state-level emissions rates per housing unit remained constant at their 2010 levels. It is important to note that these state-level emissions factors per housing unit reflect both the greening of the grid as well as changes in energy use per house. The CO_2 emissions per house are a function both of how much energy is used at a given house as well as the emissions factor of those energy sources. Figure 12 shows that residential energy consumption has increased slightly from 2010 to 2021, but Figure 13 shows

[15]Single family detached housing increased by 7.3 percent (from 80,135,946 in 2010 to 86,003,036 in 2021

[16]Emissions from US single-family detached homes have decreased by 28.4 percent (from 849.65 MMT in 2010 to 608.76 MMT in 2021); or by 20.6 percent from 2013 (766.45 MMT) to 2021).

Figure 14: Aggregate Housing Stock



Note: This figure shows the total number of housing units from 2010 to 2021 using data from the ACS 5-Year Estimates. Source: Authors' calculations, Census ACS 5-Year Estimates.

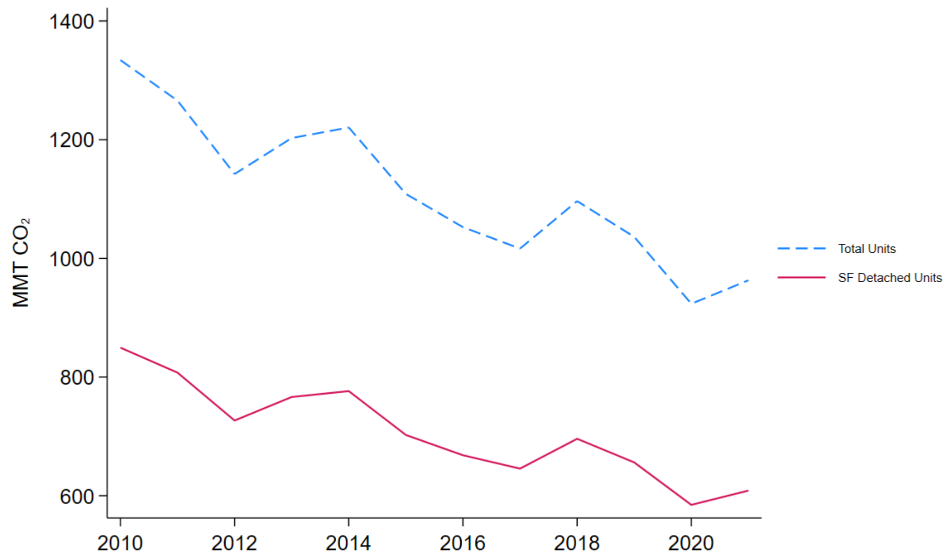
that average emissions per house are decreasing over time. Thus, changes in per-residence CO_2 emissions are primarily driven by less carbon-intensive energy generation. Holding the per-residence CO_2 emissions factor constant primarily asks: what role does the greening of the grid play in decreasing CO_2 emissions from housing?

Figure 16 shows the results of this exercise holding per-residence emissions constant to 2010 levels but allowing housing stock to grow over time. This exercise suggests that if the per-residence emissions factors had remained at their 2010 levels from 2010-2021, that CO_2 emissions from housing would have *increased* by 7.1 percent, from 1334.19 MMT in 2010 to 1428.60 MMT in 2021.[17] Or, CO_2 emissions from housing were about two-thirds of what they would have been had there only been growth in the housing stock, but no underlying changes in the energy grid or energy demand.

For the second case, we assume that housing stock remained constant at 2010 levels, but allow per-residence $CO2$ emissions to vary over time. This version asks: what role does the

[17]For single-family detached housing this would have represented a 7 percent increase from 849.7 MMT to 909.37 MMT.

Figure 15: Total MMT CO_2 for US Housing Stock



Note: This figure shows million metric tons of CO_2 emissions in aggregate for the whole of the US from 2010 – 2021. This figure was generated using data from EIA RECS, EIA SEDS, and EIA Form-861 on state-level emissions, total residential customers, number of householders, and number of housing units from the ACS. Source: Authors' calculations, EIA RECS, SEDS, Form-861, Census ACS 5-Year Estimates.

