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New Energy Efficient Housing Has Reduced Carbon Footprints in Outer but Not in Inner Urban Areas

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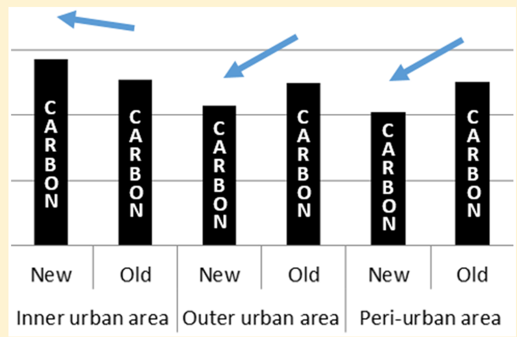
Supporting Information

ABSTRACT: Avoiding urban sprawl and increasing density are often considered as effective means to mitigate climate change through urban planning. However, there have been rapid technological changes in the fields of housing energy and private driving, and the development is continuing. In this study, we analyze the carbon footprints of the residents living in new housing in different urban forms in Finland. We compare the new housing to existing housing stock. In all areas, the emissions from housing energy were significantly lower in new buildings. However, in the inner urban areas the high level of consumption, mostly due to higher affluence, reverse the gains of energy efficient new housing. The smallest carbon footprints were found in newly built outer and peri-urban areas, also when income level differences were taken into account. Rather than strengthening the juxtaposition of urban and suburban areas, we suggest that it would be smarter to recognize the strengths and weaknesses of both modes of living and develop a more systemic strategy that would result in greater sustainability in both areas. Since such strategy does not exist yet, it should be researched and practically developed. It would be beneficial to focus on area specific mitigation measures.



1. INTRODUCTION

Dense metropolitan cores are often presented as a key to creating productive cities and a requirement for attracting creative talent in global competition. Many countries have accordingly created policies to support the growth of metropolitan cores. Simultaneously, it has been suggested that efficient cities with sustainable planning principles offer a good solution for the challenges posed by climate change.[1−4] Studies on transport demonstrate how greenhouse gas (GHG) emissions from ground transport are significantly higher in suburban areas than in dense city centers.[5−8] Also, studies that have focused on the topic more broadly have found higher energy usage and GHG emissions for suburban areas.[9−12] In many policy reports, climate change mitigation in urban planning has become almost synonymous with increasing the density of urban settlements and avoiding urban sprawl.[13−15]

To support the sustainable performance of new buildings, policy makers have developed incentives and legislation to promote high-quality, low-energy construction. It has been suggested that the new low-energy buildings are one of the most viable ways of reducing GHG emissions.[16,17] For example, the EU has implemented a series of legislative actions to promote low-energy and nearly zero energy building construction.[18,19] Also, several voluntary schemes, (e.g., Passivhaus, LEED, BREEAM) and new innovations (e.g., heat pumps, super insulations) support low GHG construction.

On the other hand, recent studies have highlighted the importance of understanding cities' GHG emissions more holistically and emphasized the significance of including all types of consumption in GHG assessments.[20−24] For example, studies by Lenzen et al.[20] and Heinonen et al.[25,26] demonstrated that when total consumption is taken into account, there is no clear evidence that one urban form would be better than another from an energy or GHG perspective. Rather, several studies indicate that other variables, such as income, household size, and lifestyles, have a much stronger effect on and explain most of the differences in energy use and GHG emissions in different areas.[25−30] For example, studies by Heinonen et al.[25] and Wiedenhofer et al.[30] found that total consumption and related energy use and emissions per capita are lowest in rural areas and highest in urban areas.

Studies using multivariate regression models have shown that when the income level remains constant, carbon footprints decrease moderately with urban density.[20,31,32] At the same time, the difference in income level between rural and urban areas is also a real phenomenon. Dense cities are more productive and offer more job opportunities and higher salaries due to agglomeration benefits.[29,33,34] Several studies have suggested that people living in rural areas have slower paced lifestyles that are centered more around the home than do residents in urban areas.[25,35] In the specific case of transport, a

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few studies have demonstrated that residents in urban areas fly much more than those in suburban or rural areas, which has significant GHG implications.[36−39]

However, rather than strengthening the juxtaposition of urban and suburban areas, we suggest that it would be smarter to recognize the strengths and weaknesses of both modes of living and develop a more systemic strategy that is sensitive to area characteristics and would result in greater sustainability in both urban and suburban areas. As Kirby and Modarres highlighted,[40] the suburbs need more academic attention and not only in a dismissive sense. People's preferences regarding a neighborhood are diverse and they change during a person's life cycle.[41−43]

