2011 2nd International Conference on Environmental Science and Technology
IPCBEE vol.6 (2011) © (2011) IACSIT Press, Singapore

Metropolitan Carbon Management

A Hybrid-LCA Approach

Jukka Heinonen, Seppo Junnila
Aalto University, School of Science and Technology, Department of Surveying
Espoo, Finland
jukka.heinonen@tkk.fi, seppo.junnila@tkk.fi

***Abstract*—The prevailing belief is that dense metropolitan areas produce less carbon emissions on per capita basis than the less dense surrounding and rural areas. This issue seems to be much more complex, and the situation might even be reversed when comprehensive analyses are conducted. In this paper we present a consumption based life cycle assessment (LCA) approach on the metropolitan carbon management, that is both comprehensive in incorporating all living related carbon emissions, and accurate in the results. Also, the method allows analyses on sub-city level without boundary cutoffs, and thus provides a sustainable basis for effective carbon management. In addition, the method enables global comparisons. The presentation of the utilized LCA method is conducted via a representative analysis of carbon consumption in a Northern European metropolis. The emphasis in the analysis is on urban structure, where we demonstrate that dense structure is not necessarily a precondition in creating low-carbon communities.**

Keywords-component; life cycle assessment (LCA), urban structure, carbon management, low-carbon communities

I. INTRODUCTION

There seems to be urgent need for reliable tools for city level carbon management. Cities are estimated to produce up to 80 % of the global green house gases (GHGs) [1]. Their role in the climate change mitigation is thus eminent. This has been widely recognized, and ambitious cut-off targets have been globally set on the city level [2, 3, 4, 5, 6]. However, strategies for achieving these targets are often weak or incomplete due to lack of applicable strategic urban planning tools.

Furthermore, the prevailing belief is that dense metropolitan areas produce less carbon emissions on per capita basis than the less dense surrounding and rural areas [7, 8]. This issue seems to be much more complex, as some recent results indicate that the situation might even be reversed when comprehensive analyses are conducted [9, 10].

It has been demonstrated that a substantial share of carbon emissions attributable to a certain good or process may occur in higher order tiers outside of the final production phase [11]. Thus, only life cycle inquiries can produce reliable information. In the city context these tend to be highly complex, as the number of variables is high, which both limits the utilization and creates room for high variation in the results due to method choices.

In addition, a vast majority of the inquiries that have assessed city level carbon emissions are conducted using regional boundaries allocating the region emissions occurring inside the set borders [f. e. 7, 12]. This perspective, though, is not sufficient for effective carbon management. This is due to two reasons. First, structural changes could substantially affect the emissions inside the chosen borders, but have no net effect on the global scale. Second, this approach produces no reliable information for the creation of low-carbon communities, for the industry structure affects the per capita carbon emissions.

In this paper we present a consumption based life cycle assessment (LCA) approach on the metropolitan carbon management, that is both comprehensive in incorporating all living related carbon emissions, and accurate in the results. Also, the method allows analyses on the sub-city level without boundary cutoffs, and thus provides a sustainable basis for effective carbon management. In addition, the method enables global comparisons.

The presentation of the utilized LCA method is conducted via a representative analysis of carbon consumption in a Northern European metropolis. In the analysis, the emphasis is on urban structure, where we demonstrate that dense structure is not necessarily a precondition in creating low-carbon communities.

II. RESEARCH DESIGN

The study presents carbon consumption in Helsinki, the capital of Finland in Northern Europe. Helsinki is the largest city in Finland with over 500.000 inhabitants. It is also a centre for over 1.000.000 inhabitants in the Helsinki metropolitan area. The population density of the city is 3.000 inhabitants/km2. However, the city includes a dense downtown area with solely apartment buildings, where the figure is substantially higher, up to over 10.000 inhab./km2, and the surrounding suburbs with a notable share of detached and row-houses and substantially lower density.

The carbon consumption is assessed on annual per capita basis for an average consumer incorporating all the emissions related to consumption with life cycle perspective. In addition, the effect of the city structure on carbon consumption is analyzed to emphasize the possibilities of carbon management. This analysis also demonstrates that other factors than density or building type, the often addressed sources of emissions [8, 13], seem to determine the carbon consumption. For the analysis, the city is divided into two parts, the downtown core and the suburbs.