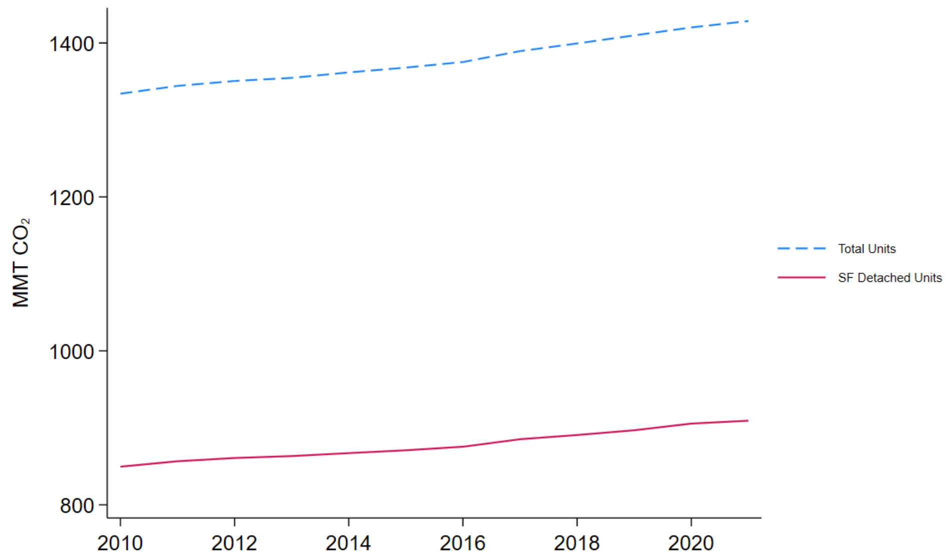
increase in housing stock play in changing CO_2 emissions?

Figure 17 shows the outcome of holding housing stock constant but allowing per-residence CO_2 emissions rates to vary over time. Emissions would have decreased by 32.4 percent, from 1334.19 in 2010 to 901.30 in 2021.[18] Or, CO_2 emissions from housing were *6.4 percent* higher in reality (901.30 MMT versus 963.09 MMT) than they would have been had there been no growth in housing stock, but underlying changes in the energy grid or energy demand.

These results suggest that if housing stock had been constant from 2010 to 2021, that we would have had 6 percent fewer emissions relative to the baseline case. And, if the per-residence emissions had remained constant from 2010 to 2021, we would have had almost 33 percent more carbon dioxide emissions from housing. Taken together, these findings indicate that the greening of the grid and changes in in energy demand during this time period played

[18]For single family detached units only, emissions would have decreased by 32.90 percent from 849.65 MMT to 570.12 MMT.

Figure 16: Total MMT CO_2 for US Housing Stock: Grid Emissions Constant



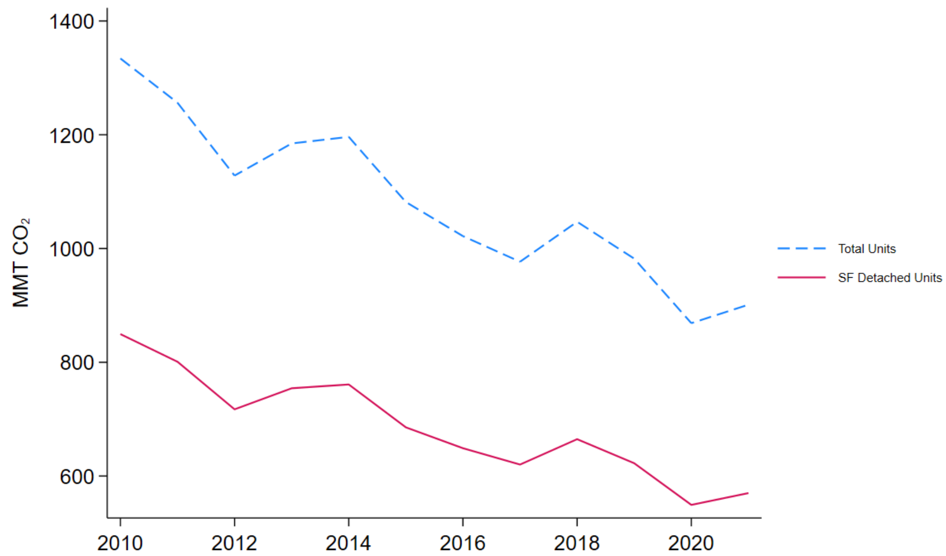
Note: This figure shows million metric tons of CO_2 emissions in aggregate for the whole of the US from 2010 – 2021. This figure was generated using data from EIA RECS, EIA SEDS, and EIA Form-861 on state-level emissions, total residential customers, number of householders, and number of housing units from the ACS. This figure holds the emissions rate per household constant since 2010 Source: Authors' calculations, EIA RECS, SEDS, Form-861, Census ACS 5-Year Estimates.

a more influential role in decreasing overall CO_2 emissions than did changes in housing stock.

4. Conclusion

This paper uses two alternative approaches to estimate CO_2 emissions from residential energy use. In the first approach, we use administrative data at the property-level from appraisals of single-family detached homes in the US. This data enables us to take into account local weather and property-level attributes that are correlated with residential energy use such as square footage, home heating fuel, home heating equipment, and home cooling equipment. Using this approach, we find that emissions from residential energy use decreased by 8.8 percent from 2013 to 2021 (654 MMT to 597 MMT). To compare across approaches, we use estimates for single-family detached housing from 2013 to 2020, which represents the overlapping sample and time period. Using the state-level approach, emissions would have decreased by 20.6 percent (from 766.45 MMT in 2013 to 608.746 MMT in 2021). In the earlier years of the sample, the appraisal data is not as representative of US housing stock as it is in 2021. For this reason, the property-level estimates from more recent years are more

Figure 17: Total MMT CO_2 for US Housing Stock: Housing Stock Constant



Note: This figure shows million metric tons of CO_2 emissions in aggregate for the whole of the US from 2010 – 2021. This figure was generated using data from EIA RECS, EIA SEDS, and EIA Form-861 on state-level emissions, total residential customers, number of householders, and number of housing units from the ACS. This figure holds the emissions rate per household constant since 2010 Source: Authors' calculations, EIA RECS, SEDS, Form-861, Census ACS 5-Year Estimates.

reliable than in earlier years.