Urban density speeds up the flow of ideas and makes cities the engines of innovation and human progress,[13,34,44] which makes cities appealing residential locations especially for young adults looking for lively neighborhoods and interesting job opportunities.[42] At the same time, many people prefer low-rise living.[45,46] When it comes to sustainability, suburban areas benefit from economies-of-scale effect at the household level: with larger households, more people share the emissions from housing energy, transport, and other goods, which significantly decreases the emissions per capita.[26]

This study assesses the climate-change implications of the concurrent urban development policies. The study focuses on new housing in different urban forms and utilizes a broad consumption-based perspective when making environmental assessments. Existing housing is used as a point of comparison. Previous consumption-based urban sustainability studies have not dealt with the difference between new construction and existing building stock when using the same model. The emissions from construction have been handled in several ways: for instance, Jones and Kammen have used fixed emissions from construction for all households,[47] Hertwich and Peters national-level investments[48] and Ramaswami the embodied energy of concrete,[22] but most studies have not specified the emissions from housing construction.[20,27,28,30] The research questions of the study are as follows:

(1) What are the GHG implications of residents living in new housing developments in different urban areas?

(2) What is the effect of the energy efficiency improvements in new housing on GHG emissions?

First, we will calculate the GHG emissions of residents living in new housing. Second, we will compare the newly constructed buildings with the existing building stock. Third, we will take a more detailed view and study how the energy efficiency improvements of new housing affect the carbon footprints of residents. Many studies have suggested significant setbacks due to the direct and indirect rebound effects of decreased energy use.[30,49,50] However, our model includes the investment in new energy efficient buildings in the evaluation, which should again reduce the amount of disposable income and thus suppress the rebound effect.

The findings of the study do not support the assumption that new housing in inner urban areas is especially sustainable from GHG perspective. Instead, the lowest carbon footprints per capita were found in new homes built in outer and peri-urban areas, even when differences in income levels were taken into account. However, the comparison of inner and outer urban areas seems quite unfruitful, because of significant differences in lifestyles, family structures and income level.

The results of the study have broader international significance, but there are some limitations that must be taken into account. Considering the level of urbanization, Finland represents a typical European country.[51] Also, the capital, Helsinki, is a typical European metropolitan area with 1.1 million inhabitants. Other cities in Finland are relatively small and the population density of Finland is low similar to the rest of Scandinavia and other Northern countries, such as Canada and Russia. The level of motorization is high as 74% of households have at least one car. The average tail-pipe emissions from driving are 167 CO_2 g/km,[52] which is high in the European context but low compared to the U.S. Heating energy comes from combined heat and power (CHP) plants especially in cities in Finland, whereas old low-rise areas use electricity, oil and wood and the new buildings increasingly geothermal heat pumps for heating. Unlike in Sweden, in Finland CHP production rely still heavily on fossil fuels, although some progress is going on. Thus, the results of the study are especially relevant for countries, which aim to increase the amount of CHP and still have significant amount of fossil fuels in their energy systems, and have political or market driven pressure to increase the energy efficiency of housing. As in Finland, also internationally inner urban areas are often more dependent on the existing infrastructure, such as district heating networks, whereas people living in detached houses can make individual choices regarding heating systems and energy efficiency.

2. RESEARCH MATERIAL AND METHODS

2.1. Research Design. To better define what we mean by urban form, we turn to the urban density classification provided by the Finnish Environment Institute.[53] The traditional division between urban and rural areas is based on municipal boundaries, whereas the new urban density classification describes an urban−semiurban−rural continuum that also exists *within cities*. The new classification was created using rich GIS data on populations, labor, commute times, buildings, road networks, and land use. In this paper, we utilize the three urban classes, but exclude rural areas from the analysis due to the notion that new housing is primarily concentrated in urban areas and rural lifestyles are quite different overall. The three urban classes are as follows:

1. *Inner urban area*. A compact and densely built area with continuous development.
2. *Outer urban area*. A dense urban area extending from the boundary of the inner urban area to the outer edge of the continuously built area.
3. *Peri-urban area*. A part of the intermediate zone between urban and rural, which is directly linked to an urban area.[53]

We include all urban areas in Finland in the study.

In the study, new housing is defined as housing constructed between the years 2003 and 2012. We selected a 10-year period beginning in 2003 for this study for several reasons. Principally, 2003 was the first year in Finland when construction markets were affected by and had to react to environmental pressure and new legislation. Two major changes were especially important: first, the new legislation concerning the energy efficiency of buildings took effect in 2003;[54,55] second, the number of heat pumps started to grow rapidly, from 30 000 to over 500 000 during 2003−2012, although these numbers include the heat pumps installed in old houses as well.[56] From

