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The Environmental Impact of Sharing: Household and Urban Economies in CO_2 Emissions

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Abstract

Studies find that per capita carbon dioxide emissions (CO_2) decrease with household size and urban density, so the demographic trends of declining household size and dense urbanization produce countervailing effects with respect to emissions. We posit that both trends operate on a common scaling mechanism realized through the sharing of carbon-intensive expenditures. With detailed data from the United States Consumer Expenditure Survey, we construct a dataset of CO_2 emissions at the household level and leverage a unique measure of residential density to estimate household and urban economies. We find that dense urban areas have per capita emissions 23 percent lower than rural areas, and that adding an additional member to a household reduces per capita emissions by about 6 percent. We also show that household economies are about twice as large in rural as compared to dense urban areas. These results suggest that the carbon benefits of dense urbanization have the potential to offset the effects of declining household size.

JEL Codes: D1, Q4, R2, R3
Keywords: emissions, urban density, sharing, household size, energy

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1. Introduction

Studies frequently find that per capita carbon dioxide (CO_2) emissions are lower for people who live in multi-person households as well as for people who live in dense urban environments. We refer to these stylized facts as *household economies* and *urban economies* in CO_2 emissions. The former are the result of household economies of scale, which are analogous to economies of scale in production. If per capita income is held constant, then households exhibit economies of scale when increases in household size raise their members' utility. Empirical research finds that, holding per capita income constant, subjective well-being increases with household size (Rojas, 2007). Indeed, these economies of scale are taken for granted whenever equivalence scales are used to assign each household a value proportional to its needs based on its size and composition.[1] Economists attribute household economies to the existence of household public goods that are relatively non-rival in consumption. For example, housing, furniture, and appliances are shared by many household members. Consistent with this, analysis of the Consumer Expenditure Survey (CES) shows that households with more members tend to spend a smaller percentage of their income on household public goods (Salcedo et al., 2012).[2]

Recently, researchers have recognized that carbon-intensive goods are largely household public goods. For example, residential energy and transportation are easily shared within households. Schroder et al. (2015) show that larger households tend to spend less on energy per person. Using expenditure data to calculate household carbon footprints, Underwood and Zahran (2015) find that per capita carbon dioxide (CO_2) emissions also decline with household size. These household economies in CO_2 emissions suggest that the trend towards smaller household size undermines the sharing of carbon-intensive goods within households, placing upward pressure on per capita emissions, and that people can reduce emissions by living together in large households (Schroder et al., 2015; Underwood & Zahran, 2015). A separate literature has recognized that people can reduce their emissions by living in dense urban environments, generating urban economies. In this paper, we address the environmental benefits of sharing carbon-intensive goods by estimating household economies and urban economies in a single model, allowing us to bridge these two interrelated areas of research.

Relative to the household scale economies literature, the relationship between urbanization and CO_2 emissions is more uncertain. Many researchers have shown that national greenhouse gas emissions increase with the share of population living in urban areas (Jorgenson et al., 2014; Ponce de Leon Barido

[1] The Organization for Economic Cooperation and Development (OECD) has used an equivalence scale that implies each additional adult needs 70% of that of a single adult, while each child needs only 50% of a single adult (OECD, 2013). More recently, both the OECD and the United States Census Bureau have used the so-called 'square-root scale' that implies, for instance, that a household of four persons has needs twice as large as one composed of a single person but does not distinguish between adults and children. The US poverty threshold assumes that additional household members (adults and children) need just 35% as much income as an adult living alone (US Department of Health and Human Services 2016).

[2] However, empirical analyses of household expenditures are not always easy to reconcile with intuition. For example, Deaton and Paxson (1998) show that per capita expenditures on food decline with household size, even though food appears to be a private good.

& Marshall, 2014), but this positive effect may depend on the level of affluence and stringency of environmental policy (Poumanyvong & Kaneko, 2010). Meanwhile, micro-level studies show that households in dense urban environments generate significantly lower CO_2 emissions than their rural counterparts (Glaeser and Kahn, 2010; Jones and Kammen, 2011; Shammin et al. 2010), even if the general equilibrium effects of increasing urban density are uncertain (Gaigne *et al.* 2012). However, not all urban forms have environmental benefits. Suburban households generally have higher emissions than both rural households and dense urban households (Jones and Kammen, 2014; Glaeser and Kahn, 2010; Ottelin et al., 2015). The mixed evidence for urban economies may arise from urbanization being a weak proxy for urban density.[3]

Cities may generate urban economies only if they provide a social and technological infrastructure that facilitates sharing. Urban density can reduce emissions by enabling the sharing of goods *between* households, functionally identical to the sharing of goods *within* multi-person households. That is, both dense urban environments and large households facilitate sharing of carbon intensive expenditures, driving per capita emissions downward. As Glaeser and Kahn (2004) suggest, cities can be conceptualized as the absence of physical space between people. So, too, can large households. In multi-person households, members *successively* and *simultaneously* share the household and its energy requirements (Yates, 2016). Using the same kitchen and living room means that this space is used relatively more intensively. Sharing meals, television viewing, loads of laundry, and heating, cooling, and lighting allows households to reduce per capita consumption of carbon intensive goods and services (Underwood & Zahran, 2015; Yates, 2016). Like households, cities enable individuals to *successively* and *simultaneously* share the built environment and its energy requirements. For example, dense housing allows households to share home heating and cooling via shared walls. Similarly, urban infrastructure, such as sidewalks, bike lanes, and public transportation, provide city dwellers with alternatives to travelling in private vehicles. Dense urban environments may also foster the inter-household sharing of private goods. Decentralized borrowing and lending of goods may become an increasingly important in the digital economy (Fremstad, 2016), and sharing-economy platforms tend to be most successful in cities where they can better match people with underutilized assets due to improved access (Yates, 2016).