Then, we estimate two alternative counterfactuals to determine the relative importance of the greening of the energy grid versus changes in property attributes. We calculate emissions under two counterfactual scenarios: (1) no change in the grid since 2010 and (2) no change in property-level characteristics after a property's first appraisal. (1) Answers the same question as the state-level approach, but (2) asks what role property attributes play in the overall change in CO_2 emissions from 2013 to 2021. The qualitative conclusion of part (1) is the same: the greening of the grid plays an important role in decreasing emissions during this time period. For part (2) we find that keeping property characteristics constant to the first appraisal, relatively little change in aggregate CO_2 emissions.

In the second approach, we use publicly available data at the state-level from the EIA, the EPA, and the Census ACS to estimate state-level CO_2 emissions from 2010 to 2021. We estimate state-level CO_2 emissions per property per year and find that in 2021, these range from 2.7 mt per house per year in California to 28.7 mt per house per year in West Virginia. Next, we aggregate these estimates using the ACS 5-year estimates of housing stock. We find that from 2010 to 2021, emissions decreased by 27.8 percent (from 1334 MMT to 963 MMT) for all US housing stock, and by 28.4 percent for all single-family detached housing stock from 850 MMT in 2010 to 608 MMT in 2020.

Then, we do a simple exercise to calculate two counterfactual scenarios: (1) no change in grid-level emissions factors from 2010 to 2020 and (2) no growth in housing stock from 2010 to 2021. We find that had the energy generation mix not changed from 2010 to 2021 emissions would have *increased* by 7.1 percent, or that emissions in reality were about two-thirds lower than they otherwise would have been had their been no change in the energy grid during this time period.

Overall, our results demonstrate that aggregate CO_2 emissions have decreased over the last decade, primarily driven by changes in electricity generation rather than changes in housing stock.

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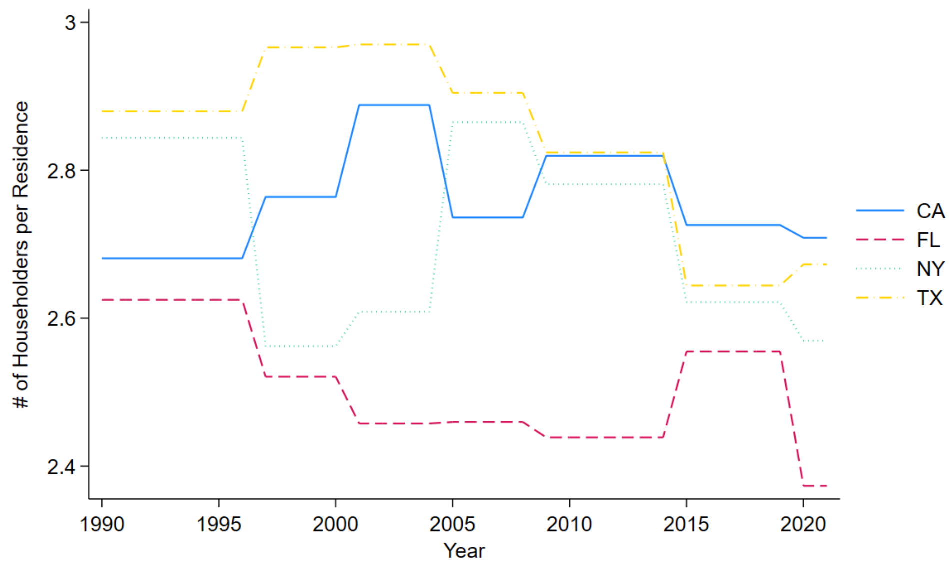
A Appendix

A.1 Tables and Figures

Figure A.1: Typical Number of Householders by State (for Four States)



Note: This figure was generated using data from EIA RECS on number of householders using the survey years: 1990, 1993, 1997, 2001, 2005, 2009, 2015, and 2020. Source: Authors' calculations and EIA RECS

