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Comparing climate change effects of rural and metropolitan lifestyles, a hybrid-LCA approach

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Authors: **Jukka Heinonen** (corresponding author, attending the conference), Researcher, Aalto University School of Science and Technology
P. O. Box 11200, 00076 AALTO, jukka.heinonen@tkk.fi

Seppo Junnila, Professor, Aalto University School of Science and Technology
P. O. Box 11200, 00076 AALTO, seppo.junnila@tkk.fi

Abstract

Climate change is often recognized as the most severe global environmental problem of the present time. Rural municipalities tend to be seen as one of the drivers of climate change. Rural lifestyle is marked unsustainable due to higher level of private driving and energy use compared to more dense metropolises. This, however, seems to be a much more complex issue and should be further studied before either one of these two lifestyles can be proclaimed more sustainable than the other.

While life cycle assessment has been widely accepted as the method to study the environmental loads of communities, a vast majority of the studies are conducted from the producer perspective. In this study we present a hybrid life cycle assessment model to study the carbon consumption of a community. This approach enables us to compare rural and metropolitan lifestyles considering full life cycle emissions of consumption. We argue that this approach, in addition to the producer perspective, will be of high importance in the near future when effective carbon management strategies are created. With two case studies from Finland we demonstrate that in this kind of study the metropolitan lifestyle seems not to be producing more sustainable communities.

1 Introduction

Climate change is often recognized as the most severe global environmental problem of the present time [1, 2]. Ambitious cut off targets have been set on the global, economic and local urban and municipal scale [3, 4, 5, 6]. However, strategies for achieving these targets are often weak or incomplete due to lack of information.

Rural municipalities, and on larger scale, urban sprawl, tend to be seen as the drivers of climate change [7, 8, 9]. Rural lifestyle is marked unsustainable due to higher level of private driving and energy use compared to more dense metropolises. This, however, seems to be a much more complex issue and should be further studied before either one of these two lifestyles can be proclaimed more sustainable than the other [10].

While life cycle assessment (LCA) has been widely accepted as the method to study the environmental loads of communities, a vast majority of the studies are conducted from the producer perspective, allocating to the communities the emissions occurring inside the borders of the community [8, 11, 12]. This approach, while offering prominent information, can lead to unsustainable strategies in cutting emissions, as, for example, relocation of a power plant outside the borders of the community would seem to cut the emissions.

In this study we present an application of a hybrid life cycle assessment model to study the carbon consumption of a community. This approach enables us to compare the rural and metropolitan lifestyles with the full life cycle emissions of their consumption. We argue that this approach, in addition to the producer perspective, will be of high importance in the near future when effective carbon management strategies are created.

The study is conducted with four samples from a large consumer survey representing different consumer profiles from Northern Europe. The consumer profiles represent lifestyles from metropolitan to rural offering a possibility to assess the carbon consumption related to these lifestyles. With this setting we demonstrate that the intense metropolitan lifestyles are not necessarily having lower carbon footprints, and thus producing more sustainable communities.

2 Method

The method utilized in this paper is life cycle assessment (LCA). The LCA method includes three different approaches: input-output-LCA, process-LCA and hybrid-LCA. Here we utilize an input-output based application of hybrid-LCA. The approach combines the comprehensiveness of input-output approach with the accurateness of a process approach [14]. The three LCA approaches are shortly presented below.

Process-LCA is the most common way of conducting an LCA [13, 14, 15]. In process-LCAs, the emissions are assessed based on energy and mass flows in the main production and supply chain processes. The objective is to define the most important emission sources and assess the precise emissions process by process. Thus the assessments should be accurate and comparable. However, even with inclusion of multiple upstream processes, the approach suffers from truncation error from the boundary selection that always needs to be made. These boundary selection based cutoffs may potentially significantly affect the result of the assessment [13]. In addition, a comprehensive process-LCA is often laborious and time consuming to conduct [13, 14].

The second approach, input-output-LCA, is a method where the carbon emissions are calculated based on monetary transactions. The approach uses monetary sectoral transaction tables to describe the interdependencies between industries in an economy [15]. The tables show the emissions that each sector causes related to a monetary transaction on one sector. The input-output method does not suffer from the truncation error described above. The method is comprehensive, always providing a full inventory of the emissions attributable to a certain good [14], except for the end of life stage, which should be added to the calculations [13]. Input output method is also quick and rather easy to use [14].