In this paper, we address the environmental benefits of sharing carbon-intensive goods. One body of research suggests that declining household size will increase CO_2 emissions, while another suggests that urban density can reduce emissions. With the exception of Ala-Mantila et al. (2016)[4], little work has connected the countervailing effects of these demographic trends. With consumption sharing as the hypothesized mechanism generating both household and urban scale economies, we estimate the net effect of declining household size and urbanization, showing that urban density has the potential to offset declining household economies resulting from the demographic drift toward more and smaller households.

[3] Liddle (2013), for instance, finds that the correlation between national population density and urban density is relatively low (0.35) and that national urbanization levels are actually negatively correlated with urban density.

[4] Using household data from urban areas with populations greater than 15,000 people in and around Helsinki, Finland, they find evidence that opportunities for inter-household sharing, via dense housing and urban transportation infrastructure, can offset losses associated with smaller households in cities.

To estimate household and urban economies in CO_2 emissions, we use a nationally-representative sample of United States (US) households, leveraging a unique measure of residential density. In the next section we discuss our data and methods, including our measure of residential density. In Section 3 we present our results. Finally, in Section 4 we discuss the implications and importance of our findings and in Section 5 we conclude with limitations and suggestions for future research.

2. Data and Methods

This paper uses detailed expenditure data to estimate CO_2 emissions at the household level. Using data from the US Consumer Expenditure Survey (CES) from 2012-2014 we construct a nationally representative pooled cross-section of American households. The Interview Survey, used here, captures approximately 85-95 percent of household expenditures.[5] Each household can appear in the survey for no more than four consecutive quarters. CES Interview Survey data on household expenditures cover 14 broad categories: food, alcoholic beverages, housing, apparel, transportation, healthcare, entertainment, personal care, reading, education, tobacco products, cash contributions, personal insurance, and miscellaneous. These 14 categories disaggregate into 50 detailed expenditure categories that we match to estimated carbon intensities to determine household CO_2 emissions.

We use CO_2 intensities for these 50 detailed expenditure categories similar to those in Shammin & Bullard (2009) and Underwood & Zahran (2015), which are based on an economic input–output life cycle assessment (EIOLCA) model developed by Hendrickson et al., (2006) and presented in Table A1 of the Appendix. These CO_2 intensities are adjusted to account for the carbon content of fuel type[6] and updated to reflect current prices and energy intensities using US city-average product-specific consumer price indices where available[7], and the economy-wide reduction in energy intensity (as measured by BTU per dollar of real GDP) from 2003-2013 of 14 percent. We calculate total household CO_2 emissions by first determining the emissions resulting from expenditures on each of the 50 detailed categories by multiplying reported quarterly expenditures in the CES Interview Survey by the associated annual intensity in Table A1. These disaggregated emissions are then summed over the 50 categories to obtain total quarterly household CO_2 emissions for the entire sample. In Table A1 we categorize these emissions somewhat differently than the CES to highlight the three primary components of household emissions: *residential energy*, *transportation*, and *food and beverages*, which together constitute 80 percent of household emissions.

[5] The Interview Survey does not collect expenses for very frequently purchased items such as housekeeping supplies, personal care products, and nonprescription drugs which account for around 5 to 15 percent of expenditures.

[6] This adjustment, not implemented in Underwood & Zahran (2015), accounts for the differences in the carbon intensities of natural gas, gasoline, and heating fuel. The EIOLCA model captures all emissions associated with the extraction, refining, and distribution of these fuels, but does not account for the emissions released when these fuels are burned by the final consumer.

[7] For expenditure categories where product specific indices were unavailable the "all items" CPI was used. These include mortgage interest; property taxes; life and personal insurance, retirement, pensions, and Social Security; health insurance (product-specific pricing only available from 2006); and miscellaneous.

Mean annualized household expenditures and emissions as well as expenditure and emissions shares are summarized in Table 1. Residential energy and gasoline account for only 11 percent of total expenditures, on average, but comprise two-thirds of total annual household CO_2 emissions which average 32.3 metric tons for the typical household in the United States over the period 2012-2014, according to our sample (see Table 2). We also estimate mean annualized per capita CO_2 emissions to be 15.2 metric tons, consistent with data from the United Nations (16.7 metric tons in 2012) and the US Department of Energy (16.1 metric tons in 2013) (Boden et al., 2016; United Nations, 2016).