Table A.1: Metric Tons of Carbon Dioxide per-Residence 1990 – 2021

State	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
AK	12.68	11.95	11.70	11.44	11.81	11.93	11.99	11.36	10.99	12.38	11.73	12.05	11.18	11.10	11.58	12.96
AL	13.51	14.24	14.51	15.97	14.67	15.92	17.27	15.38	15.94	15.86	17.32	16.37	17.41	16.93	16.47	17.05
AR	13.19	13.19	12.56	11.78	11.94	12.67	13.59	10.48	10.95	11.20	11.24	11.72	11.19	11.19	11.07	10.63
AZ	10.65	10.59	10.82	10.77	10.96	8.75	8.62	8.91	9.57	9.81	10.99	11.27	10.84	11.08	12.00	11.39
CA	3.77	3.64	3.61	3.62	3.86	3.28	3.16	3.26	3.75	3.78	3.64	3.89	3.56	3.51	3.64	3.23
CO	12.93	12.97	12.66	12.79	12.30	12.20	12.49	11.98	11.74	11.83	12.69	12.98	12.96	13.01	12.50	12.55
CT	9.70	9.41	10.01	9.24	8.87	8.52	9.18	9.85	8.60	8.98	9.71	9.07	8.58	9.55	10.10	9.31
DC	4.17	4.07	4.45	4.55	4.21	4.66	5.12	4.48	3.76	4.17	4.08	3.70	4.23	4.57	4.58	4.10
DE	13.84	14.15	12.92	13.89	13.18	12.28	12.54	9.80	9.42	9.08	9.19	9.34	9.22	10.20	10.45	10.68
FL	8.94	9.38	9.02	9.30	9.27	9.40	9.70	9.18	10.09	9.43	9.56	9.18	9.36	9.62	9.36	9.19
GA	11.76	10.68	10.30	11.12	10.59	11.22	11.19	10.51	10.62	10.34	11.33	10.41	11.26	11.13	11.27	11.72
HI	4.92	3.98	4.79	4.56	4.64	4.77	4.96	4.73	4.88	4.99	5.01	4.94	5.36	4.86	5.01	5.67
IA	13.67	14.59	13.24	14.34	13.83	14.65	14.92	14.62	14.66	14.86	15.20	14.42	14.74	14.64	14.25	13.50
ID	2.22	2.43	2.10	2.53	2.21	2.39	2.57	2.55	2.51	3.11	3.27	3.31	2.93	2.95	3.55	3.41
IL	9.93	10.38	9.72	10.75	10.47	10.92	11.76	11.85	10.72	11.24	11.74	10.81	11.69	11.64	11.54	11.16
IN	18.61	19.23	18.08	19.06	18.78	19.18	19.66	20.36	19.57	20.48	21.09	19.30	19.96	20.20	19.66	19.28
KS	14.37	14.61	12.49	15.37	14.62	14.34	16.44	14.71	15.18	15.60	16.81	15.34	16.94	16.67	15.79	15.05
KY	16.17	17.24	16.10	18.56	17.24	18.02	18.59	18.05	18.12	18.68	19.65	18.68	18.27	17.94	18.01	18.89
LA	9.99	9.93	10.03	10.48	10.35	10.62	9.65	8.82	9.44	9.19	9.79	9.41	9.91	9.59	9.62	10.19
MA	10.25	10.00	10.69	10.35	10.25	9.37	9.11	9.68	9.15	9.19	9.44	9.37	9.47	10.00	9.27	9.00
MD	8.96	8.96	8.80	9.55	9.51	9.19	9.78	8.74	8.84	9.25	9.21	8.83	8.63	9.05	9.31	9.21
ME	7.83	7.49	7.40	7.36	7.48	8.93	9.24	9.10	9.83	10.25	10.07	11.34	10.97	12.64	13.13	11.21
MI	12.31	12.54	12.22	12.43	12.54	12.75	13.22	13.15	12.48	12.93	12.85	12.42	12.83	12.64	12.39	12.15
MN	10.35	10.59	10.04	10.60	10.41	10.64	11.29	10.65	9.80	9.87	10.59	10.07	10.48	11.23	10.58	9.95
MO	13.74	14.24	13.14	13.07	13.84	15.02	15.89	16.06	16.14	15.90	16.21	16.76	16.83	17.85	17.74	17.15