The inherent problems related to input-output method include high level of aggregation of industry classifications, possible temporal (inflation and currency rate differences) and regional (industry structure differences) asymmetries between the data and the model, and the assumption of domestic production of imports [13, 14, 16]. As can be seen, these problems differ from those related to the process approach thus creating space for hybrid-LCA models, which combine the strengths of the two approaches and reduce the weaknesses related to them [13, 17].

Hybrid-LCA models have emerged to allow life cycle assessments with lacking information, and to create models that significantly reduce the truncation error while maintaining process specificity. There are three different categories in hybrid-LCAs. First, in tiered hybrid LCA's higher order upstream phases are covered with input-output analysis, whereas direct emissions and the most important upstream phases are examined with process analysis. Second, in input-output-based hybrid analysis output sectors are disaggregated to include process data and to avoid aggregation and truncation problems. The third category is integrated hybrid analysis model, which incorporates process level information into the input-output model. [13]

The model utilized in this study is an application of tiered hybrid-LCA approach. The model is input-output based with the key emission sources assessed with process data and the higher order phases covered with IO matrices to maintain full coverage. The key element of this type of hybrid model is global perspective on the carbon emissions. The consumption of goods in one place may generate carbon emissions anywhere in the world depending on the production and supply chains. Whereas a majority of all LCA models have geographical boundaries, the type of hybrid-LCA utilized in this study is always comprehensive in incorporating the production and supply chains in to the inventories. Due to the geographical boundaries cities may seem to cause less carbon emissions, as the production of goods consumed in the cities occurs outside of the city area [27, 28]. Taking all consumption into account and counting the emissions without regional boundaries allows unbiased comparison of different area types, and further a basis for efficient carbon management. The model utilized and the construction of the model is further described in the next section.

3 Research design

3.1 Selection of samples from rural to metropolitan lifestyles

The study includes four representative samples of consumers from Finland covering a range of types of living from rural to metropolitan. The first sample consists of consumers living in Finnish rural areas. In rural areas less than 60 % of the inhabitants live in urban areas with the largest urbanization smaller than 15.000 inhabitants. Then there are areas where 60 % to 90 % of the inhabitants live in urban areas with a maximum of

4.000 inhabitants. The second sample comprises consumers from municipalities where 60 to 90 % of the inhabitants life in urban areas with the minimum of 4.000 inhabitants and the maximum of 15.000 inhabitants. These are called semi-urban areas in the paper. The third sample, the cities, consists of consumers of municipalities where the minimum of 90 % of the inhabitants live in urban areas, or those where the largest urbanization is larger than 15.000 inhabitants. The fourth sample is the Helsinki metropolitan area consisting of the capital of Finland, Helsinki, and the three large cities surrounding Helsinki. The Helsinki metropolitan area includes more than 1.000.000 inhabitants. In addition, the Finnish average carbon consumption was assessed for comparison.

With this selection of lifestyle based samples we are able to demonstrate the changes in carbon consumption as the density of the area grows and the dominant type of habitation changes from detached houses to apartment buildings. In rural areas detached housing is dominating and the areal structures are loose. On the other end, in the Helsinki metropolitan area, the urban structure is substantially denser and apartment buildings dominate housing. Semi-urban areas and cities place between the two extremes.

3.2 Input data

The study is conducted utilizing the Finnish consumer survey 2006 data [24]. The data from the survey were used for the input-output modeling of the carbon consumption in the first phase of the study, and for the input-output part of the tiered hybrid model. In addition, the emission calculated with process data was also assessed utilizing the consumption volume.

The consumer survey 2006 data represents the consumption of an average Finnish consumer. The level of detail of the survey is very high including around 1.000 categories and sub-categories of goods and services. The sample size is also high with nearly 10.000 participants on the national level making the data excellent for scientific use. In addition, smaller samples can be produced based on diverse variables, type of areal structure and region being the ones used in this study.

The utilized process data include the average Finnish emissions of heat and electricity production [19], fuel combustion emissions of private driving and public transport [20], and disaggregation of the public transport sector according to the local profiles of public transport use [21]. Also, a regional price level correction was made for property prices according to the statistics of The Housing Finance and Development Centre of Finland (ARA) [22].