[Insert Table 1]

The spatial clarity provided by the CES is imprecise, largely due to its sample design, which focuses on metropolitan statistical areas (MSAs) as the geographical basis for sample selection. While this method yields a nationally representative sample, the coding of the urban population is imperfect.[8] We combine information on the type of housing structure, the number of units in the structure, and the urban/rural designation in the CES to construct a novel measure of residential density. We split households into four categories: (1) rural households, comprised of rural households in single-family detached homes or mobile homes; (2) suburban households, comprised of urban households in single-family detached homes or mobile homes; (3) semi-detached urban households, comprised of urban households in multi-family structures with at least one shared wall and no more than four floors; and (4) dense urban households, comprised of urban households in row/townhouse inner units, high-rise apartments, or other apartment buildings. This method enables the classification of all but four percent of observations, yielding a sample of 72,608 quarterly observations from 28,444 unique households (consumer units).[9] The socioeconomic characteristics of the households in each density category are summarized in Table 2. As expected, households in suburban areas tend to be older, wealthier, and larger than households in dense urban areas, while rural households have incomes similar to urban households but are considerably larger.

[Insert Table 2]

We estimate the magnitude of household and urban economies in CO_2 emissions using a linearized STIRPAT model, in which technology and population are held constant (see Liddle, 2015). Our model assumes that log household emissions per capita are a function of affluence, but also household size and

[8] According the BLS, urban population is defined as all persons living in a MSA and in urbanized areas and urban places of 2,500 or more persons outside of MSAs. Thus, urban, defined in the CES, includes the rural populations within MSAs.

[9] Practically speaking, a consumer unit can be considered a household; however, technically it is defined by the BLS as: (1) all members of a particular household who are related by blood, marriage, adoption, or other legal arrangements; (2) a person living alone or sharing a household with others or living as a roomer in a private home or lodging house or in permanent living quarters in a hotel or motel, but who is financially independent; or (3) two or more persons living together who use their income to make joint expenditures.

urban form. We use household expenditures rather than income as our measure of affluence, because expenditures provide a better measure of a household's permanent income (Mathur and Morris, 2012). Our basic model is:

$$\ln(hh\ CO_2\ emission\ per\ capita)_{it} = \beta_0 + \beta_1 \ln(pc\ expenditures)_{it} + \beta_2 adults_{it} + \beta_3 children_{it} + \beta_4 suburban_{it} + \beta_5 semidetached\ urban_{it} + \beta_6 dense\ urban_{it} + [\beta X_{it}] + \varepsilon_{it} \quad (1)$$

where i denotes each household and t denotes each quarter. We estimate this model using population weights for all 72,608 households-quarter observations with standard errors clustered at the household level. The vector X_{it} includes all our control variables, including year fixed effects. If people do *not* share carbon-intensive goods like home heating and cooling or transportation *within* or *between* households, then our estimates of β_2 through β_6 will be equal to zero. However, if there are household economies or urban economies in CO_2 emissions, then these coefficients should be negative. Since we estimate these parameters simultaneously, we can compare the relative size of these coefficients to net the countervailing effects of declining household size and dense urbanization in the United States.

3. Results

Table 3 presents our baseline results. Column (1) simply regresses emissions per capita on expenditures per capita. We find that a 10 percent increase in household expenditures per capita is associated with a 7.2 percent increase in per capita emissions. This model ignores the possibility of sharing goods that generate emissions within households and between households. Column (2) includes the number of adults and children in the household to estimate the effect of intra-household sharing on emissions. Consistent with Underwood and Zahran (2015), results indicate that adding an additional adult to a household while maintaining the same per capita expenditures reduces per capita emissions by about 1.7 percent, while adding a child reduces per capita emissions by 6.4 percent.[10]

[Insert Table 3]

We estimate urban economies by including indicator variables for suburban, semi-detached urban, and dense urban households. Compared to rural households, Column (3) reports a small environmental benefit to living in a suburban setting but substantial benefits to living in urban environments. Living closer to neighbors presumably reduces emissions, because shared walls reduce heating and cooling costs and greater urban density reduces carbon-intensive forms of transportation. Controlling for this local measure of residential density also increases our estimate of household economies of scale in CO_2 emissions, with an additional adult or child now reducing per capita emissions by 4.6 or 7.2 percent, respectively. Our finding that carbon-intensive goods are more easily shared with children than with adults is consistent with the OECD equivalence scale that assumes kids need fewer resources than adults.

[10] Using the standard formula for computing the exact percentage change, $= 100 \times e^{(\beta-1)}$

Since our estimates of household emissions are expenditure-derived, one potential confounding factor is that many renters do not directly pay for energy because utilities are included in rental agreements. Households that have utilities included in rent may report zero expenditures on natural gas, electricity, and/or heating oil when in fact they are still consuming these goods. In our sample, 37 percent of households are renters, of which 53 percent live in dense urban areas. Moreover, 30 percent of renters report that natural gas, electricity, and/or heat is included in their rent. Column (4) includes indicator variables for whether or not a household is a renter and whether or not specific utilities are included in rent. The environmental benefit of living in an urban setting remains substantial, but the effect is reduced by a one-third compared with the results in Column (3). We find similar urban economies when we estimate the effect separately for renters and non-renters. To maintain the largest possible sample, we keep these rental controls in all subsequent analysis.

