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Modeling and visualization of residential sector energy consumption and greenhouse gas emissions

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ABSTRACT

The paper presents a calculation and visualization approach for energy use and greenhouse gas emissions from residential stock. The used calculation method is based on a bottom-up approach and is implemented in a case district. The visualization of the energy and emission results employs geographical information system (GIS) techniques. We show two examples of how impacts of behavioral and technical changes in the building stock can be assessed and visualized by using the approach. The results obtained provide meaningful and detailed information about the energy performance and greenhouse gas emissions of the residential stock. The information can be, for instance, used in various hot spot analyses. Additionally, the impacts of energy efficiency measures and behavioral changes can be assessed. These types of analysis can be useful for policy makers in order to prioritize actions cost efficiently, such as carrying out renovations in the residential sector.

1. Introduction

Housing uses a great amount of energy worldwide. The residential sector can account for 16–50% of total national energy consumption (Saidur et al., 2007). In the EU-27 countries, households are responsible for about one-fourth of the total final energy consumption (EEA, 2013). In general, as fossil fuels are widely used in energy production, housing sector-related greenhouse gas (GHG) emissions are also usually high (Huppes et al., 2006; Nissinen et al., 2007; Seppälä et al., 2011; Tukker and Jansen, 2006). The increasing pressure of meeting global and EU emission reduction targets drives the research and modeling needs in the building sector. Finland should diminish GHG emissions outside the emission-trading sector to at least 16% below 2005 levels by 2020, according to the Decision (406/2009/EC) of the European Parliament and of the Council of 23 April 2009. Recently, smaller communities, such as municipalities, have also taken the initiative in order to mitigate climate change (see, e.g. HINKU Forum, 2013; Brøset, 2010). Structured information about energy consumption and GHG emissions is needed, so that decision-makers, real-estate managers, and residents can manage the existing building stock sustainably.

In the Nordic countries, the cold climate explains the high energy demand for space heating during the relatively long winter period. In Finland, about one fourth of the final energy consumption is used for space heating (Statistics Finland, 2013a). In terms of GHG emissions, the energy use of residential buildings caused about 11 million metric tons (Mt) (about 15%) of Finland's total emissions in 2009.

Emissions of the building stock have been modeled at national levels (see e.g. Kesicki, 2012; Sartori et al., 2009). End-use energy consumption models for residential buildings can be divided into two groups: top-down and bottom-up. Typically, bottom-up approaches use statistical or engineering methodologies, whereas top-down modeling handles housing stock as an energy sink, and thus no detailed analysis on end-use can be done. For a detailed description and applications of both approaches we recommend the review by Swan and Ugursal (2009) and the references therein. The importance of geographical location for the implementation of a GHG reduction policy is emphasized by Kavgic et al. (2010) in a more recent review. The geographical location is indeed crucial when it comes to promoting the use of renewable energy, such as forest biomass for oven-based house-specific heating, pellet or wood-chip fired boilers, or a small-scale combined heat and power

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plant (CHP) for 10–20 houses, for example. In order to find the best solution for a region in both the economic and the environmental sense, one must consider the availability of the resources needed, e.g., forest biomass. For instance, before extending a district heating network, the pipe network needed for the system has to be assessed. Nowadays there is a growing need for such sub-national assessments.

Regional energy consumption and emission analyses have been conducted (see e.g. Blum et al., 2010; Brecha et al., 2011; Cheng and Steemers, 2011), and the models can be a useful tool to help policy formation at both national and sub-national level (Cheng and Steemers, 2011). In Finland an engineering model for heating energy and emission assessment was also developed and used for analyzing municipalities in North Karelia (Snäkin, 2000). However, the model does not account for the heat gains from solar energy and occupancy.

In order to transfer global emission reduction goals into local mitigation actions, new ways of presenting data can be beneficial. In the case of buildings, a geographical information system (GIS) is one option for data visualization. Tornberg and Thuvander (2005) contributed to the development of visualization strategies for building-related environmental data by linking GIS and building stock modeling. With their spatial model, energy consumption can be linked to groups of buildings and may be used for identification of hot spots signifying high energy use. Jones et al. (2001) use GIS techniques to illustrate the high energy consumption areas and consumption of those properties. Maps can be used to provide structured information about the distribution of energy use and GHG emissions to local governments and other target groups such as residents' associations. This type of information has already been visualized at a building/street scale in the US (Gurney et al., 2012). Additionally, GIS methods can be useful in analyzing the future potential of heating systems (see e.g. Nielsen and Möller, 2013).