Table A.2: Metric Tons of Carbon Dioxide per-Residence 1990 – 2021

State	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
AK	14.93	12.65	12.56	0	10.37	10.54	10.64	9.17	9.14	9.59	8.87	9.68	8.85	8.52	9.96	10.02
AL	17.34	17.60	16.65	14.08	16.60	15.00	12.74	12.55	12.97	13.29	11.95	10.55	11.86	10.64	7.85	8.51
AR	10.92	11.31	11.73	12.85	14.29	14.49	13.80	14.94	15.09	11.30	11.88	11.85	14.45	12.47	8.57	10.44
AZ	11.49	11.84	11.89	11.02	11.29	10.73	10.23	10.81	9.91	8.05	7.21	7.10	7.47	7.05	6.79	6.29
CA	3.36	3.43	3.45	3.42	3.30	3.15	3.27	3.19	2.82	2.70	2.55	2.54	2.52	2.62	2.70	2.70
CO	12.28	12.80	12.23	9.16	9.35	9.07	8.59	8.97	8.54	10.16	9.83	9.46	9.54	9.83	8.33	8.54
CT	8.29	8.10	7.81	8.40	8.37	7.69	7.49	7.86	7.95	7.68	6.59	6.53	7.84	7.66	7.61	8.10
DC	3.12	3.54	3.51	3.32	3.39	2.92	2.70	3.01	2.96	3.02	2.23	2.57	2.90	2.53	1.91	2.24
DE	9.10	10.07	9.51	6.89	7.82	6.85	6.99	6.78	6.52	6.49	6.25	5.37	5.60	4.67	4.04	4.23
FL	8.77	8.69	8.02	7.63	8.42	7.51	7.04	6.83	7.11	7.26	7.03	6.69	6.54	6.09	5.73	5.52
GA	11.36	11.87	11.20	10.77	11.99	9.80	7.89	7.89	8.85	7.58	7.70	6.87	7.32	6.71	5.69	6.03
HI	5.61	5.54	5.24	4.80	4.63	4.40	4.04	3.71	3.62	3.60	3.57	3.59	3.70	3.73	4.26	4.11
IA	12.86	14.03	14.84	14.13	14.93	13.67	12.01	12.48	12.53	9.90	8.94	8.88	10.67	9.45	6.87	7.98
ID	3.26	3.30	3.60	3.97	3.70	3.86	3.63	4.41	3.76	3.38	3.38	3.70	3.56	4.04	3.59	3.68
IL	10.43	11.16	11.44	11.76	11.91	11.56	10.36	11.78	11.96	9.61	8.87	8.55	9.61	9.08	7.67	8.30
IN	18.04	18.83	19.07	17.41	18.05	16.67	14.66	15.31	16.01	13.78	13.37	12.91	14.91	12.87	10.94	11.49
KS	13.77	15.18	14.72	15.50	15.47	14.84	12.53	13.76	13.40	10.33	9.62	8.55	9.85	9.13	9.76	10.25
KY	18.35	18.76	18.41	16.58	18.35	17.66	15.51	16.79	18.48	17.77	17.09	14.56	16.25	14.29	11.13	12.20
LA	9.35	9.30	9.62	10.06	11.46	11.65	10.14	9.95	9.56	8.87	7.87	7.10	7.79	6.99	6.27	6.86
MA	7.77	8.26	8.08	8.04	8.08	7.41	6.32	6.63	6.78	6.59	5.66	5.94	5.92	5.86	5.56	5.73
MD	8.21	8.66	8.10	7.33	7.54	6.51	5.63	5.79	6.41	5.99	5.62	4.53	5.79	4.71	4.01	4.46
ME	9.10	8.92	7.36	7.90	7.62	7.25	6.12	6.09	6.72	6.88	6.81	6.44	6.64	6.15	5.48	5.54
MI	10.73	11.39	11.37	12.51	12.19	11.77	10.74	11.77	11.76	10.33	9.55	9.53	10.50	10.19	8.92	9.20
MN	9.29	9.58	9.52	9.31	8.60	8.50	7.33	8.31	9.09	7.42	7.30	7.19	8.01	7.56	7.57	7.85
MO	16.16	16.06	16.21	15.88	16.65	16.75	14.88	16.10	15.95	13.28	12.91	13.71	14.51	13.02	12.09	12.91