Table (4) tests the robustness of our baseline results. Columns (1), (2), and (3) introduce geographical controls to the model to account for potential regional differences in the number of heating and cooling degree days, the age of the housing stock, transportation infrastructure, and prices of goods. Column (1) includes regional fixed effects denoting the four US Census regions (Northeast, Midwest, South, and West) which we are able to identify for the entire sample. Column (2) includes state-level fixed effects for the 39 states identified in the CES. Column (3) includes MSA-level fixed effects which are only identified for urban households in one of the 21 MSAs identified in the CES. In Columns (2) and (3) we estimate the effect of living in an urban household relative to living in a suburban household.[11] Given our robust finding that suburban households emit about 5 percent less than rural households, our results in Columns (2) and (3) are consistent with the results in Column (1). In subsequent analyses we include regional fixed effects to account for any regional differences while retaining the largest number of observations. Columns (4), (5), and (6) add gender, race, and education controls for the reference person of the household, and our estimates remain robust to these specifications.

[Insert Table 4]

Across all models in Table 4 we consistently find statistically significant evidence for both household and urban economies in CO_2 emissions. Our point estimates suggest that increasing household size by one person reduces per capita CO_2 emissions by about 6 percent (roughly 5 percent for an adult and 7 percent for a child). Moreover, households in dense urban settings have per capita CO_2 emissions around 23 percent lower than households in rural settings, while households in less dense (semi-detached) urban settings have per capita CO_2 emissions about 16 percent lower, consistent with previous research on the effects of urban density (Brownstone & Golab, 2009; Glaeser & Kahn, 2010; Jones & Kammen, 2011).

We argue that these household and urban economies are generated through sharing carbon-intensive goods, which is facilitated by reductions in space between people. Given our operationalization

[11] Although our sample includes 3,371 rural households, none of them are in a MSA, and only 318 of them have a state-level identifier. Since all the rural households with a state identifier are in Kentucky, we drop them from our analysis in Column (2).

of residential density that leverages shared walls, sharing is a common scaling mechanism driving down per capita emissions in both household and urban economies. Larger households are able to share expenditures on residential energy with other members of the household, shifting expenditures towards less carbon-intensive goods and services and reducing per capita emissions. In much the same fashion that household members share goods, households in dense urban areas are able to share expenditures on residential energy and transportation with other households through shared walls and alternatives to private transport, shifting expenditures towards less carbon-intensive expenditures and reducing per capita emissions. Figure 1 shows how the fraction of household expenditures devoted to residential energy and transportation (including gasoline) varies with both household size and density. Increasing urban density [Figure 1, Panel (a)] reduces both the residential energy and transportation share of expenditures, while increasing household size [Panel (b)] acts to reduce only the share of expenditures on residential energy. Both household economies and urban economies shift consumption towards less carbon-intensive expenditures through sharing. The difference, is that cities, through the provision of social and technological infrastructure, can provide opportunities for sharing unavailable to a household.

[Insert Figure 1]

Table 4 shows that relocating a rural household to a dense urban area would reduce per capita emissions by over three times as much as adding an additional adult to the household. This suggests that harnessing urban economies may, in fact, offset the lost household economies associated with declining household size. However, our results in Table 4 implicitly assume that household and urban economies are additive, and that there is no interaction between these two forms of sharing carbon-intensive goods. If these effects are both driven by spatial proximity, then dense urban areas may, to some extent, act as functional substitutes for large households. In other words, since cities reduce the space between households, they may also erode household economies, as Ala-Mantila et al. (2016) find in Finland. To investigate this possibility, we estimate a model in which household economies are allowed to vary by urban density:

$$\begin{aligned}\ln(hh\ CO_2\ emission\ per\ capita)_{it}\\ &= \beta_0 + \beta_1 \ln(pc\ expenditures)_{it} + \beta_2 adults_{it} + \beta_3 children_{it} + \beta_4 suburban_{it}\\ &+ \beta_5 semidetached\ urban_{it} + \beta_6 dense\ urban_{it} + \delta_1(adults \times suburban)_{it}\\ &+ \delta_2(adults \times semidetached\ urban)_{it} + \delta_3(adults \times dense\ urban)_{it}\\ &+ \delta_4(children \times suburban)_{it} + \delta_5(children \times semidetached\ urban)_{it}\\ &+ \delta_6(children \times dense\ urban)_{it} + [\beta X_{it}] + \varepsilon_{it}\end{aligned} \tag{2}$$

where all terms carry from Eq. (1). Our results in Table 5 show that household economies in rural areas are substantially larger than those in dense urban areas. While adding an adult to a rural household reduces per capita emissions by about 8 percent, adding an adult to a dense urban household reduces them by about 3 percent. We find similar results for children, and the difference in household economies between rural and dense urban households are statistically significant at the 1 percent level. Our estimates of household economies in suburban and semi-detached urban areas also fall neatly between our estimates for rural and dense urban areas, providing evidence that household economies of scale in CO_2 emissions depend on urban form.

[Insert Table 5]

We see a simple explanation for why this is the case. Household economies are driven mostly by the ability of members to share carbon-intensive goods such as transportation and home heating and cooling (Underwood and Zahran, 2015). In rural and suburban areas, adding an additional person to a household opens up opportunities for households to save energy by carpooling and increasing the number of shared walls. In dense urban areas, these household economies are smaller because cities provide even better ways of sharing transportation and home heating and cooling. Walking, cycling, and mass transit reduce the benefit of intra-household carpooling while apartment buildings and fully-attached row homes reduce the benefit of sharing walls within households. These results are consistent with the hypothesis that increasing urban density has the potential to offset the upward pressure placed on per capita emissions by declining household size.

