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Heat loss rate of the Finnish building stock

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Abstract

This paper presents a bottom-up model for studying the heat loss rate of the building stock. The model is a step towards more complex building-stock power modeling, whose goal is to predict the sources and the amount of demand response potential under different conditions. The heat loss rate is the fraction of thermal power needed to compensate for the heat loss via exterior walls, windows, roofs, floors and ventilation in the buildings. The heat loss rate depends on the physical characteristics of the building envelope and ventilation and on weather conditions.
We first examine the current state of power and energy modeling. We then describe the research object of this study and the calculation method. The calculation results presented in the third section are illustrated at the hourly level, sorted by the main source of the heating energy of the building. In addition to the analysis of the building stock level, the heat loss rate was calculated on a building level using some typical building information models for validation purposes. The validation indicated that the results obtained with the two methods were consistent and that the order of magnitude was reasonable. The Finnish building stock was used as a research object in the demonstration of the model. Finally, some further needs for research are discussed.

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*Keywords:*buildings stock; energy systems; heat loss rate; power modeling

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1. Introduction

Energy efficiency is a central issue in the fields of both politics and academic studies. The European Union has set targets to significantly reduce the annual consumption of primary energy and greenhouse gas emissions by 2020 (Directive 2009/28/EC). Legislation supporting this development has been widely enacted on national levels. Furthermore, the amount of regulation related to energy efficiency is continuously growing. A number of studies have been carried out regarding the energy consumption of building stock (Balaras et al. 2005; Balaras et al. 2007; Dascalaki et al. 2011; Howard et al. 2007; Magalhães and Leal 2014; Mata et al. 2013; Tommerup and Svendsen 2006).

In the Nordic climate, such as in Finland, the peak power consumption maxima occur in winter when the use of heating energy is at its highest. Although the highest power peaks appear during winter, the peaks are not only a phenomenon of the coldest season. Power use varies as a function of time every day throughout the year. The power and energy use of buildings is influenced by different factors, such as the weather, the physical characteristics of the building, HVAC systems and their settings, building automation and the behavior of users (Zhao and Magoulès 2012).

The capacities of both the power distribution network and the power production infrastructure are sized based on the estimated maxima of power usage. Thus, the investment costs of the energy distribution and production systems depend on the expected future peaks. For example, in Finland there are reserve electric power plants on standby for exceptional power demand situations. These power plants have a low annual utilization rate. The additional fuels used during the power demand peaks consist mainly of fossil sources. Thus, if the power demands of the buildings could be managed more successfully, the need for additional reserve power plants would be lower, possibly leading to both economic and environmental benefits.

To better manage the power use, there have been theoretical discussions - and currently even practical applications - on so-called demand response, in which the timing of energy consumption is managed. Energy consumption is managed with the help of signals based on prevailing conditions outside of the place of energy consumption (Jota et al. 2011). In demand response, at least part of the energy consumption is timed based on an indicator of the demand situation, such as using the hourly energy price in the energy markets or the current electric power frequency as an input signal. The demand response can be an automatic or manual process. It can also be used to even out the differences in power demand in both peaks and gaps and to help adjust the energy systems. Energy users can participate in reducing the peaks of energy systems by cutting their consumption. This can be done, for example, by changing the timing of the energy use or by changing the energy source (Albadi and El-Saadany 2008).

When energy efficiency is examined, the focus in the building sector has often been on the total energy consumption during the investigated period of time, such as one year. Current construction regulations guide the evaluation of energy consumption in buildings at the annual level. For example, in the calculation of the E-value, the target of the inspection in energy calculations for construction permits or energy certificates is currently stated as the annual energy consumption. However, from the perspective of the entire energy system, not only the total annual energy consumption but also each instance of consumption is important. The situation may be changing. In the Energy Performance of Buildings Directive (2012/27/EU), power management and its demand response were seen as a part of energy efficiency. This mode of thinking is progressing toward national legislation of the EU's member states.

We have developed a model for estimating the heat loss rate in building stock with the goal to predict the amount and the sources of demand response potential in different situations. By the heat loss rate we mean the thermal power needed to compensate for heat loss via the walls, roof, floor and ventilation in the buildings (fig. 1). This method is introduced and demonstrated in this paper.

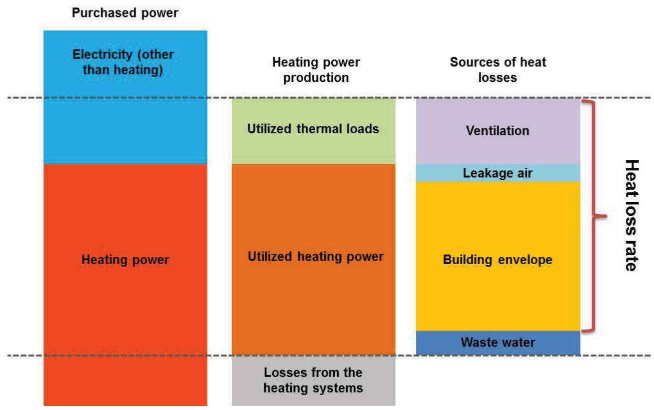

Figure 1. Terminology: concept of heat loss rate and different levels of power in the buildings.