Table A.3: Metric Tons of Carbon Dioxide per-Residence 1990 – 2021

State	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
MS	7.03	6.48	6.01	7.08	7.00	7.35	8.23	7.88	8.57	8.64	9.35	12.20	9.72	9.51	9.80	9.89
MT	18.59	19.73	19.11	17.93	19.29	18.43	17.06	20.51	18.64	19.32	18.62	22.90	20.08	22.36	22.41	22.09
NC	8.90	8.96	9.99	10.71	9.54	10.06	11.41	10.52	10.37	10.05	10.83	10.43	10.87	10.95	10.99	10.98
ND	51.89	54.15	55.13	56.02	54.54	53.90	57.27	53.33	53.80	50.61	51.73	49.57	50.85	49.53	46.50	47.36
NE	12.56	13.35	11.89	14.15	13.02	13.85	14.25	14.45	14.58	13.98	14.55	15.47	14.93	14.99	14.14	13.83
NH	9.90	9.55	9.86	9.79	9.73	9.65	9.80	10.40	9.76	9.51	9.50	8.80	8.82	12.11	12.72	11.83
NJ	7.15	7.11	7.57	7.51	8.33	7.76	8.16	7.06	6.29	6.67	7.11	7.16	7.03	7.63	7.42	7.21
NM	16.84	14.81	15.84	15.51	15.05	14.31	14.77	15.25	15.23	15.60	16.07	16.15	15.23	15.93	16.02	16.05
NV	15.94	16.55	15.90	15.23	15.31	12.78	13.44	12.45	13.15	12.48	14.15	13.48	11.44	12.18	12.76	12.48
NY	8.31	7.98	8.21	7.82	7.70	7.70	7.83	6.99	6.69	7.08	7.64	7.59	7.16	7.70	7.58	8.69
OH	12.33	12.97	12.93	13.60	12.79	13.14	14.03	13.77	13.22	13.53	14.03	12.99	14.48	14.92	14.28	14.28
OK	16.46	17.00	16.15	17.97	16.98	17.52	18.37	15.14	15.42	14.48	15.38	15.73	16.70	16.46	15.16	16.70
OR	2.48	3.22	3.13	3.51	3.67	2.66	3.01	2.66	3.68	4.03	4.13	4.50	3.86	4.26	4.17	4.87
PA	14.06	14.11	14.36	14.86	14.37	14.27	14.99	12.89	12.22	12.72	13.56	13.18	13.79	14.47	14.40	14.45
RI	6.60	7.49	9.26	8.79	8.90	8.28	10.11	9.72	9.05	8.50	8.58	9.08	8.56	8.76	8.43	8.30
SC	7.08	7.21	6.84	7.86	7.49	7.39	8.43	7.62	7.98	8.43	9.10	8.75	9.09	9.07	9.82	9.66
SD	10.40	9.91	8.53	9.12	9.36	8.98	9.39	10.04	8.85	9.48	9.85	9.26	8.91	9.21	8.94	7.37
TN	11.25	10.71	11.10	12.79	11.84	12.14	12.68	11.96	11.50	11.25	12.24	11.37	11.17	10.34	10.56	10.85
TX	12.98	12.77	12.09	13.10	12.24	12.09	12.70	12.97	13.27	13.10	13.74	13.26	13.66	13.32	12.87	12.66
UT	17.89	17.43	16.82	17.50	17.04	15.56	15.66	15.87	15.65	15.92	15.79	15.44	16.25	16.13	16.24	15.74
VA	6.57	6.85	7.14	7.95	7.45	7.56	8.32	7.79	7.76	7.91	8.84	8.55	8.48	8.70	8.57	8.44
VT	6.43	7.02	7.25	7.18	6.67	6.17	6.55	6.49	6.19	5.98	6.93	6.66	6.21	6.59	7.39	6.66
WA	3.27	3.40	3.50	3.92	4.12	3.41	4.13	3.66	3.90	3.97	4.45	5.06	4.46	4.59	4.46	5.05
WI	11.21	11.82	11.11	11.49	11.31	11.60	12.34	12.43	11.50	12.11	12.37	11.62	12.03	11.94	11.68	11.51
WV	37.56	36.40	37.33	38.33	40.87	40.82	44.12	42.84	42.64	44.95	44.85	41.55	48.72	48.71	46.73	47.43
WY	40.78	42.19	43.36	43.76	44.18	45.16	46.39	43.50	48.31	46.21	46.91	45.15	45.79	45.89	44.50	42.87

Table A.4: Metric Tons of Carbon Dioxide per-Residence 1990 – 2021

State	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
MS	9.89	10.34	9.78	8.84	10.32	8.65	8.05	7.94	8.90	9.69	9.81	8.75	10.19	9.69	9.54	9.29
MT	21.61	20.79	21.79	24.09	26.92	24.10	21.64	23.01	23.65	20.20	18.65	18.96	18.26	19.37	12.92	14.58
NC	10.05	10.64	10.17	9.24	10.61	8.69	7.58	7.67	8.00	7.11	6.87	6.16	6.66	6.19	4.82	5.20
ND	43.41	44.17	45.26	46.30	41.98	39.00	35.74	35.62	33.36	28.71	26.90	25.45	27.54	25.14	22.68	21.57
NE	13.37	13.27	14.14	15.28	15.15	15.94	13.91	15.88	15.26	12.59	11.42	10.97	13.43	12.83	11.16	10.80
NH	10.29	10.15	9.94	9.87	9.43	9.25	7.41	7.57	8.36	7.80	6.52	6.61	7.14	6.95	6.60	6.41
NJ	6.22	6.91	6.74	6.81	6.91	6.43	5.84	6.47	7.22	6.62	6.22	5.96	6.64	6.50	5.51	5.70
NM	15.59	15.17	15.02	15.45	13.99	14.37	13.21	13.29	11.39	10.33	9.82	9.41	8.26	9.14	8.50	7.74
NV	8.63	8.43	8.60	8.33	7.90	7.04	6.88	7.31	6.94	5.81	5.75	5.47	5.61	5.70	5.58	5.50
NY	7.30	7.97	7.43	6.42	6.44	6.13	5.92	5.99	6.46	6.04	5.37	5.20	6.02	5.80	5.14	5.55
OH	13.20	13.71	13.50	12.73	13.14	12.19	10.36	11.56	11.70	10.31	9.86	9.60	10.23	9.27	8.14	8.19
OK	16.41	16.14	16.60	17.44	17.15	17.28	15.18	15.09	14.30	12.45	11.01	9.67	11.21	9.57	8.37	8.68
OR	4.22	5.22	5.49	4.75	4.64	3.91	3.81	4.53	3.90	3.81	3.70	3.95	3.86	4.54	3.54	3.39
PA	13.36	13.92	14.23	12.35	12.93	12.26	11.23	11.79	11.66	11.02	10.07	9.50	10.19	9.74	8.81	9.57
RI	7.06	7.81	7.67	9.00	8.96	9.16	8.94	8.73	8.58	8.45	6.82	7.03	8.61	7.71	7.69	8.31
SC	9.29	9.60	9.62	9.22	10.36	9.02	7.48	6.58	7.66	6.63	6.41	5.66	6.69	5.75	5.09	5.42
SD	7.53	6.81	8.47	8.10	7.93	6.59	6.39	7.07	6.74	4.53	5.51	5.32	6.35	6.90	5.59	5.29
TN	10.81	10.81	10.37	8.56	9.67	8.68	7.46	7.32	8.13	7.29	7.36	6.49	6.16	5.60	4.24	4.96
TX	11.82	11.75	11.51	10.66	11.04	11.55	10.22	10.32	10.04	8.91	8.26	8.05	8.16	7.55	7.03	6.91
UT	15.92	16.20	16.24	17.57	16.83	16.24	14.67	16.25	14.93	12.33	11.06	10.98	11.22	11.45	11.98	12.81
VA	7.17	7.89	6.97	6.80	7.34	6.11	5.16	6.32	6.39	5.99	5.85	5.11	5.71	4.99	4.79	4.27
VT	5.85	5.85	5.07	6.59	5.70	5.69	4.82	5.69	6.14	5.63	5.25	5.64	6.05	6.46	4.98	4.95
WA	4.18	4.66	4.93	4.42	4.14	3.40	2.97	3.86	3.70	3.36	3.28	3.79	3.46	4.15	3.54	3.45
WI	10.08	10.35	10.71	9.40	9.53	9.49	8.22	9.96	9.62	9.76	9.30	9.58	9.97	9.45	8.02	8.26
WV	42.87	43.58	42.32	36.29	41.17	38.60	34.52	36.47	38.64	35.28	36.66	33.07	32.65	30.02	24.88	28.70
WY	41.12	41.50	40.70	44.69	43.39	42.65	42.64	46.63	42.70	36.40	36.16	36.45	36.39	34.29	29.59	28.11