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Table 1. Descriptive Data on Studied Subgroups

	new buildings (constructed 2003–2012)			old buildings (constructed before 2003)		
	inner urban area	outer urban area	peri-urban area	inner urban area	outer urban area	peri-urban area
household size (persons)	1.7	2.8	3.6	1.7	2.2	2.3
share of households living in apartment buildings	83%	27%	6%	80%	34%	13%
share of households living in detached houses	5%	44%	79%	9%	36%	69%
share of owner-occupied homes	40%	81%	94%	53%	72%	82%
share of car-free households	39%	7%	3%	45%	20%	12%
average living space per household (m2)	66	108	134	68	94	115
average living space per capita (m2)	37	39	37	39	43	51
average income per household (€/year)	40 100	56 000	71 100	37 800	45 400	47 400
average income per capita (€/year)	22 900	20 100	19 800	21 600	20 600	21 100
Shares of Household Types						
young (18–24 yrs.)	20%	4%	1%	11%	4%	3%
adult singles	23%	18%	5%	29%	21%	17%
adult couples	25%	19%	13%	17%	21%	20%
seniors (over 65 yrs.)	19%	10%	12%	24%	20%	27%
young families and single parents	7%	30%	43%	11%	18%	15%
other families with children	6%	19%	27%	8%	16%	19%
total	100%	100%	100%	100%	100%	100%

the research method perspective, the 10 year period also seemed to be a suitable time span to even out yearly fluctuations in new construction and offer a sufficient sample size for each area type studied.

Table 1 describes the differences between new and old building stock and the types of urban areas studied. As the table shows, household and housing types change along with urban forms. Also, while there are significant differences in household sizes between the three urban classes, differences exist as well between the new and old buildings located in outer and peri-urban areas. As the result, the living spaces per capita are interestingly quite similar for all urban forms in newly constructed buildings, whereas in old building stock the living space per capita clearly decreases with urban density. This could be explained by the human life cycle: large families move to new housing in suburban areas, but as the children grow older and move away from home, the living space per capita in the same areas increases. However, this pattern may be changing, since people are nowadays moving more often and prefer to adjust their housing size to fit each life phase.[57]

2.2. Research Material. The research material used for the study derived from Statistics Finland's Household Budget Survey 2012.[58] The survey consists of detailed data on Finnish households' monetary consumption. It is arranged based on the international COICOP division (Classification of Individual Consumption by Purpose) and contains socioeconomic background information on the respondents. The survey covers all of Finland, with a stratified cluster sampling design and total sample size of about 3500 households. Of these households, 289 lived in newly constructed buildings: 100 in the inner urban area, 134 in the outer urban area, and 55 in the peri-urban area. The sample sizes of older building stock were 981, 730, and 288, respectively. The data set includes weight coefficients to correct any biases in the demographics of the sample, and we employed these coefficients throughout the study.

2.3. Hybrid Life Cycle Assessment. We employed a hybrid life cycle assessment (LCA) method to calculate the carbon footprints of Finnish households. Hybrid LCA methods combine the strengths of both the environmentally extended input-output LCA (EE IO-LCA) and the process LCA. The EE IO-LCAs are normally based on input-output tables for national economies, which are extended with environmental data, for example GHG emissions or the Eco-Index.[59] The input-output tables consist of sectorial monetary transaction matrices. The EE IO-LCA method avoids truncation errors from system boundary selection, which is its main benefit compared to the process LCAs.[60] Another asset is the simplicity of the method, which makes it much quicker to use than process-based methods.[61] However, the comprehensiveness of the EE IO-LCA comes with the downside of aggregation error and the inherent linearity and homogeneity assumptions. We used a tiered hybrid method, in which process LCA data is integrated into the input-output model.[60]

2.4. The Hybrid-LCA Model Used in the Study. To calculate the carbon footprints, we utilized the environmentally extended input-output model for the Finnish economy, called ENVIMAT.[62,63] It includes GHG intensities for 52 commodity groups classified based on the COICOP division. Since ENVIMAT is based on the year 2005, we used inflation coefficients to change the GHG intensities to correspond to the year 2012. The inflation coefficients were specific for each COICOP commodity group and provided by Statistics Finland. We created the carbon footprints of households by combining the inflation-corrected emission intensities with Household Budget Survey data. The household budget data and the ENVIMAT model match perfectly since both are based on the COICOP classification.

National input–output models often include the assumption that imported goods are manufactured using domestic technologies. In the ENVIMAT model this weakness has been alleviated with hybrid approach, not typically used in input-output analyses. Life-cycle inventory (LCI) data from international LCA databases, such as Ecoinvent Database,[64] have been integrated into the input-output model to assess the emissions from imported goods. The details of the method are described in a research article by Finnish Environment Institute (Seppälä et al. 2011).[63]

As explained earlier, the input-output method suffers from aggregation error, and it can be made more accurate by combining it with a process LCA. Housing energy and private driving are the two biggest GHG emission sources for