4. Discussion

Demographic modernization is generally characterized by declining household size and urbanization. From 1960 to 2010 the number of households in the United States increased 74 percent faster than population size, with mean household size decreasing 29 percent, from 3.3 to 2.6 members (Vespa et al., 2013). Over the same period, the percentage of one-person households doubled, from 13 to 27 percent, and today 35 million adults in the United States live alone. Meanwhile, the percent of the US population living in urban areas grew from under 70 percent in 1960 to over 80 percent in 2010. Small households, including solo-dwellers, tend to cluster in dense urban areas. In New York City over one million people live alone, and in Manhattan nearly 50 percent of all residences are one-person dwellings (Klinenberg, 2012). With the shift towards smaller households alongside an increase in dense urbanization over the past 50 years, our results indicate that the former trend exacerbated CO_2 emissions while the latter mitigated them. Our estimates of household and urban economies can shed light on which countervailing effect was dominant in the United States.

The US Census provides data on how household size and urban form evolved from 1960 to 2010. We generate a proxy for our residential density variable using Census data on whether a household is located in a metropolitan area, and whether the household is in 1-family structure, a 2-family structure, or a 3-or-more-family structure.[12] The Census data shows that average household size declined by 20 percent

[12] This definition is not perfect, and cannot categorize 29 percent of households in 1960, 2 percent in 1980, 3 percent in 1990, and 9 percent in 2010. However, we consistently find recent losses in household economies were 2-3 times as large as the gains in urban economies, regardless of which year we use as our starting point.

over this period and that the largest declines occurred in rural households. Meanwhile the fraction of rural households decreased by about 50 percent and the fraction of dense urban households increased by about 50 percent. Extrapolating from our point estimates in Table 5, we calculate the total effect of these demographic changes on per capita CO_2 emissions holding other factors constant. This exercise suggests that the lost household economies were nearly three times as large as the increased urban economies over this period. Everything else equal, declining household size increased per capita emissions by about 9 percent while dense urbanization decreased per capita emissions by about 3 percent. Going forward, the net effect of these demographic forces will depend on the relative rates of change in urban density and household size.

It should be noted that these demographic trends are not uniquely American. The growth in the number of households is outpacing population growth worldwide. Liu (2013) finds that 79 percent of 172 countries surveyed had population growth lower than growth in the number of households from 1985 to 2000 and by 2030 the single-person household will the most common household type globally (Jennings et al., 2000). Meanwhile, the global urban population has grown rapidly since 1950, from 746 million to 3.9 billion in 2014, now comprising 54 percent of the world's population, according to the United Nations. Today, 78 percent of the population in developed nations live in urban areas while just 48 percent of developing nations do.[13] By 2050, these figures are projected to be 85 and 63 percent, respectively, meaning that the majority of expected population growth over the next few decades will occur in cities of the developing world (United Nations, 2014). Our results suggest that whether or not the combination of these global demographic trends puts upward or downward pressure on per capita emissions worldwide will depend on how effectively cities can facilitate sharing.

According to Creutzig et al. (2015), the climate change mitigation benefits of urbanization are highest in the developing world, where cities can avoid the "lock-in of high carbon emission patterns for travel" that characterize many urban areas of the developed world. However, cities of the developed world can also reap the benefits of urban density. Research shows that individuals can meaningfully reduce emissions through a series of "reasonably achievable" behaviors like car-pooling and the purchase of efficient vehicles and appliances or even secondhand goods (Dietz et al., 2009). If cities can provide the social and technological infrastructure that facilitate these behavioral changes, then it is possible that dense cities can help people leverage the benefits of sharing in the 21st century in the same way that large households have done so in the past.

5. Conclusion

Some previous work has analyzed both household and urban economies in CO_2 emissions, but little research has addressed both these effects in the same model. We highlight the similarities in how households and cities generate economies of scale in CO_2 emissions. Building upon Ala-Mantila et al. (2016) we construct a large nationally-representative dataset of CO_2 emissions at the household level and develop a unique

[13] As classified by the United Nations. Developed (more-developed) regions include Europe, North America, Australia/New Zealand and Japan, while developing (less developed) regions includes all regions of Africa, Asia (excluding Japan), Latin America and the Caribbean plus Melanesia, Micronesia and Polynesia

measure of residential density. However, our spatial clarity is still somewhat imprecise. Our estimates of urban economies likely capture the full impact of high density housing on emissions but may miss the full impact of spatial proximity on emissions (i.e. access to employment, commerce, and public amenities). As a result, our estimates of urban economies may be biased downward and future research could utilize geo-coded household expenditure data to improve upon our results.

We posit that both multi-person households and dense urban areas reduce the space between individuals and provide opportunities for sharing carbon-intensive goods, yielding both urban and household economies in CO_2 emissions. We find that dense urban areas have per capita emissions 23 percent lower than rural areas and that adding an additional member to the household reduces per capita emissions by about 6 percent. However, we also show that the magnitude of household economies depends on residential density, and that adding an adult or child to a household reduces per capita emissions by about twice as much in rural areas than in dense urban areas. Our point estimates suggest that relocating to a dense urban area would reduce per capita emissions by over three times as much as adding an adult to a household. Yet over the last half century the decline in household economies of scale outpaced the increase in urban economies in the United States. Going forward, this suggests a higher rate of dense urbanization will be necessary to offset the carbon implications of declining household size.