A.2 UAD and RECS Variable Standardization

The RECS and the UAD share a number of common variables to describe physical characteristics of single-family detached properties. We take a number of steps to standardize these variables. The variables include:

- Exterior Wall Type – brick, wood, siding, stucco, shingle, stone, concrete, other
- Roofing Type – ceramic, wood, metal, slate, shingles, concrete, other
- Window Frame Type – wood, metal, vinyl, composite, fibreglass, mixed, other
- Window Glass Type – single pane, double pane, triple pane
- Heating Fuel – natural gas, propane, fuel oil, electric, wood, other
- Heating Equipment Type – steam, central furnace, central heat pump, electric, gas/oil, stove, fireplace, portable, other
- Air Conditioning Equipment Type – central ac, central heat pump, ductless, window/wall, portable, evaporative
- Square Feet
- Number of Bedrooms
- Number of Bathrooms
- Year Built

We harmonize the names and categories of these variables across the two datasets to ensure consistent defintions of each variable.

Table A.5: 2020: Monthly BTUs (1000s) Use

	(1) Monthly BTU (1000s)	(2) Monthly BTU (1000s)	(3) Monthly BTU (1000s)	(4) Monthly BTU (1000s)
Monthly HDD65	6.700**	6.781**	6.580**	6.561**
	(0.180)	(0.173)	(0.167)	(0.168)
Monthly CDD65	4.310**	4.660**	5.081**	5.066**
	(0.283)	(0.252)	(0.245)	(0.246)
Square Feet		1.288**	1.285**	1.262**
		(0.099)	(0.096)	(0.096)
No. Bedrooms		428.552**	321.649**	330.893**
		(65.435)	(62.845)	(62.777)
No. Bathrooms		279.705**	226.975**	227.501**
		(92.773)	(87.299)	(87.224)
Year Built		−17.900**	−16.619**	−16.623**
		(1.984)	(1.829)	(1.865)
1[NG Heat]			1921.991**	2024.426**
			(106.610)	(121.233)
1[Propane Heat]			−554.286*	−505.385*
			(239.815)	(244.529)
1[Fuel Oil Heat]			−649.428	−691.009*
			(332.290)	(339.142)
1[Wood Heat]			−2321.746**	−2938.669**
			(238.902)	(761.231)
1[Other Heat]			−2330.687**	−2229.136**
			(304.469)	(591.885)
1[Steam Heat]				1050.015**
				(287.696)
1[Heat Pump]				298.138*
				(128.586)
1[Oil Heat]				−66.743
				(249.644)
1[Pellet Stove Heat]				1005.716
				(779.605)
1[Portable Heat]				573.500*
				(281.442)
1[Other Heat]				337.811
				(559.808)
1[Central AC]				317.600*
				(131.389)
1[Window AC]				284.086
				(188.478)
1[Evap AC]				185.356
				(331.487)
Constant	3589.124**	34528.651**	31444.645**	31057.538**
	(60.559)	(3867.281)	(3566.592)	(3628.493)
Month-of-Year FE	Y	Y	Y	Y
IECC Zone	Y	Y	Y	Y
N	105170	105170	105170	105170
Adj. R-Squared	0.29	0.38	0.43	0.43

* p<0.05 ** p<0.01. The standard errors reported in parenthesis have been clustered at the individual level. Weighted by RECS sampling weights.