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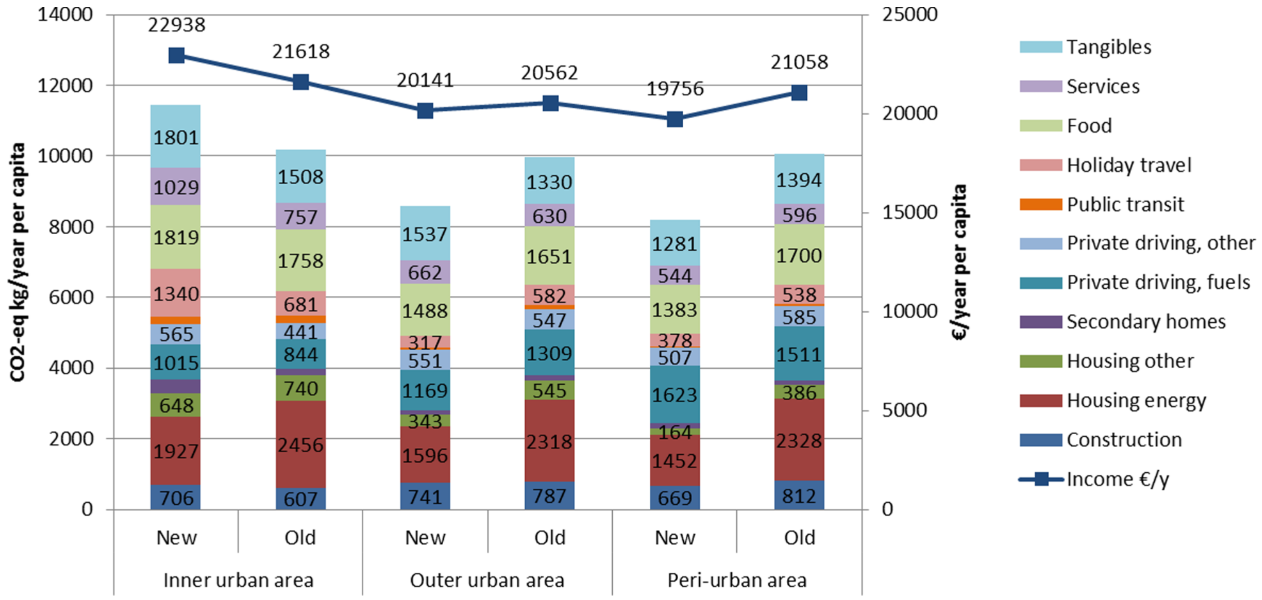

Figure 1. Comparison of carbon footprints of residents living in new (constructed 2003−2012) and old (constructed before 2003) buildings in the three studied urban forms.

households. To improve their GHG assessment in our model, we used a process LCA approach, which is described below. Also, since construction is at the nexus of the study, and since housing expenditures and rental and loan payments do not reflect very well the GHG emissions from construction, we assessed the construction-related emissions using a GHG coefficient based on living space (m^2) instead. The GHG emissions from other consumption, including public transit and holiday travel, were assessed with the ENVIMAT input−output model.

Private Driving. In the ENVIMAT model, only one GHG-intensity is given for the category "Use of private vehicles." This includes, for example, fuels, spare parts, maintenance, and other vehicle services. To create a tiered hybrid-model,[60] we segregated the fuels according to the more detailed input data and calculated the emissions from the combustion phase separately for diesel and petrol based on the volumes (liter). We then added the emissions from the upper tiers by utilizing the ENVIMAT model's producer price table for oil products. Based on the calculations, the GHG intensity of fuels was 1.8 CO_2-eq kg/€ in the year 2012. The residue, 0.36 CO_2-eq kg/€, was then utilized for other activities under the category "Use of private vehicles."

Housing Energy and Maintenance. The main heat sources in Finland are district heating, electricity, and oil. We utilized a tiered hybrid-LCA method[60] to calculate their GHG emissions. Emissions during the combustion phase were 209 CO_2-eq/MWh for district heating and 223 CO_2-eq/MWh for electricity in the year 2012.[65] The ENVIMAT model was utilized to assess the upper tier emissions, which were 57 CO_2-eq kg/MWh and 86 CO_2-eq kg/MWh, respectively. We used energy prices (€/MWh) from the year 2012, and we took into account the different prices for different housing types. We assessed the emissions from heating oil similarly as we assessed the emissions from motor fuels. We calculated separately the emissions from the combustion phase based on the purchased quantities and added the emissions from upper tiers based on the ENVIMAT model's producer price table.