Also, a brief comparison of the results with a production based and regionally defined analysis is made to demonstrate the importance of the approach presented here. Both provide eminent information, but, as is shown, comprehensive understanding of the carbon emission sources and mitigation possibilities requires both approaches.

The Finnish consumer survey 2006 [16] was utilized as the primary input data. The utilized samples of the data represent the consumption of average consumers of Helsinki downtown and the suburbs. The level of detail of the survey is very high including around 1.000 categories and sub-categories of goods and services.

The process data utilized include the emissions of heat and electricity production of Helsinki Energy [17], fuel combustion emissions of private driving and public transport [18]. 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) [19].

III. 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 process approach [14]. The three LCA approaches are shortly presented below.

Process-LCA is the most common way of conducting an LCA [11, 14, 15]. In process-LCA's, the emissions are assessed based on energy and mass flows in the main production supply chain processes. Even with the 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 [11]. In addition, a comprehensive process-LCA is often laborious and time consuming to conduct [11, 14].

The second approach, input-output-LCA, is a method where the 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 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 of the end of life stage that should be added to the calculations [11]. The input-output method is also quick and rather easy to use [14].

The inherent problems related to the input-output method include high level of aggregation of industry classifications, possible temporal (inflation and currency rate differences) and regional (industry structure differences) asymmetries of data and the model, and the assumption of domestic production of imports [11, 14, 16]. As can be seen, these problems differ from those related to the process approach thus creating space for hybrid-LCA models that combine the strengths of the two approaches and reduce the weaknesses related to them [11, 17].

Hybrid-LCA models have emerged 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 the input-output analysis, whereas direct emissions and the most important upstream phases are examined with the process analysis. Second, in the input-output-based hybrid analysis output sectors are disaggregated to include process data and avoid aggregation and truncation problems. The third category is integrated hybrid analysis model that 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 key emission sources assessed with process data and the higher order phases covered with IO matrices to maintain the full coverage.

The construction of the hybrid model advanced so that first a direct input-output assessment was conducted utilizing two different models, the Carnegie-Mellon EIO-LCA [18] and the respective Finnish model ENVIMAT [21]. As the results of the two assessments were very similar, the EIO-LCA was chosen as the basis of the hybrid model.

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

Concerning energy, the production phase emissions were replaced with local process data in the output matrices for electricity (284 g/kWh), district heat (286 g/kWh) and oil (267 g/kWh). In addition, the communal building energy, paid within rent or housing management charges, was added to the energy consumption of a consumer according to a study including 18 apartment house companies in 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 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]. Finally, the emissions related to public transport were enhanced by replacing the EIO-LCA output matrix with the Finnish ENVIMAT [24] matrices for rail and coach and taxi transport.

To match the input data with the model, the data was aggregated down to 43 consumption categories. These were further aggregated down to 10 consumption areas, which indicate the urban structure 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, Heat and electricity contain all housing energy use including 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 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 consists mostly 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 the 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.

IV. RESULTS

The quite unconventional results of the study indicate that low density suburban living creates less carbon emissions compared to the metropolitan lifestyle in the dense downtown. The assessed annual per capita carbon consumptions in the two types of metropolitan living are 14,9 ton CO2-ekv. in downtown Helsinki and 12,1 in the suburbs. The Finnish average, assessed in Heinonen&Junnila (2010), is 10,2 ton CO2-ekv. [10]. The standard of living is higher among the inhabitants of the downtown areas, where the average annual net earnings are 26.300 € per capita according to the input data [16]. In the suburbs the respective figure is 19.800 €, the Finnish average being 14.300 €. While this partly explains the differences, it would seem that whereas consumption volume correlates with the earnings, only a diminishing share of the growth in income is used. This diminishes the differences in carbon consumption. Figure 1 shows the per capita carbon consumption, net earnings and the volume of consumption in Helsinki and in Finland on the average.

Figure 1

What can be seen from the figure is that the structure of the carbon consumption is similar in general, but the volume grows following the consumption volume. The urban structure related sectors identified in the direct IO assessment for process data enhancement, Heat and electricity, Building and property, Maintenance and operation and transportation (Private driving and Public transportation), dominate the total carbon consumption with a share of 60-75 % in all the areas. Also, it seems that the share of these diminishes as earnings and the consumption volume grow, indicating the necessary goods character of these.