3.3 Tiered hybrid-LCA model

The study advanced in two calculation phases, direct input-output assessment and hybrid assessment. Before the first calculation, the consumption sectors in the input data were comprised from the original 1.000 categories to 43 aggregated sectors representing the areal and lifestyle related consumption. After this, the carbon consumption was calculated using direct input-output assessment. At this phase we utilized two different models, the US industry based Carnegie-Mellon EIO-LCA 2002 [18] and the respective Finnish model ENVIMAT [21]. As the results of the two assessments were very similar, we chose the Carnegie Mellon EIO-LCA as the basis of our hybrid model. The model provides output tables for 428 industry sectors, and thus is the most disaggregated model available reducing the aggregation error inherent in input-output approaches. This was considered critical as the input data utilized in the study is highly complex. Also, the Finnish economy is a small and open economy with over 50 % of the value of total consumption oriented to import goods [25], a significant part of Finnish consumption based emissions thus originating abroad.

The selection of the model includes some potential sources of bias in addition to those inherent for all input-output models. Of these, the potential industry structure asymmetry error was assessed not significant according to the simultaneous assessment with the ENVIMAT model. Second, to decrease the temporal asymmetry problem arising from inflation and currency rate differences between the US and the Finnish economies, the model was adjusted with purchasing power parity (PPP) multiplier [23], a method that was utilized by Weber and Matthews in their recent study of the global and distributional aspects of the American household carbon footprint [16]. Third, as inherent in all input-output based models, the emissions tables exclude the use and the end of life phases. Here, as we used consumption data including all private expenditure, also these phases are automatically included as the prices of goods on the aggregate level include the excluded phases and thus create emissions profiles for them, too (gross domestic product includes all private expenditure and thus also the prices for the missing life cycle phases).

The final problem that needs to be assessed in input-output calculations is the accuracy problem arising from the use of the use of industry averages in the output matrices. However, in this study the use of hybrid assessment model significantly reduces this problem. The sectors including local process data cover more than 50 % of the total carbon emissions, and all the most significant emission sources, as is further described below.

Next, the first calculation was used for the design of the tiered hybrid-LCA model. In the tiered hybrid-LCA the most important processes producing carbon emissions were enhanced with process data according to the input-output model, but the rest of each matrix was left untouched to maintain the full coverage of the model.

In the direct input-output assessment three sectors were found to cover two thirds of the carbon consumption. These sectors were emissions related to housing energy use (heat and electricity), building related emissions and transport related emissions. According to this assessment these four key sectors were enhanced with process data.

Concerning energy, the direct energy production phase emissions were replaced with process data in the output matrix. We utilized the average Finnish emission profiles for electricity, district heat and oil according to Kurnitski and Keto [19], these being 240 g/kWh for electricity, 286 g/kWh for heat and 267 g/kWh for oil. For wood used for heating zero carbon emissions were assumed. The electric power production profile in Finland is nuclear power 28 %, fossil fuels 36 %, peat 8 % and renewable energy sources 28 % [25].

In addition, the communal building energy, normally paid with rent or housing management charges in apartment buildings and row-houses, was added to the energy consumption of a consumer. This disaggregation of rents and housing management charges was done according to former Kiiras et al. Study, and an updating study including 10 housing corporations from the Helsinki metropolitan area. Furthermore, all the other operation and maintenance costs included in rents and housing management charges, water, waste, cleaning, maintenance and repair construction, etc., were re-allocated under appropriate consumption categories according to the same results.

In private driving, the first tier emissions related to the fuel combustion phase were replaced with process data. This was done according to the data from The Technological Centre of Finland's LIPASTO study [20].

Next, the emissions from expenditure on building and property were enhanced with regional data. The share of the price of property has substantial regional variations, and as the emissions related to building and property differ heavily, regional price adjustments were utilized according to the property price statistics of The Housing Finance and Development Centre of Finland (ARA) [22].

Finally, although emissions related to public transport were minor in the input-output calculation, they were enhanced with the Finnish data as the sector forms an important substitute for private driving, and the emissions profile of EIO-LCA significantly differ from that of Finland. Here the enhancement was done by replacing the EIO-LCA output matrix with that of the respective Finnish ENVIMAT study [24].