The Household Budget Survey includes housing energy that households have bought directly for themselves, like electricity, oil, firewood, and so forth. However, it does not include energy that has been bought by housing companies, which, for example, covers the majority of district heat consumption in Finland.[66] Thus, we compensated the maintenance charges and rents in the Household Budget Survey by utilizing statistics from Statistics Finland on the financial statement from the housing companies.[67] These statistics provide the average expenses of housing companies per square meter of living space for different types of housing and for buildings of different ages. We then utilized the living space and year of construction to allocate the amount of energy consumed by housing companies to the residents. The housing companies are normally also responsible for building maintenance. To capture the GHGs from these activities, we created a new category, "housing, other," which consists of the maintenance costs of housing companies and of similar household expenses, like water and waste fees.

Construction. To be consistent in our methodological choices, we utilized an IO-LCA-based estimate to assess the emissions from construction. A study by Ristimäki et al. serve as our main point of reference.[68] They studied a new residential area that included seven multistory buildings in Finland. Their estimate for the total GHG emissions from construction was 1.1 CO_2-eq t/m^2, which included both the building itself and the required site infrastructure for the new residential development. Since we did not have a comparable estimate for typical row-houses and detached houses, we used the same estimate for all housing types. We utilized the average demolition ages (44−64 years) for different types of housing in Finland based on a study by Huuhka and Lahdensivu[69] to calculate the "annual" carbon footprint resulting from construction. There are some important uncertainty issues related to emissions from construction and the long life cycle of buildings, which are discussed in detail in the uncertainties section.

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Table 2. Results from the Regression Analyses: The Connection between Urban Form and Carbon Footprints of Residents[a]

prob > F = 0,000 in all models	new buildings (289 obs.)				old buildings (1994 obs.)			
	regression 1a		regression 1b		regression 2a		regression 2b	
dependent variable:	R^2	0.436	R^2	0.490	R^2	0.425	R^2	0.472
ln (carbon footprint per capita)	coef.	$P > \|t\|$	coef.	$P > \|t\|$	coef.	$P > \|t\|$	coef.	$P > \|t\|$
ln (disposable income per capita)	0.62	0.000	0.49	0.000	0.64	0.000	0.59	0.000
inner urban area	0.20	0.006	0.09	0.251	0.01	0.634	−0.04	0.194
outer urban area	0.05	0.001	0.02	0.792	0.03	0.000	0.02	0.466
peri-urban area								
young			0.10	0.253			0.29	0.000
adult singles			0.33	0.003			0.29	0.000
adult couples			0.35	0.000			0.18	0.000
seniors			0.20	0.009			0.16	0.000
other families with children			0.11	0.141			−0.01	0.761
young families and single parents								
constant	2.88	0.001	4.00	0.000	2.79	0.000	3.23	0.000

[a]Area types are compared to peri-urban areas and household types to young families.

3. RESULTS

The main results of the study are as follows: (1) new housing in inner urban areas is not as sustainable from GHG perspective, as suggested in the existing literature and urban policies; (2) in outer and peri-urban areas, residents living in new housing clearly have lower GHG emissions than residents living in old housing stock mainly due to the lower emissions from housing energy. In inner urban areas, other consumption outweighs the GHG benefits of lower energy consumption for new housing.

3.1. GHG Emissions from New and Old Housing in Different Urban Forms. Figure 1 illustrates the comparison of carbon footprints for residents of new and old buildings in the three studied urban forms. Surprisingly, residents living in new buildings in inner urban areas have the highest GHG emissions per capita, which can partly be explained by the highest income per capita, but remains true also when income is controlled. The overall influence of income is tested and discussed more in depth in Section 3.2. As expected, due to improved energy efficiency and installed heat pumps, the GHG emissions from housing energy are lower in new housing than existing housing stock in all urban forms. Also, the other housing-related emissions are lower in new buildings due to lower renovation requirements. In inner urban areas, however, the benefits are overridden by the emissions from other types of consumption, such as holiday travel, secondary homes, and other goods and services. Even the benefits derived from improving energy efficiency fall short compared to buildings in other types of areas. By contrast, there are additional GHG reductions in some other consumption categories in the outer urban and peri-urban areas, such as holiday travel, and the total emissions are clearly lower for residents living in new rather than old buildings.

One possible explanation for the smaller carbon footprints in new housing is the well-known rebound effect of consumption: the housing loan consumes a large share of overall income, which takes away from other types of consumption. This phenomenon has been previously discussed by, for example, Wiedenhofer and his colleagues.[30] In inner urban areas, most of the households lived in rented apartments (see Table 1), which could explain why the rebound effect did not show up. To test the hypothesis, we looked at the subgroup of residents owning their apartment in inner urban areas. Even within this subgroup, the emissions were higher in new housing compared with old housing (Figure 2, Supporting Information (SI)). Similarly, the carbon footprints differed more than the monetary expenditures in new and old housing in outer urban and peri-urban areas (Figure 3, SI), which in turn is due mainly to the fact that energy is a relatively inexpensive commodity compared to the intensity of emissions. Notwithstanding, it seems plausible that there are two rebound effects working in opposite directions here: (1) the rebounds from energy efficiency increase other types of consumption,[30,49,50] and (2) investing in new energy efficient buildings suppresses the overall levels of consumption.