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Table 1

Table 1: Expenditure and Emissions Shares

Expenditure Category	Annualized Mean Expenditures (US dollars)	Mean Expenditure Share (%)	Annualized Mean Emissions (kg CO_2)	Mean Emissions Share (%)
Total Expenditures	$50,308	100.0%	32,262	100.0%
Residential Energy	$1,990	5.3%	12,327	39.0%
Natural Gas	$272	1.0%	2,677	8.0%
Electricity	$977	4.0%	9,110	29.7%
Heating Oil and other fuels	$95	0.3%	539	1.3%
Transportation	$8,865	14.0%	11,132	31.0%
Gasoline and motor oil	$2,638	6.1%	9,228	27.2%
Vehicle Purchases, Services, and Public Transit	$6,227	7.9%	1,904	3.8%
Food and Beverages	$7,568	18.3%	2,763	10.2%
Other Expenditures	$31,886	62.5%	6,041	19.9%
Housing	$10,308	22.4%	1,542	6.3%
Indirect Utilities	$1,828	4.5%	453	1.6%
Domestic Services	$1,172	2.1%	220	0.7%
Household Equipment	$1,249	2.1%	705	1.9%
Clothing and Footwear	$1,001	1.9%	461	1.4%
Personal Insurance	$5,742	10.0%	601	1.8%
Healthcare	$4,005	8.3%	424	1.4%
Entertainment	$2,300	4.3%	742	2.3%
Education	$1,206	1.5%	174	0.5%
Alcohol and Tobacco	$695	1.7%	141	0.5%
Miscellaneous	$2,380	3.8%	577	1.6%

Notes. Total expenditures include residential energy, transportation, food and beverages, and other. Residential energy includes natural gas, electricity, and heating oil. Transportation includes gasoline and vehicle purchases, services, and public transit. N = 72,608.

Table 2

Table 2: Mean Household Characteristics by Spatial Density					
Density	Rural	Suburban	Semi-detached urban	Dense urban	Overall
Household income (US $)	$51,234	$76,842	$47,466	$45,346	$65,715
Income per capita (US $)	$23,987	$32,272	$25,557	$26,411	$29,866
Annualized total household expenditures (US $)	$10,478	$14,191	$10,216	$9,522	$12,577
Annualized per capita expenditures (US $)	$5,097	$6,198	$5,707	$5,727	$5,980
Age of reference person	54	52	45	45	50
Household size	2.45	2.70	2.27	2.04	2.50
CO_2 intensity (kg/$)	0.91	0.78	0.70	0.63	0.75
Annualized total household CO_2 emissions (kg)	8,043	9,253	6,291	5,378	8,066
Annualized per capita CO_2 emissions (kg)	3,964	4,073	3,448	3,126	3,804
Observations	3,235	46,047	6,018	17,308	72,608

Notes: Means are calculated using population weights.

Table 3

Table 3: Baseline Model				
	(1)	(2)	(3)	(4)
Log expenditures per capita	0.728***	0.688***	0.665***	0.644***
	(0.004)	(0.005)	(0.005)	(0.005)
Number of adults		-0.017***	-0.048***	-0.059***
		(0.003)	(0.005)	(0.006)
Number of children		-0.066***	-0.074***	-0.081***
		(0.003)	(0.003)	(0.003)
Suburban			-0.065***	-0.059***
			(0.010)	(0.010)
Semi-detached urban			-0.242***	-0.175***
			(0.013)	(0.012)
Dense urban			-0.365***	-0.246***
			(0.011)	(0.011)
Renter				-0.032***
				(0.005)
Natural gas in rent				-0.058***
				(0.011)
Heat in rent				-0.124***
				(0.009)
Electricity in rent				-0.412***
				(0.013)
2013	0.005	0.004	0.004	0.004
	(0.005)	(0.005)	(0.004)	(0.004)
2014	-0.014***	-0.014***	-0.013***	-0.014***
	(0.005)	(0.005)	(0.005)	(0.004)
Constant	1.913***	2.320***	2.722***	2.931***
	(0.032)	(0.043)	(0.045)	(0.048)
Observations	72,608	72,608	72,608	72,608
R-squared	0.643	0.650	0.689	0.722

Notes: Column (3) compares the emissions of suburban and urban households to rural households. All regression results use population weights. Standard errors are clustered at the consumer unit, with robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 4