This study focuses on determining and visualizing the energy usage and GHG emissions from the residential stock using a bottom-up approach. The calculation is based on detailed register data about existing building stock. Our aim is to quantify and show energy and GHG emission results based on the location and characteristics of each property. This way, detailed regional spatial analyses, such as energy or emission hot spot analyses, are possible. The analysis could in principle be done for the whole of Finland. However, in order to make a detailed analysis of buildings, and to control input data validity, we chose to start with a small district. A district in Tampere, Kaukajärvi, was selected for the case area. This paper presents the results of the GHG emission evaluation for the Kaukajärvi district. GIS have been employed to visualize the results. We also discuss and draw conclusions about the potential applications of such method and results obtained.

2. Methodology

2.1. Case area

Kaukajärvi district is located within the city of Tampere, some 170 km north-west of Helsinki. Kaukajärvi has about 11 000 habitants. The main climatic parameters in the Tampere region are the following: the annual mean temperature, mean precipitation and mean wind speed are 4.4 °C, 598 mm, and 3.2 m/s, respectively (Pirinen et al., 2012). The residential stock in Kaukajärvi includes about 700 buildings. Relevant data on the stock are given in Table 1. The total volume of the residential stock is about 1.7 million cubic meters (10^6 m^3). Over 50% of the residential stock volume in Kaukajärvi consists of apartment buildings. The distribution of building stock volume by primary heating fuel, as well as emission factors applied (the unit being grams of carbon dioxide equivalent, g CO_2eq) are given in Table 2. The dominant heating source is district heating, which is common in Finland in areas with a high proportion of apartment buildings. On the other hand, most of the row and single family houses in Kaukajärvi use direct electricity and light fuel oil as the primary heating sources. In this region, wood or pellet heating systems were not installed originally as primary heating systems. Based on the construction year, residential buildings vary in construction materials used and in technical solutions for heating, among other things. For instance, after the Second World War there was a lack of good construction materials in Finland. In addition, the popularity of prefabricated houses had an impact on the technical properties of the residential stock. However, the first energy efficiency measures for buildings were implemented in 1976, after the energy crisis of 1973 in Finland.

Table 1
Kaukajärvi statistics based on building and real-estate register (Population Register Centre). Data from 2010.

Building type	Population		Volume		Floor area	
	Number [−]	%	m^3	%	m^2	%
Single family house	1605	15.0	241 609	14.7	72 308	15.0
Row houses	2177	20.3	285 064	17.3	88 542	18.4
Apartment buildings	6944	64.7	1 120 128	68.0	321 212	66.6
Kaukajärvi, (total)	10 726	100	1 646 801	100	482 062	100

2.2. Modeling approach

The modeling approach to building energy consumption is based on the international standard ISO-13790 related to the energy performance of buildings. In addition, two national sources for calculating the power and energy requirements for the heating of buildings were followed: the Building Code (Ministry of Environment, 2007) and the EKOREM model (Heljo et al., 2005). The modeling follows the energy balance method, i.e. the amount of energy coming into the building equals the outgoing energy. The approach is based on quasi-steady state methods explained in the international standard (EN ISO 13790). In this method, energy consumption of the stock is calculated over a whole season and the dynamic effects are taken into account by using empirically

Table 2
The distribution of building stock volume by primary heating fuel and the used emission factors.

Heating type	Share of usage in Kaukajärvi [%]	Emission factor [g CO_2eq/kWh][a]	Source for emission factor
Wood, pellets	0.0	–	–
Heavy fuel oil	0.3	267	Statistics Finland (2013b)
Light fuel oil	2.1	279	Statistics Finland (2013b)
Gas	0.0	–	–
Coal	≪1	370	Statistics Finland (2013b)
Electricity	9.9	400	Heljo and Laine (2005)
District heating	87.0	226	Heljo et al. (2005)
Geothermal (ground-source heat pumps)	1.0	400/COP[b]	Heljo et al. (2005)
Other	≪1	300	Heljo et al. (2005)

[a] g CO_2eq/kWh = grams carbon dioxide equivalent per kilowatt-hour.
[b] Value 2.4 was used as the coefficient of performance (COP) for ground-source heat pumps.

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