3.2. Results from Multivariate Regression Analyses. We ran several multivariate regression models using income per capita as the explanatory variable to further analyze the differences in carbon footprints between the studied urban forms. The results are presented in Tables 2−4. First, we analyzed separately the new and old buildings (Table 2). The residents of the new buildings in inner urban areas have the highest carbon footprints, even when the differences in income levels are taken into account (regression 1a) (p < 0.05). However, when we also included household type in the model, the results were no longer statistically significant (regression 1b). Actually, the regression coefficients related to different urban forms were rather small in all of the regression models, and in many cases they were statistically insignificant compared to the coefficients of income and household type, which seem to play the major role in determining carbon footprints. Furthermore, as the correlation matrix shows (Table 3), there were relatively strong correlations between some urban forms, household types, and income level. It is likely that there are causal chains and simultaneous causalities between the urban form and other variables (including variables omitted here, like attitudes and preferences), which complicates the interpretation of the results from the multivariate regression analyses, as suggested by previous studies.[36,70]

With the second set of regression models, we independently compared the pairs of new and old buildings in each urban form (Table 4). In the inner urban areas, the carbon footprints of residents in new and old buildings did not differ statistically when taking into account income level or both income level and household type (regressions 3a and 3b). In the outer urban areas, however, the residents of new buildings had smaller carbon footprints in both cases (regressions 4a and 4b), and the

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Table 3. Pairwise Correlations between Regression Variables from Regression 1a−1b

	ln (carbon footprint per capita)	ln (disposable income per capita)	inner urban area	outer urban area	peri-urban area
ln (disposable income per capita)	0.64	1			
inner urban area	0.22	0.10	1		
outer urban area	−0.08	−0.02		1	
peri-urban area	−0.14	−0.08			1
young	−0.07	−0.15	0.27	−0.13	−0.13
adult singles	0.24	0.22	0.14	−0.03	−0.12
adult couples	0.39	0.34	0.20	−0.07	−0.13
seniors	0.09	0.08	0.16	−0.09	−0.06
young families	−0.41	−0.34	−0.30	0.11	0.19
other families	−0.04	0.00	−0.17	0.08	0.09

results were statistically significant. Likewise, the residents of new buildings in the peri-urban areas had smaller carbon footprints, but the results were statistically significant only when taking into account income level alone (regression 5a) and not when including household type in the model (regression 5b).

4. DISCUSSION

4.1. Interpretation of the Results and Policy Implications. Strong governmental policies in many countries support the densification of urban cores and require increasing levels of energy efficiency for buildings based on environmental claims. The aim of the study was to assess the GHG implications of new housing in different urban forms and to compare them against existing building stock in the same areas. Surprisingly, we found the smallest carbon footprints in newly constructed outer and peri-urban housing, whereas the carbon footprints in inner urban areas did not seem to meet the expectations of the environmental claims. In all areas, the emissions from housing energy were significantly lower in new buildings, but in the inner urban areas those with the highest affluence tend to be concentrated in the new building stock and their high levels of consumption more than counteract the gains in energy efficiency.

In absolute terms, the emissions per capita are highest in new buildings in inner urban areas and lowest in new buildings in outer and peri-urban areas. The carbon footprints of residents in the existing housing stock lie in the middle, with rather similar emissions in all urban forms. Surprisingly, even when income level and household type are taken into account via regression analysis, the inner urban areas do not perform significantly better than the outer and peri-urban areas. It should be also noted that there are some inherent problems with regression analyses when studying consumption behavior and related emissions. First, we kept the income level constant in the model, even though the residential location of a household may affect its income level due to agglomeration benefits. Second, keeping the household type constant seems artificial, since, as Table 1 shows, typical households moving to new detached houses in peri-urban areas tend to be families with children, whereas typical households moving to new housing in inner urban areas tend to be small adult households.

From a broader perspective, the comparisons of inner and outer urban areas typically done in environmental urban studies do not seem quite fruitful because of the significant differences in lifestyles, preferences, and demographics and only minor influence on carbon footprints. Instead, we should focus on reducing GHG emissions within each area type. For example, inner urban areas would benefit greatly from low-carbon CHP investments as well as from developing and using more low-carbon construction materials suitable for multistory buildings.[71−74] Also, though somewhat idealistic, communal living, that is to say, sharing spaces and equipment, would significantly reduce the emissions of small households. Fully equipped studio apartments use much more energy and other resources per capita than larger apartments with more residents, as also noted, for example, in a study by Jones and Kammen.[75]