After the construction of the hybrid model we made the initial 43 consumption categories up to 10 consumption areas, which indicate the type of region and standard of living related carbon consumption. The consumption areas are:

1. Heat and electricity
2. Building and property
3. Maintenance and operation
4. Private driving
5. Public transportation
6. Consumer goods
7. Leisure goods
8. Leisure services
9. Travelling abroad
10. Health, nursing and training services

Of these 10 consumption areas, Heat and electricity contain all housing energy use, including both household heat and electricity and the share of communal building energy. Building and property is dominated by construction, whereas Maintenance and operation comprise emissions of maintenance and repair construction, water and waste water, waste and cleaning. Private driving, in addition to gasoline combustion, includes all activities related to driving, purchases and maintenance of private vehicles. Public transportation mostly consists of travelling by coach or train.

Goods and services classes comprise daily consumption and consumption of durable goods, so that leisure related expenses are separated for demonstration of the allocation of emissions and lifestyle differences. Travelling abroad include all private flying and accommodation abroad. Finally Health, nursing and training services are put together as they only include private services, which in Finland form a minor share of all the services of these sectors.

4 Results

The study produced quite an unconventional outcome. In Finland, the metropolitan lifestyle seems to be at least as carbon intensive as the rural lifestyle. Of the lifestyle patterns studied, the carbon consumption of an average consumer in rural areas is 9,0 tons of carbon dioxide equivalents (ton CO2-ekv.), in semi-urban areas 9,9 ton CO2-ekv., in cities 10,9 ton CO2-ekv., and in the Helsinki metropolitan area 12,5 ton CO2-ekv. The Finnish average is 10,2 ton CO2-ekv. according to the model. Thus the results suggest that in rural areas significantly less emissions are caused on per capita level compared to metropolitan living. Figure 1 shows the annual per capita carbon consumption of different lifestyles divided into the 10 consumption areas presented above.

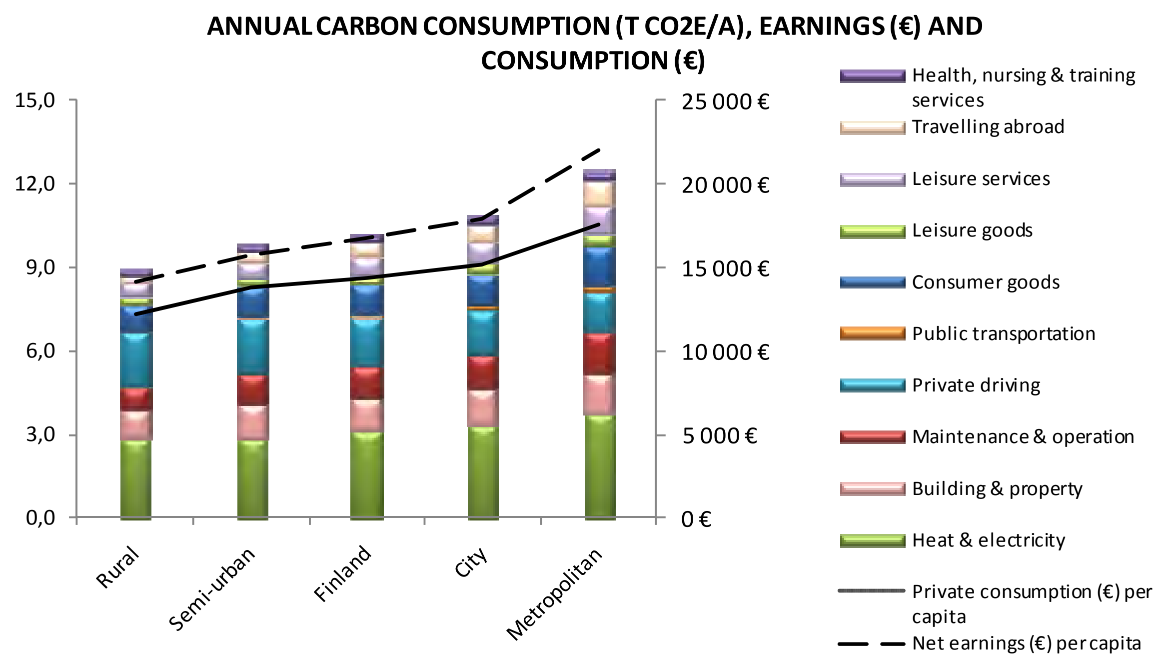

Figure 1: The annual per capita carbon consumption of different lifestyles divided into 10 consumption areas.