Some patterns related to the relation between carbon consumption and the urban structure can be identified from the results. First, it would seem that density has only minor effect on the overall carbon consumption. Concerning emissions from housing energy use, the emissions grow as the density grows. In the downtown Helsinki energy use related carbon consumption is 4,6 ton CO2-ekv., whereas in the suburbs it is 4,1 ton and the Finnish average is 3,1 ton.

In addition, when all housing related carbon consumption is examined, the same pattern is found in all of the categories. The carbon consumption from Maintenance and operation is 2,0 ton CO2-ekv. in the downtown area and 1,5 ton in the suburbs, the Finnish average being 1,1 ton. In Building and property category the differences are smaller, but still the carbon consumption is 1,4 ton CO2-ekv. in the downtown area, 1,3 ton in the suburbs and 1,2 ton in Finland on the average.

Where the density seems to have a positive effect on the carbon consumption is the transport sector. As Figure 1 shows, private driving related carbon emissions diminish from the Finnish average of 1,8 ton CO2-ekv. to 1,3 ton in the suburbs of Helsinki and 1,1 in the downtown following the growth in the areal density. The opposite of these, the use of public transport, as a low-carbon option for private driving, is in a minor role in Finland on the average, the emissions being 0,1 ton CO2-ekv., whereas in Helsinki they are 0,3 ton both in the suburbs and the downtown area.

The rest of the categories, consumption on goods and services, clearly reflect the relation between income and carbon consumption. However, this part of the carbon consumption was not the focus of this study, and also cannot be analyzed in depth with the presented hybrid model. The model shows that travelling abroad and use of services grow as the earnings grow, as Figure 1 shows, but on the part of daily consumption, it is not possible to differentiate amount and quality. Amount has direct effect on emissions, but if only quality of the consumed goods grow, the effect on the emissions is unclear.

V. DISCUSSION

The purpose of this study was to present a consumption based life cycle assessment model of green house gas emissions, carbon consumption, for the use of strategic urban planning. The model presented is an application of tiered hybrid-LCA. In the study, the applicability of the model was demonstrated with an analysis of the largest metropolis in Finland, Helsinki. Further, Helsinki was divided into downtown areas and suburbs to analyze the urban structure related differences in carbon consumption, and to test the applicability of the method on a sub-city scale.

We argue that this type of consumption based modeling of emissions is of high importance and adds essential information to more common regional production based assessments. Especially, when solutions for effective city level carbon management are searched, consumption based tools are essential.

The hybrid-LCA model was created in two phases. In the first phase we assessed the annual carbon consumption using two different input-output models, the Carnegie Mellon EIO-

LCA [20] 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 the four closely urban structure related categories of energy related to housing, building and property, maintenance and operation of the building, private driving and public transportation. In the second phase we assessed the carbon consumption in the downtown Helsinki and in the suburbs with the hybrid model. In addition, the Finnish average was used for comparisons from Heinonen&Junnila (2010) [10].

The assessment followed the pattern identified in Heinonen&Junnila (2010) [10], showing significant growth in the carbon consumption as the areal density grows. According to the hybrid-LCA model, the annual per capita carbon consumption in Helsinki downtown is 14,9 ton CO2-ekv., but only 12,6 ton in the suburbs and 10,2 ton in Finland on the average. It seems that this is mainly due to high correlation with the volume of private consumption, 21.200 €/a in the downtown area, 16.300 €/a in the suburbs and 14.300 €/a in Finland, which dominates other effects. However, the data revealed interestingly that only a diminishing share of annual net earnings is consumed as the standard of living grows. This has an equalling effect on the carbon consumption between higher and lower income areas.

The second structural pattern identified is the correlation between density and private driving. When all emissions related to private driving are calculated, including car manufacturing, deliveries and maintenance of vehicles, the carbon emissions are 1,1 ton CO2-ekv. in the downtown area, 1,3 ton and in Finland on average 1,8 ton. This result, while in accordance with several earlier studies [in Finland f. e. 9, 26], is too weak to cancel the wealth effect on overall carbon consumption. Thus, growth in trip generation due to decline in the density of the city structure has only relatively minor effect on overall carbon consumption.