In outer and peri-urban areas, the level of dependence on existing systems and infrastructures is much lower and allows residents to make independent low-carbon decisions regardless of possibly slow political systems concerning decisions about infrastructure. Low-carbon living could be based on technological solutions, such as energy efficient housing, heat pumps, home energy management systems (HEMS), and hybrid or electric vehicles combined with new energy solutions for homes.[76,77] These types of technological solutions are also likely to have positive spillover effects in addition to or instead of the negative rebound effects of consumption.[21] In light of our results, it seems that the new legislation regarding the

Table 4. Results from Regression Analyses: The Effect of Living in a New Building on Carbon Footprints of Residents

	inner urban area (1076 obs.)				outer urban area (864 obs.)				peri-urban area (343 obs.)			
prob > F = 0,000 in all models	regression 3a		regression 3b		regression 4a		regression 4b		regression 5a		regression 5b	
dependent variable:	R^2	0.431	R^2	0.469	R^2	0.413	R^2	0.473	R^2	0.447	R^2	0.496
ln (carbon footprint per capita)	coef.	$P > \|t\|$	coef.	$P > \|t\|$	coef.	$P > \|t\|$	coef.	$P > \|t\|$	coef.	$P > \|t\|$	coef.	$P > \|t\|$
ln (disposable income per capita)	0.62	0.000	0.59	0.000	0.64	0.000	0.56	0.000	0.68	0.000	0.57	0.000
new building (dummy)	0.05	0.339	0.03	0.562	−0.12	0.000	−0.08	0.012	−0.14	0.029	−0.06	0.374
young			0.22	0.000			0.30	0.001			0.29	0.020
adult singles			0.23	0.000			0.37	0.000			0.39	0.002
adult couples			0.14	0.006			0.22	0.000			0.31	0.001
seniors			0.15	0.000			0.16	0.000			0.18	0.022
other families with children			−0.06	0.241			0.04	0.405			0.07	0.364
young families and single parents												
constant	2.97	0.000	3.20	0.000	2.80	0.000	3.51	0.000	2.37	0.006	3.32	0.001

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energy efficiency of buildings is working quite well for new housing in outer and peri-urban areas. However, retrofitting older buildings to match the new energy efficiency standards would be equally or even more important.[78−80]

Finally, since low-rise areas are appealing residential locations for many people, this possibility could be tapped by creating valuable suburban areas where the value would come from immaterial benefits instead of from carbon-intensive commodities, such as overly large houses or heavy construction. For example, safety, nature, and social bonds are important for the residents of suburban areas.[46,81−83] These sorts of immaterial benefits can create value without causing high GHG emissions. Also, we should retain and further develop the walkability of these areas. For example, in Finland, despite that more than 90% of residents in low-rise areas have at least one car in their household, children still most often walk or ride their bicycles to school. Residents also value their local grocery stores,[46] and walk or cycle most of the short (less than 1 km) grocery trips.[84]

4.2. Some Limitations and Uncertainties. The study contains three main sources of uncertainty: uncertainties inherent in the method, weaknesses with the data, and uncertainties related to the GHG emissions from construction and the time perspective. We discuss these uncertainties below. It is also good bear in mind that if wider environmental conclusions are to be drawn, our study was limited only to GHG emissions. There are other important environmental and social issues related to different urban forms as well. Furthermore, our model did not include land use changes, which have GHG implications not considered here.[85]

Uncertainties Related to the Method. Input−output analysis includes the so-called linearity assumption; in other words, that one euro spent on a certain consumption category always causes the same emissions.[86] The method does not take into account the differences in prices and types of consumption within the categories. However, it is possible that such differences between the studied area types exist. Also, it would be important in the future to develop and spread the use of multiregional input-output models (MRIO) to assess the emissions from imported goods accurately. In the ENVIMAT model the emissions from imports have been assessed utilizing LCI-data from international databases, but MRIO models would be methodologically more coherent.

Restrictions of the Research Material. Statistics Finland's Household Budget Survey is based on telephone interviews, consumption diaries, receipt information, and administrative registry data. Although this is an established way of collecting budget survey data, it includes the possibility of human error. Also, because of the limitations with the data, we had to utilize data on the expenses incurred by housing companies for buildings constructed in the years 2000−2012 to estimate construction costs for the years 2003−2012, that is to say, for the new building subgroup in our study. This somewhat overestimates the housing energy emissions for new apartment and row-houses.

Uncertainties and Limitations Related to the Emissions from Construction and Time Perspective. The estimate of GHG emissions from construction is uncertain and does not take into account the differences between high-rise and low-rise construction. For example, studies by Norman et al.,[11] Nässén et al.,[87] and Bawden[88] have shown how emissions from construction per square meter are lower for detached houses and townhouses than for higher residential buildings. This is due to two main reasons: (1) differences in construction materials and (2) the additional spaces needed in high-rise buildings, such as staircases, elevators, underground parking spaces, and additional storage space. However, it has been suggested that the construction of infrastructure in low-rise areas causes more emissions because of the longer distances and lack of existing infrastructure. More research is warranted in this area. Also, it would be important to study, how parking facilities in new high-rise buildings influence transport mode choices of the residents.