The carbon consumption is closely related to the standard of living, as is indicated in Figure 1 by the dashed line indicating annual net earnings per capita. But, as the solid line of annual private consumption interestingly shows, only a diminishing share of the earnings is consumed as the level of earnings grow. This has an equalling effect on the carbon consumption of different lifestyles.

However, despite the earnings and the volume of consumption, the same categories dominate the carbon consumption in all types of area. Energy related to housing is the single most dominant sector, as well as the primary explanation for the results. It seems that the emissions related to housing energy grow as the type of area changes to denser and more apartment house dominated city and metropolitan areas. The same 2,9 ton CO2-ekv. carbon emissions are caused by energy use in rural and semi-urban areas, whereas in cities the figure is 3,3 ton and in the Helsinki metropolitan area 3,7 ton. While the level of energy consumption only slightly varies between the different area types, the carbon content of the energy used seems to be better in rural and semi-urban area types (Figure 2). Figure 2 presents the annual energy consumption in monetary terms divided into the four consumption categories presented earlier.

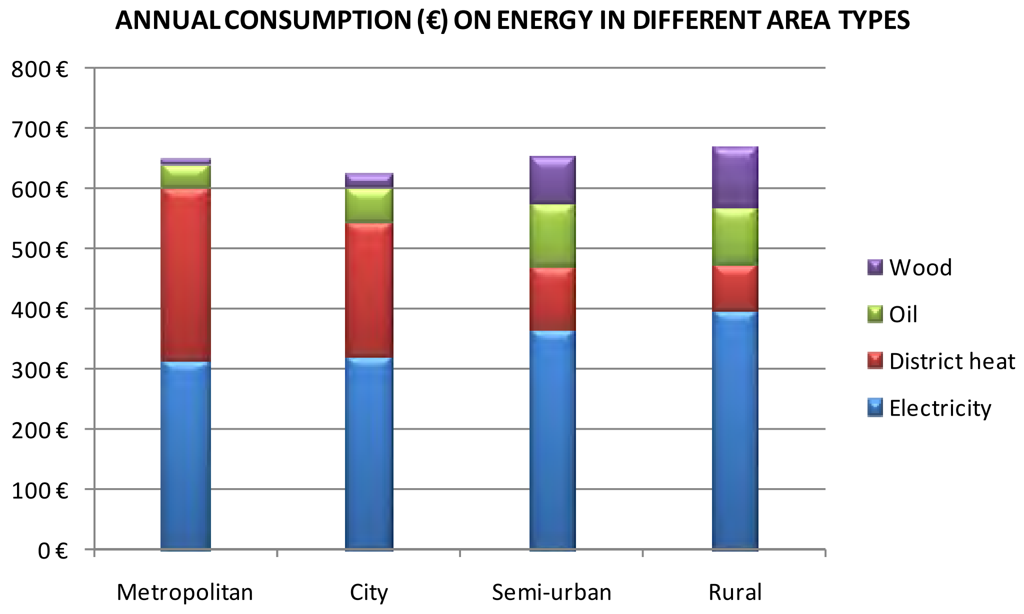

Figure 2: The annual per capita consumption on energy in different area types.

Emissions from the construction and maintenance of the building, (Building and property and Maintenance and operation) together form another significant share of the total carbon consumption. As in emissions from energy use, the same growing pattern from rural to metropolitan living is seen in the emissions. In rural areas, 1,8 ton CO2-ekv. emissions relate to these two categories, whereas in the Helsinki metropolitan area the figure is as high as 2,9 tons. In semi-urban areas the carbon consumption in these categories is 2,3 tons and in cities 2,6 tons. The input data reveals that the spending on acquisition of homes is on a substantially higher level in more urbanized areas causing higher emissions. The same applies to a majority of all operation and maintenance costs explaining the rest of the difference. Figure 3 represents the consumption volumes in different area types.