Third pattern was that the 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 density and population grow.

In overall, according to this study, it would seem that the density of the urban structure should not be the primary target in strategic urban planning. The connection between carbon consumption and density is mostly related to private driving and too weak to bring off a significant change. The true potential of carbon management lies in energy production and consumption.

The reliability of the study was assessed from different perspectives. First, the hybrid-LCA approach and here also the IO-LCA model selection bring up possible sources of bias. We chose the Carnegie Mellon EIO-LCA as the basis of our hybrid model. The model is the most disaggregated model available reducing the aggregation error inherent in all input-output approaches, which was considered critical as the input data utilized in the study is highly complex. Also, Finnish economy is an open economy with more than 50 % of the value of total consumption oriented to import goods [25]. In addition, the potential industry structure asymmetry error due to the model selection was assessed not significant according to the comparative assessment with the ENVIMAT model.

Next, to decrease the temporal asymmetry problem arising from inflation and currency rate differences between the US and 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 American household carbon footprint [16].

Further, 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 include 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 industry averages in the output matrices. However, in this study the use of hybrid assessment model significantly reduces this problem.

Second, the reliability of the input data was assessed. In this study, the Finnish consumer survey [16] provided the primary input data. The level of detail of the data is very high with more than 1.000 categories of goods and services. Also, the sample size is representative including roughly 10.000 subjects (0,2% of the Finnish population).

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 concerns predominantly our comprised consumption class "health, nursing and training services" which had minor significance in this study.

Third, a positioning of the results among earlier applicable studies was made. Of these, the 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 is 10,2 tons. Regarding the chosen method in a carbon consumption study, 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 American household carbon consumption [16].

REFERENCES

[1] The Sixth Environment Action Programme of the European Community 2002-2012, http://ec.europa.eu/ environment/climat/home_en.htm (30.9.2009).

[2] Mayor of London, http://www.london.gov.uk/ mayor/priorities/environment.jsp (15.1.2010).

[3] European Union, Committee of the Regions, The EU's Assembly of Regional and Local Representatives, Press Release, COR/09/92, Brussels, 7 October 2009: Green partnership: EU and US mayors pledge to work together on climate change,

http://europa.eu/rapid/pressReleasesAction.do?reference=COR/09/92&format=HTML&aged=0&language=EN&guiLanguage=en (19.2.2010).

[4] Association of Finnish Local and Regional Authorities, Anu Kerkkänen (2009): Climate Change Control in Municipal Decision Making (Kuntaliiton esiselvitys: Kokonaisuuden hallinta ja ilmastonmuutos kunnan päätöksenteossa).

[5] Mayor of the City of Helsinki Jussi Pajunen's speach commenting the report on energy policy 23.1.2008, (Jussi Pajusen puhe energiapoliittisen selonteon yhteydessä), http://www.hel.fi/wps/portal/Helsinki/Artikkeli?WCM_GLOBAL_CONTEXT=/Helsinki/fi/P__t_ksenteko+ja+hallinto/Kaupunginjohtajat/Kaupunginjohtaja+Jussi+Pajunen/Puheet/energiapolitiikka (19.2.2010).

[6] Tampere Central Region, Climate Strategy 2030 (Tampereen kaupunkiseudun kuntayhtymä, Ilmastostrategia 2030), http://www.tampereenseutu.fi/seutuhankkeet/yhdyskunta-suunnittelun_ohjelma/ilmastostrategia_2030/ (30.7.2010).

[7] Dodman, D. (2009): Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories, Environment and Urbanization, 21 (1), 185-201.

[8] Norman, J., MacLean, H., L., Kennedy, C., A. (2006), Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions, Journal of Urban Planning and Development 132 (1), 10-21.

[9] Heinonen, J., Junnila, S. (2010): A life cycle assessment of carbon mitigation possibilities in metropolitan areas , Sustainable Building 2010 conference proceedings.

[10] Heinonen, J., Junnila, S. (2010): Comparing climate change effects of rural and metropolitan lifestyles, a hybrid-LCA approach, Pacific Rim Real Estate Society (PRRES) Conference 2011 proceedings.