The uncertainties related to the time-perspective are manifold. First, to compare the construction phase emissions to annual carbon footprints, we divided the construction phase emissions by the expected lifespan of the buildings. However, carbon footprints as a result of consumption are created based on consumption patterns at the moment. In reality, the GHG emissions from construction are released before and at the time of construction, and they will not change in the future, whereas the carbon footprints resulting from consumption are likely to be quite different in the year 2065 from what they are now. For example, the GHG emissions from energy production are expected to decrease significantly in the forthcoming decades.[89,90] Furthermore, GHG emissions caused in the early phase of a product's life cycle have a stronger effect on global warming than emissions caused later on.[91] Actually, several recent studies have emphasized that construction phase emissions receive too little attention in the life cycle assessments of new buildings.[80,92−94] For example, Säynäjoki et al. demonstrated that the carbon spike caused by construction results in higher cumulative emissions for several decades compared to the existing building stock, despite current energy efficiency requirements.[80] They concluded that renovating existing buildings would be more energy efficient than building new ones.

Another issue related to the time perspective is the development of residential areas over time. New outer and peri-urban areas appeared to be energy efficient in our study partly because they are inhabited by large families. However, as the children grow older and move away from home, the living space per capita in the same areas increases, as Table 1 demonstrates. This will also increase the GHG emissions per capita. One policy implication would be that older couples with "empty nests" should be encouraged to move into smaller apartments. This would release the large family apartments and houses for new families with children. Another possibility would be to encourage them to sublet their home. Thus, the overall utilization rate of housing would increase and the need for new construction would decrease.

4.3. Conclusions. New housing is concentrated in urban environment in growing metropolitan areas. Policy makers and urban planners are concerned about the effects of urban sprawl in these areas and are devising policies to restrict it. It has been suggested that dense residential areas with good accessibility to public transit constitutes an effective way to mitigate climate change. However, the problem behind these policies is a narrow understanding of the scope of the issue. Transit-oriented development is likely to reduce the emissions from private driving, but it may have unintended consequences for other types of consumption and related GHG emissions. The climate change mitigation policies in urban planning should have a broader scope and understanding of GHG implications for all consumption. In the study, we did not find support for the assumption that inner urban areas would be especially sustainable from GHG perspective.

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Because of only a small effect on carbon footprints and significant differences in lifestyles, preferences, and demographics, highlighting a supposed dichotomy between dense city centers and suburban areas does not seem very fruitful. Instead, to reduce GHG emissions effectively we need a more systemic strategy for developing urban areas. It would be beneficial to focus on area-specific mitigation measures in low-rise and high-rise areas. For example, low-rise areas are less dependent on existing infrastructure, and because of this, new energy efficiency measures and other technological solutions can spread quickly in such areas, as our findings suggest. Low-energy housing, heat pumps, HEMS, photovoltaic panels, and hybrid and electric vehicles are good examples of such technologies. Similarly, the value of new low-rise areas should mostly come from immaterial benefits, such as safety, closeness of nature, coziness, and social bonds, instead of overly large houses with fast highway connection to the city centers and airports. Existing areas could also be developed from this perspective. In inner urban areas, one of the main reasons for the high GHG emissions per capita has to do with the small household sizes. Fully equipped studio apartments cannot be considered energy or resource efficient. However, the demand for such housing is continually rising since the average household size has decreased for several decades now and is still decreasing in Finland, as in many countries. The emissions could be reduced by designing dense areas around the idea of sharing space resources better. For example, the sharing of apartments would reduce the housing related emissions effectively. Also, low-carbon centralized energy production investments will be necessary. Similarly, the development and spread of low-carbon construction materials suitable for multistory buildings should be enhanced. The substantial GHG emissions from flying should also be targeted.

Two areas, where more research is needed, rose from the study. First, one specific issue are the GHG impacts from constructing new residential areas. There is a lack of studies, which would show the overall impacts of low- versus high-rise areas, including the construction of infrastructure. Of course, the impacts would be area specific, but more case studies would be helpful. Second, more research is needed to show the effects of mitigation measures taken to practice. Too often the measures are based on theoretical calculations, which do not take into account the rebound effects and other real world limitations. This includes also understanding better the impacts over time, when currently new neighborhoods mature and the residents as well as the technological environment change. We call for a research with wider system boundaries conducted in real life context.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information (SI) includes the scope and boundaries of the carbon footprint model, a figure illustrating the carbon footprints of apartment owners in inner urban areas and a figure illustrating the expenditure per capita of residents living in new and old buildings in the three studied urban forms. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b02140.

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Notes

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