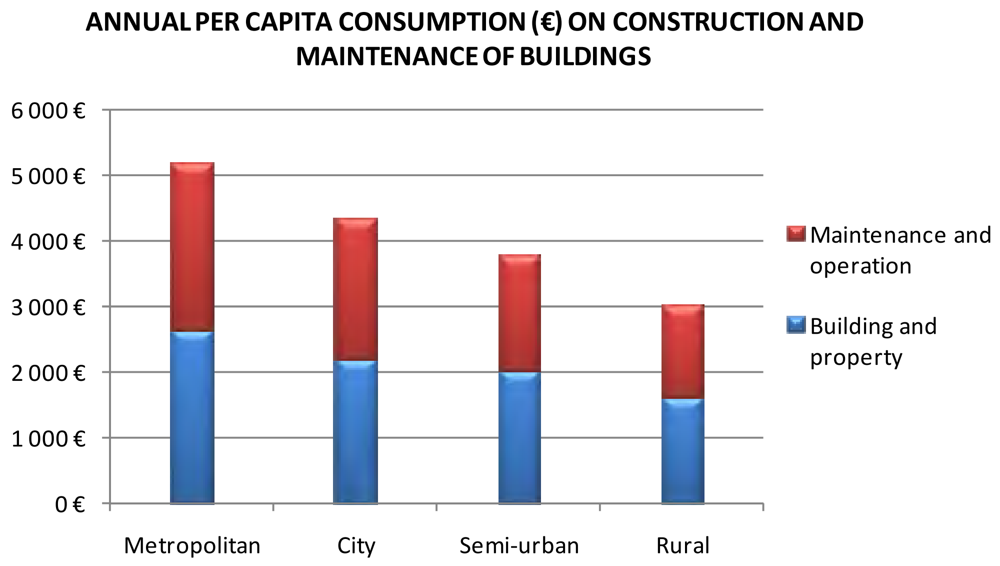

Figure 3: Annual per capita carbon consumption on construction and maintenance of buildings in the different area types.

Emissions related to private driving follow earlier studies having a growing pattern as the density of the areal structure diminishes from the metropolitan to the rural type [f. e. 9, 26]. In rural and semi-urban areas the carbon consumption from private driving is 2,0 tons, but in cities 1,6 tons and in the Helsinki metropolitan area only 1,4 tons.

Public transport has little significance in carbon consumption, but is an important substitute for private driving. Here the denser urban structure seems to lead to higher level of public transport use, as the emissions grow from 0,05 and 0,06 tons of CO2-ekv. in rural and semi-urban areas to 0,15 and 0,24 tons in cities and the Helsinki metropolitan area.

The rest of the categories comprise carbon emissions from consumption on goods and services. The share of these of the total carbon consumption varies from 25 % in rural areas to 33 % in the Helsinki metropolitan area. The positive correlation of income and carbon emissions of consumed goods and services is high, shown especially in travelling abroad, but to some extent in all the categories. In addition, in the most urbanized areas the consumption of services has an extra emphasis. However, more detailed analysis of this share of carbon consumption is not possible with the calculation model utilized, as it is impossible to differentiate volume from quality. The first should raise the emissions, but the relation between emissions and quality is unclear. This does not harm the study, though, as this share of the consumption was not in the focus of this study.

5 Discussion

The purpose of this study was to present an application of tiered hybrid-LCA model for comparing carbon consumption in rural and metropolitan areas. This was done with four samples of consumers from Finland representing different area types from rural to semi-urban, city and metropolitan areas. In the study we created a consumption based carbon footprint that includes all life cycle emissions including production and delivery chains. We also structured the carbon footprint so that areal structure related emissions could be identified and analyzed. We argue that this type of consumption based modeling of emissions is of high importance and adds valuable information to more common regional production based assessments. Especially, when solutions for low-carbon living and low-carbon areal structures are searched, consumption based assessments of the emissions are essential.

The hybrid-LCA model was created in two phases. In the first phase we assessed the annual carbon consumption of an average consumer in Finland using two different input-output models, the Carnegie Mellon EIO-LCA [18] and the Finnish ENVIMAT [21]. According to the similar results of these assessments, the EIO-LCA was selected as the basis of the hybrid model. The assessments were also used to select the categories that were enhanced with process data. These were energy related to housing, building and property, maintenance and operation of the building, private driving and public transportation, which together accounted for roughly two thirds of the total carbon consumption.