Table 4: Robustness

	(1)	(2)	(3)	(4)	(5)	(6)
Log expenditures per capita	0.651***	0.663***	0.686***	0.652***	0.658***	0.675***
	(0.005)	(0.005)	(0.007)	(0.005)	(0.005)	(0.005)
Number of adults	-0.055***	-0.048***	-0.033***	-0.055***	-0.053***	-0.051***
	(0.006)	(0.006)	(0.008)	(0.006)	(0.006)	(0.005)
Number of children	-0.079***	-0.073***	-0.067***	-0.079***	-0.079***	-0.075***
	(0.003)	(0.003)	(0.004)	(0.003)	(0.002)	(0.003)
Suburban	-0.046***			-0.046***	-0.053***	-0.046***
	(0.010)			(0.010)	(0.010)	(0.010)
Semi-detached urban	-0.156***	-0.090***	-0.079***	-0.156***	-0.163***	-0.155***
	(0.012)	(0.008)	(0.011)	(0.012)	(0.012)	(0.012)
Dense urban	-0.231***	-0.167***	-0.151***	-0.231***	-0.239***	-0.226***
	(0.011)	(0.007)	(0.009)	(0.011)	(0.011)	(0.011)
Renter	-0.025***	-0.020***	-0.025***	-0.025***	-0.031***	-0.036***
	(0.005)	(0.006)	(0.008)	(0.005)	(0.005)	(0.005)
Natural gas in rent	-0.049***	-0.051***	-0.073***	-0.049***	-0.049***	-0.048***
	(0.011)	(0.011)	(0.013)	(0.011)	(0.011)	(0.011)
Heat in rent	-0.131***	-0.125***	-0.089***	-0.131***	-0.130***	-0.128***
	(0.009)	(0.009)	(0.011)	(0.009)	(0.009)	(0.009)
Electricity in rent	-0.406***	-0.410***	-0.391***	-0.406***	-0.405***	-0.406***
	(0.013)	(0.014)	(0.017)	(0.013)	(0.013)	(0.013)
2013	0.004	0.001	-0.007	0.004	0.004	0.005
	(0.004)	(0.004)	(0.006)	(0.004)	(0.004)	(0.004)
2014	-0.014***	-0.021***	-0.039***	-0.014***	-0.014***	-0.014***
	(0.004)	(0.004)	(0.006)	(0.004)	(0.004)	(0.004)
Constant	2.852***	2.843***	2.520***	2.839***	2.796***	2.529***
	(0.049)	(0.055)	(0.077)	(0.050)	(0.049)	(0.065)
Geographical controls?	Region	State	PSU	Region	Region	Region
Gender controls?	N	N	N	Y	Y	Y
Race controls?	N	N	N	N	Y	Y
Education controls?	N	N	N	N	N	Y
Observations	72,608	63,686	32,004	72,608	72,608	72,608
R-squared	0.726	0.737	0.754	0.727	0.729	0.731

Notes: All columns compare the emissions of suburban and urban households to rural households, except (3) and (4), which compare urban households to suburban households (because the only rural households with state identifiers are in Kentucky, and because there are no rural households in any MSA). All regression results use population weights. Standard errors are clustered at the consumer unit, with robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