[11] Suh, S., Lenzen, M., Treloar, G., J., Hondo, H., Horwath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., Norris, G. (2004): System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches, Environmental Science & Technology 38 (3), 657-664.

[12] Carney, S., Green, N., Wood, R., Read, R. (2009): Greenhouse gas emission inventories for 18 European regions, The Greenhouse Gas Regional Inventory Project.

[13] Rauhala, K., Mäkelä, K., Estlander, K., Tolsa, H., Martamo, R., Lahti, P., Perälä, M. (1997): Environmentally favorable urban form and transport system, Technical Research Centre of Finland, VTT Research Notes 1839.

[14] Junnila, S. (2006): Empirical Comparison of Process and Economic Input-Output Life Cycle Assessment in Service Industries. Environmental Science and Technology, 40 (22), 7070-7076.

[15] Joshi, S. (1999): Product Environmental Life-Cycle Assessment Using Input-Output-Techniques, journal of Industrial Ecology, 3 (2-3), 95-120.

[16] Statistics Finland 2006, the data only partly publicly available at http://www.stat.fi (1.10.2009).

[17] Energiateollisuus ry, Energiatilasto 2008, http://www.energia.fi/FI (20.1.2010).

[18] LIPASTO traffic emissions, VTT Technical Research Centre of Finland, http://lipasto.vtt.fi/yksikkopaastot/henkiloliikennee/tieliikennee/henkilo_tiee.htm (1.3.2010).

[19] The Housing Finance and Development Centre of Finland (ARA), Reports A 12/2006, http://www.ara.fi/download.asp?contentid=21121&lan=FI (23.12.2009).

[20] Carnegie Mellon University Green Design Institute (2008): Economic Input-Output Life Cycle Assessment (EIOLCA), US 2002 Industry Benchmark model (Internet), Available at http://www.eiolca.net (1.2.2010).

[21] Seppälä, J., Mäenpää, I., Koskela, S., Mattila, T., Nissinen, A., Katajajuuri, J-M., Härmä, T., Korhonen, M-R., Saarinen, M., Virtanen, Y. (2009): Assessment of the environmental impacts of material flows caused by the Finnish economy with the ENVIMAT model (Suomen kansantalouden materiaalivirtojen ympäristövaikutusten arviointi ENVIMAT-mallilla), The Finnish Environment 20/2009.

[22] Statistics Finland, the division of aggregate consumption in Finland, www.stat.fi (15.12.2009).

[23] ICP Global Results: Global Purchasing Power Parities and Real Expenditures, http://siteresources.worldbank.org/ICPINT/Resources/icp-final-tables.pdf (20.12.2009).

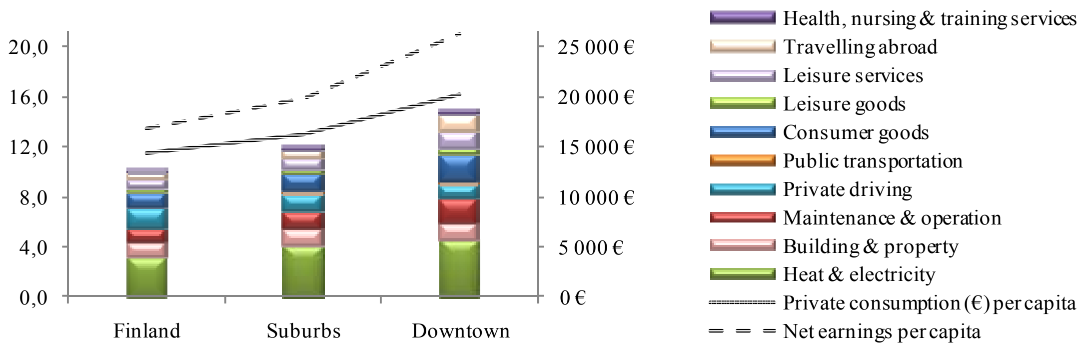

Figure 1. Annual per capita carbon consumption (ton CO_2-ekv.), earnings (€) amd consumption (€) in Helsinki downtown, the suburbs and in Finland.