Building-related power studies can be executed at different levels. For a better understanding of the concept of "heat loss rate", three of these levels are described in the very simplified figure 1. The major scale in the building level can be considered to be purchased power, the amount of power that the building owner buys from a utility company. Purchased power includes the power required for heating and electricity used in other operations. The next level of power studies is of heating power production. These can be considered system-level studies. Heating power demand is covered by utilizing thermal loads in the buildings as well as the heating power from the heating systems. However, there are always losses due to inefficiencies in the heating and heat distribution systems. The heating power consumed is used to replace the heat losses caused by differences between the outside and indoor temperature as well as needs for warm water.

2. Methodology

As outlined in a review by Zhaos & Magoulès, methods for predicting building energy consumption include engineering methods, statistical methods, neural networks, support vector machines and grey models (Zhaos & Magoulès 2012). The approach of this study is a bottom-up engineering modeling method similar to that of Mattinen et al. (2014), where building characteristics and weather data have been utilized as input data, but user behavior is not taken into account. The reason for this is that the heat loss rate is dependent only on physical characteristics of the building envelope and ventilation. It well known that weather parameters used in these types of models are some of the most important factors when analyzing the power and energy demands of buildings (Bhandari et al. 2012; Fumo 2014). In our developed model the weather data used can be chosen freely.

For the analysis, the building stock was divided into different building-type categories similar to those used by Statistics Finland (see Figure 2). Within the building types, the data are further divided into different cross-section years (in 5-year age groups) to describe the physical attributes of buildings from different eras. This provides an opportunity to exploit official building stock data. It should be noted that the statistics do not include free-time residences, separate sauna buildings belonging to residential buildings or buildings of the Armed Forces.

In the model, the heat loss rate is calculated by taking account of thermal conductivities of different building types and cross-section years, the difference between outside and inside temperatures and the volume of the stock. Thermal conductivity is calculated by utilizing the thermal transmittance factors (U-values), specific areas of different structural elements (A) as well as the technical specifications of the ventilation. As an example, the calculation method for computing the thermal conductivity for windows is presented below (equation 1).

$$C_{windows}\left[\frac{W}{K \times m^3}\right] = U \times A \left[\frac{Window, m^2}{Building, m^3}\right] \tag{1}$$

where: U = Typical thermal transmittance of windows for the specific building type and era
A = Typical area of windows for the specific building type and era

After implementing the formula above for each part of the building envelope (except the base floor), the results are summed to find the total thermal conductivity (C_{all}) of the building envelope and ventilation (equation 2).

$$C_{all} = C_{windows} + C_{ext.walls} + C_{roof} + C_{ext.doors} + C_{ventilation} \tag{2}$$

These calculation steps are implemented for all building types and different cross-section years. The heat loss rate can be calculated at any time (t) by utilizing the thermal conductivity (C_{all}), the volume of the stock (V_{stock}) and the difference between outside and inside temperature (ΔT) (equation 3).

$$P(t)_{heat\ losses} = C_{all} \times \Delta T(t) \times V_{stock} + P(t)_{heat\ losses,floor} \tag{3}$$

The heat loss rate through the base floor ($P_{heat\ losses,\ floor}$) must be calculated separately because the temperature difference between the ground under the building and indoors is not equal to that of the other parts of the building envelope. The temperature is much more stable under the building. This discrepancy was taken into account by calculating the heat transfer through the base floor following the method described in the standard SFS-EN ISO 13370 "Thermal performance of the buildings. Heat transfer via the ground. Calculation methods" (2008).

2.1. Finnish residential and service building stock

The research object of this study is the Finnish residential and service building stock (figure 1). The Finnish residential and service building stock is one of the youngest in Europe. Approximately 70 % of the stock was built between 1970 and 2010. The average location of buildings in Finland is the northernmost of European Union countries. 63 % of the stock (m^3) consists of residential buildings of which single family houses form the largest component with a share of 34 %.

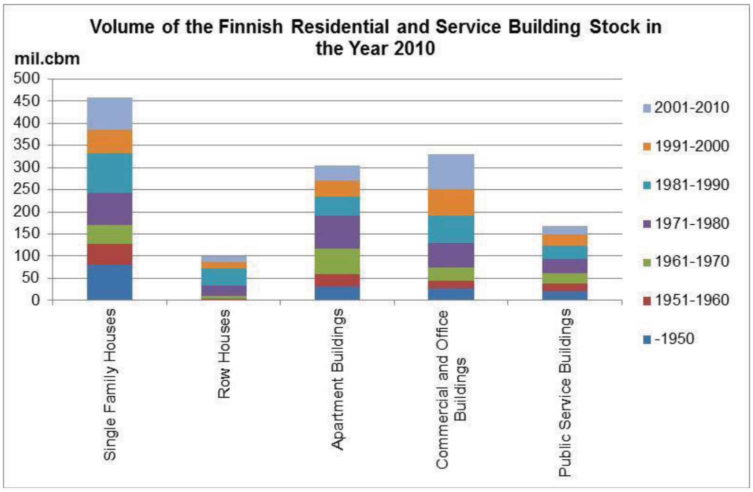

Figure 2. Building type and age distribution of the 2010 Finnish residential and service building stock.