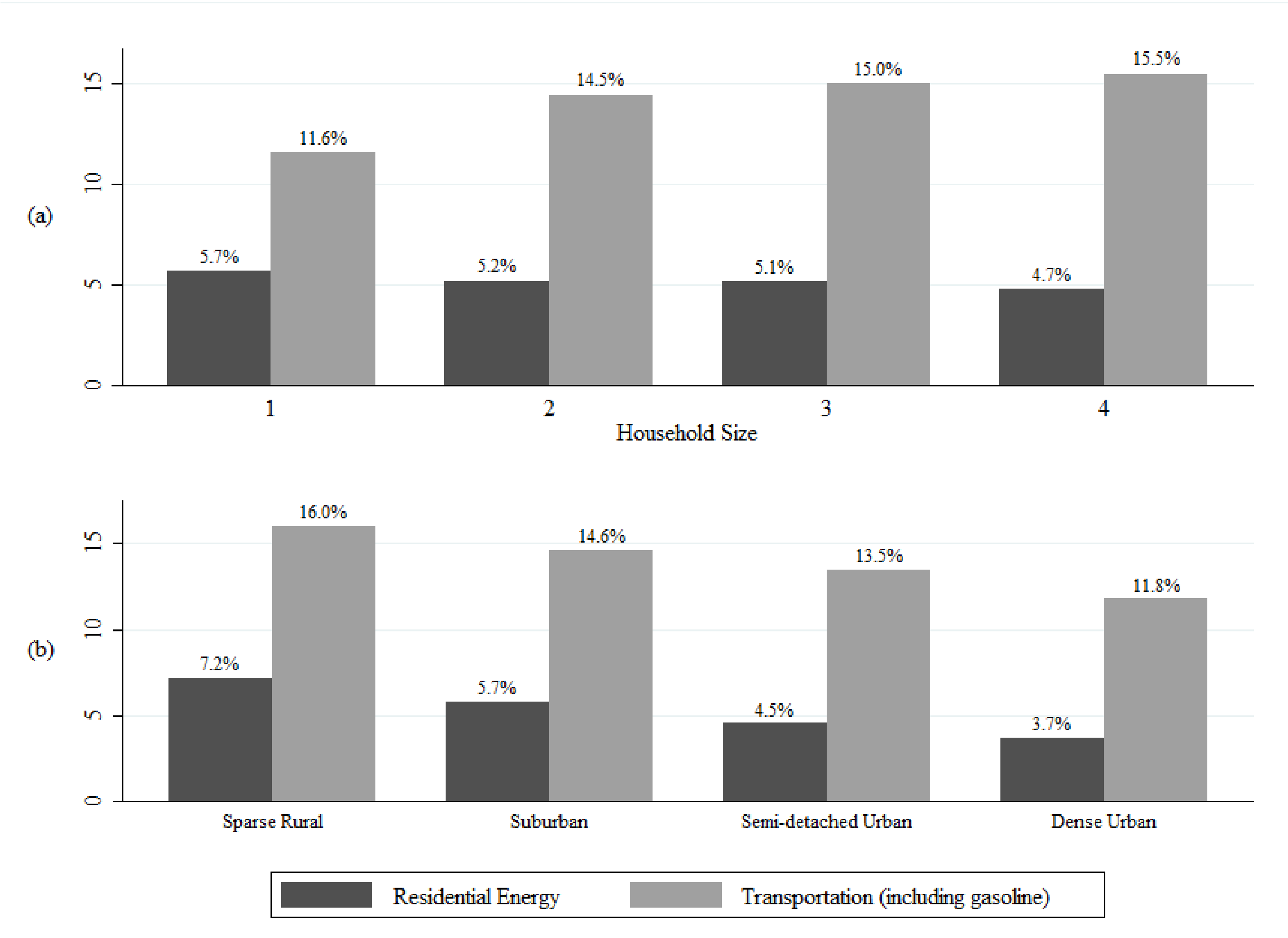
Table 5

Table 5: Household Economies Across Density

Log expenditures per capita	0.676***
	(0.005)
Number of adults	-0.079***
	(0.011)
Number of children	-0.111***
	(0.008)
Suburban	-0.113***
	(0.030)
Semi-detached urban	-0.234***
	(0.029)
Dense urban	-0.341***
	(0.027)
Suburban × num. adults	0.026**
	(0.013)
Semi-detached urban × num. adults	0.025*
	(0.013)
Dense urban × num. adults	0.047***
	(0.012)
Suburban × num. children	0.034***
	(0.009)
Semi-detached urban × num. children	0.057***
	(0.011)
Dense urban × num. children	0.059***
	(0.009)
Constant	2.587***
	(0.066)
Rental controls	Y
Geographical controls?	Region
Gender controls?	Y
Race controls?	Y
Education controls?	Y
Observations	72,608
R-squared	0.732

Notes: The comparison group is rural households, All regression results use population weights. Standard errors are clustered at the consumer unit, with robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Figure 1. **Residential Energy and Transportation Expenditure Shares by Household Size (a) and Urban Density (b)**



Appendix

Table A1

Table A1: Carbon Intensity by Expenditure Category

Expenditure Category	2012	2013	2014
		(kg CO_2/$)	
Residential Energy			
Natural gas	7.092	6.772	6.326
Electricity	6.465	6.332	6.111
Fuel oil and other fuels	3.808	3.852	3.774
Transportation			
Gasoline and motor fuel	3.385	3.485	3.625
New and used cars and trucks	0.527	0.525	0.526
Other vehicles	0.727	0.724	0.725
Vehicle finance charges	0.145	0.145	0.145
Maintenance and repairs	0.245	0.241	0.237
Vehicle insurance	0.059	0.057	0.054
Vehicle rental, leases, licenses, and other charges	0.141	0.14	0.14
Public transportation	1.213	1.18	1.191
Food and Beverage			
Food at home	0.396	0.392	0.383
Food away from home	0.319	0.312	0.305
Other			
Housing			
Mortgage interest	0.137	0.135	0.133
Property taxes	0.000	0.000	0.000
Maintenance, repairs, insurance, and other expenses	0.861	0.835	0.797
Rent payments	0.224	0.218	0.211
Other lodging	0.327	0.324	0.31
Indirect Utilities			
Telephone	0.183	0.183	0.184
Water and other public services	0.422	0.404	0.39
Domestic services and household operations			
Domestic services excluding child care	0.171	0.168	0.164
Babysitting and child care	0.148	0.145	0.142
Other household expenses	0.238	0.234	0.228
Household equipment and supplies			
Household textiles	0.746	0.774	0.791
Furniture	0.503	0.509	0.523
Floor coverings	0.524	0.546	0.545
Major appliances	0.489	0.501	0.533
Small appliances and miscellaneous housewares	0.485	0.493	0.504

Expenditure Category	2012	2013	2014
		(kg CO_2/$)	
Miscellaneous household equipment	0.592	0.613	0.641
Clothing and footwear			
Apparel and services	0.472	0.467	0.467
Footwear	0.43	0.42	0.418
Personal Insurance			
Life and other personal insurance	0.106	0.105	0.103
Retirement, pensions, and Social Security	0.106	0.105	0.103
Healthcare			
Health insurance	0.061	0.06	0.059
Medical services	0.145	0.14	0.137
Prescription drugs	0.197	0.196	0.189
Medical supplies	0.209	0.208	0.203
Personal care	0.254	0.251	0.247
Entertainment			
Fees and admissions	0.015	0.015	0.015
Televisions, radios, and sound equipment	0.355	0.354	0.354
Pets, toys, and playground equipment	0.644	0.659	0.684
Other entertainment	0.391	0.389	0.388
Education and reading			
Reading	0.234	0.226	0.221
Education	0.141	0.136	0.132
Alcohol and tobacco			
Alcoholic beverages	0.307	0.302	0.299
Tobacco and smoking supplies	0.083	0.081	0.079
Miscellaneous			
Miscellaneous expenditures	0.258	0.254	0.25
Cash contributions	0.243	0.239	0.236