Table A.6: 2020: Monthly Electricity Use

	(1) Monthly kWh	(2) Monthly kWh	(3) Monthly kWh	(4) Monthly kWh
Monthly HDD65	0.254*	0.256*	0.304*	0.308*
	(0.023)	(0.022)	(0.021)	(0.021)
Monthly CDD65	1.140*	1.170*	1.071*	1.032*
	(0.060)	(0.056)	(0.055)	(0.054)
Square Feet		0.163*	0.169*	0.166*
		(0.018)	(0.018)	(0.018)
No. Bedrooms		41.199*	49.294*	49.819*
		(11.865)	(11.628)	(11.563)
No. Bathrooms		25.199	25.794	22.791
		(16.730)	(16.313)	(16.089)
Year Built		−0.328	−0.603*	−0.896*
		(0.287)	(0.286)	(0.289)
1[NG Heat]			−253.134*	−242.973*
			(22.400)	(25.877)
1[Propane Heat]			−168.683*	−127.861*
			(38.172)	(40.320)
1[Fuel Oil Heat]			−296.199*	−214.855*
			(36.186)	(38.673)
1[Wood Heat]			−113.260*	−66.756
			(54.522)	(96.687)
1[Other Heat]			279.118*	342.360*
			(134.366)	(136.404)
1[Steam Heat]				−67.093
				(34.301)
1[Heat Pump]				83.572*
				(34.721)
1[Oil Heat]				60.753
				(31.492)
1[Pellet Stove Heat]				29.023
				(109.338)
1[Portable Heat]				88.533
				(74.944)
1[Other Heat]				45.346
				(68.951)
1[Central AC]				162.334*
				(21.779)
1[Window AC]				122.988*
				(29.942)
1[Evap AC]				42.014
				(45.129)
Constant	654.257*	805.631	1474.609*	1914.391*
	(9.763)	(560.464)	(561.429)	(565.339)
Month-of-Year FE	Y	Y	Y	Y
IECC Zone	Y	Y	Y	Y
N	105170	105170	105170	105170

* p<0.05 ** p<0.01. The standard errors reported in parenthesis have been clustered at the individual level. Weighted by RECS sampling weights.

Table A.7: 2020: Monthly Natural Gas Use (Therms)

	(1) Monthly NG Therms	(2) Monthly NG Therms	(3) Monthly NG Therms
Monthly HDD65	0.072*	0.074*	0.073*
	(0.002)	(0.002)	(0.001)
Monthly CDD65	0.004*	0.008*	0.010*
	(0.002)	(0.002)	(0.001)
Square Feet		0.010*	0.010*
		(0.001)	(0.000)
No. Bedrooms		2.168*	2.213*
		(0.607)	(0.196)
No. Bathrooms		1.425	1.634*
		(0.978)	(0.296)
Year Built		−0.185*	−0.159*
		(0.017)	(0.006)
1[Steam Heat]			14.174*
			(1.025)
1[Other Heat]			12.202*
			(3.108)
1[Central AC]			−5.102*
			(0.479)
1[Window AC]			−1.621*
			(0.779)
1[Evap AC]			−3.771*
			(0.960)
Constant	26.735*	361.693*	313.520*
	(0.725)	(33.219)	(11.821)
Month-of-Year FE	Y	Y	Y
IECC Zone	Y	Y	Y
N	55652	55652	55652

* p<0.05 ** p<0.01. The standard errors reported in parenthesis have been clustered at the individual level. Weighted by RECS sampling weights.

Table A.8: 2020: Monthly Propane/Fuel Oil/Kerosene (gal.)

	(1) Monthly P/FO/K (gal.)	(2) Monthly P/FO/K (gal.)	(3) Monthly P/FO/K (gal.)
Monthly HDD65	0.025*	0.022*	0.021*
	(0.008)	(0.007)	(0.007)
Monthly CDD65	0.022	0.023	0.023
	(0.014)	(0.013)	(0.014)
Square Feet		0.005	0.004
		(0.003)	(0.003)
No. Bedrooms		3.190	4.093
		(2.439)	(2.391)
No. Bathrooms		7.435*	6.837*
		(2.856)	(2.868)
Year Built		−0.092	−0.090
		(0.061)	(0.060)
1[Steam Heat]			13.913*
			(4.619)
1[Oil Heat]			−5.681
			(6.601)
1[Other Heat]			−5.644
			(12.504)
1[Central AC]			4.282
			(4.561)
1[Window AC]			0.744
			(4.938)
1[Evap AC]			0.944
			(14.746)
Constant	42.468*	191.562	183.807
	(3.882)	(121.089)	(117.083)
Month-of-Year FE	Y	Y	Y
IECC Zone	Y	Y	Y
N	6113	6113	6113

* p<0.05 ** p<0.01. The standard errors reported in parenthesis have been clustered at the individual level. Weighted by RECS sampling weights