In the second phase we assessed the carbon consumption of the different area types and the Finnish average consumer with the hybrid model. This assessment showed a growing pattern in the carbon consumption related to growth in the areal density, as in rural areas the annual carbon consumption of an average consumer is 9,0 ton CO2-ekv., in semi-urban areas 9,9 ton, in cities 10,9 and in the Helsinki metropolitan area 12,5 ton. The volume of private consumption, 12.200 € in rural areas, 13.800 € in semi-urban areas, 15.200 € in cities and 17.600 € in the Helsinki metropolitan area, explains a share of the differences, but significant consumption structure related factors were also identified in the study.

First, interestingly it seems that the type of housing, detached house in rural areas or dwelling in cities and metropolitans, has quite a small effect on overall energy consumption. In addition, in emissions the pattern found was that the emissions grow as the structure gets denser and housing more apartment building based. This contradicts some earlier studies, which have shown substantial differences between the two types of areas and housing [e.g. 7, 9]. The explanations the input data offers are clear, though. First, when also the building energy was allocated to the consumer in addition to household energy, the total amount of energy used was roughly equal in all types of the area (see Figure 2). Second, the profile of energy sources explain the difference in emissions, as in areas with detached housing a significant amount of wood is used for heating. Also, as electricity dominates the total energy consumption in the rural areas, and has slightly better emissions profile than district heat and oil, the emissions in rural areas are lower with equal consumption volume. And third, the size of an average household is 2,33 persons in rural areas, 2,27 in semi-urban areas, 2,01 in cities and 1,93 in the Helsinki metropolitan area. Now, even if there was difference in energy use on building level, the per capita perspective would diminish this.

Second structural pattern identified was that the relation between the type of the region and the emissions from private driving seems clear, as has been noted also in several earlier studies [in Finland f. e. 9, 26]. Again, though, the effect on the carbon consumption per capita is quite weak when all the emissions related to driving are calculated, including car manufacturing, deliveries and maintenance of vehicles. According to the hybrid model, the share of fuel combustion of all private driving related emissions is 50-70 %, the rest being dominated by car manufacturing related emissions. Thus, growth in trip generation due to decline in the density of the city structure has only a relatively minor effect on the overall carbon consumption.

Third pattern was that the level of consumption on services grows together with the density of the structure. This seems to be closely related to the income level, but was also assumed to indicate growth in the availability of different services as the urbanization grows.

Overall, according to this study, it would seem that rural and semi-urban lifestyles are not to be blamed for climate change. Instead, it would seem that it is possible to construct relatively low-carbon communities regardless of the types of housing and the location of the community. The primary focus in low carbon living should be on the emissions of energy production and building energy consumption and only secondary on private transportation or dense urban planning. The first directly affects the whole area using the energy, plus indirectly the emissions related to usage of goods and services produced using the energy in question. The second substantially affects the carbon consumption of those living in the specific building, but on wider scale has low impact, at least in a short period.

The reliability of the study was assessed from three perspectives. First, a positioning of the results among earlier applicable studies was made. Of these, calculation with the Finnish ENVIMAT study output tables showed an annual per capita carbon consumption of 10,1 ton CO-ekv. for an average Finnish consumer, whereas the figure with the hybrid model was 10,2 tons. On the method level, a reference has been published quite recently by Weber and Matthews, who used the EIO-LCA approach to study the global and distributional aspects of the American household carbon consumption [16].

Second source of possible biases is the hybrid model itself. Based on the assessments and amendatory actions described in the method and research design sections, we argue having avoided or diminished these substantially.

Finally, the reliability of the input data was assessed. In this study, the Finnish consumer survey [24] provided the primary input data. The level of detail of the data is very high. The survey presents private consumption divided into more than 1.000 categories of goods and services, thus providing an excellent basis for IO based LCAs. Also, the sample size is representative including roughly 10.000 subjects (0,2% of the Finnish population). In this study the sample sizes remained sufficient (over 1.000 observations in each sample) and thus biases related to these were assessed small.

Despite the very high quality input data, free public services and heavily subsidized services create a source of bias in the Finnish economy system, as these form a noteworthy share of the total private consumption. However, no amendatory actions were taken, since the assessment in the Finnish ENVIMAT study showed that the bias predominantly concerns our comprised consumption class "health, nursing and training services", which had minor significance in this study.

As the final test of the robustness of the results, we conducted a longitudinal study using preceding consumer survey data from 2001. The test results were very similar, except for a scale difference due to the change in the standard of living between the two surveys. This test strongly supports the robustness of our findings.

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