In the Finnish building stock, the types of heating systems are diverse. This is especially the case for single family houses, for which most of the heating energy demand is met by electricity, wood/pellets or oil. The remainder of the residential and service-building stock is mainly connected to district heating. There is variation between cities and rural areas, where district heating service is usually not available.

2.2. Weather data

To demonstrate the model, we have utilized the official weather data of test reference year 2012. These weather data were created specifically to be used in building-related energy modeling. The weather data were gathered based on hourly observations at three different geographical locations in Finland during 1980-2010, one in northern Finland, one in the middle of the country and one in southern Finland. Based on the data, Finland can be divided into four different climate zones (Jylhä et al. 2011). To demonstrate the power model, the data related to the zone covering the middle of Finland were used. The hourly temperatures of the test reference year in the chosen climate zone are presented in figure 3.

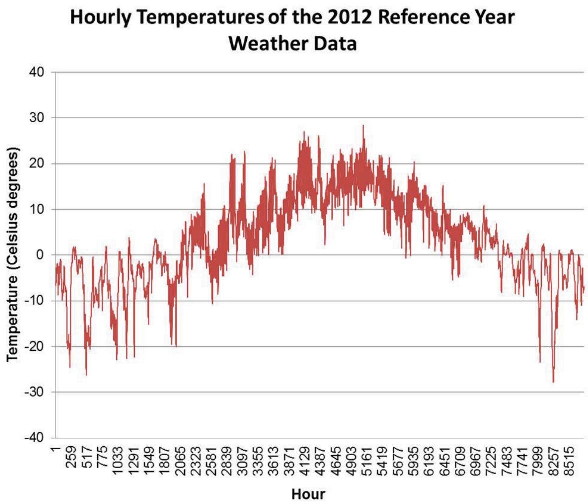

Figure 3. Hourly temperatures of the 2012 reference year in climate zone 3 (Jylhä et al. 2011).

3. Results

For this paper, we calculated the heat loss rate of the 2010 Finnish residential and service-buildings stock for every hour of the test reference year 2012 (Fig. 5). To validate the developed model, we tested our results by comparing them to those obtained by modeling single reference buildings with the IDA Indoor Climate and Energy simulation tool. For the comparison we modeled a single family house from the 1980's and an apartment building from the 1970's; these buildings were chosen because inside their respective building groups they are each one of the largest age groups (m^3). A ten-day period from the reference year weather data (15^{th}-25^{th} of February) was chosen for the comparison. This time span includes some low temperatures as well as temperature fluctuations.

Some key input variables for both modeling tools are presented in table 1. We had access to the building models for the IDA-simulations from previous projects and decided to utilize those by applying some changes. First, the thermal transmittance factors (U-values) of the structures were set to correspond to those of the developed power model. The same procedure was carried out regarding the ventilation and inside temperature.

One may notice differences between the thermal transmittances of the windows in 1970's apartment building and 1971-75 building stock. The correction was made because the area of windows (m^2) in the building model used in the IDA-simulation was on average substantially smaller than in the corresponding part of the building stock.

Instead of modifying the building model, the process was made smoother by increasing the thermal transmittance factor of the windows in the building model.

Table 1. Input variables used in IDA-simulations and in the developed power model.

	Input variables used in the IDA ICE simulation		Input variables used in the power model	
	1970's apartment building	1980's single family house	1971-75 apartment building stock	1981-85 single family house stock
Volume (m^3)	9017	352	47,2 million	44,0 million
Floor area (m^2)	2521	136	13,7 million	14,2 million
Indoor temperature (Celcisus degrees)	22,5	21,0	22,5	21,00
Thermal transmittance of the roof (W/m^2K)	0,34	0,21	0,34	0,21
Thermal transmittance of the external walls (W/m^2K)	0,42	0,28	0,42	0,28
Thermal transmittance of the windows (W/m^2K)	3,50	1,70	2,20	1,70
Thermal transmittance of the floor (W/m^2K)	0,40	0,30	0,40	0,30
Thermal transmittance of the external doors (W/m^2K)	1,40	1,00	1,40	1,00
Rate of ventilation through the heat recovery unit (1/h)	0,50	0,30	0,50	0,30
Rate of ventilation bypassing the heat recovery unit (1/h)	0,00	0,05	0,00	0,05
Rate of leakage air (1/h)	0,15	0,15	0,15	0,15
Share of the stock with heat recovery unit installed	-	-	1 %	20 %
Annual efficiency of the heat recovery unit	0,45 %	9,0 %	45 %	45 %

To compare the results fairly, the annual efficiency of heat recovery units for single building IDA-simulations needs to be considered. This was resolved by multiplying the annual efficiency of the single heat recovery unit with the share of the stock with heat recovery units installed. The results of the calculations can be seen in table 1. Note that actions of inhabitants affecting the power demand of a building were not modeled in either case.

The results of the comparison of the two modeling tools are presented in figure 4. The modeling results are consistent with each other. However, regarding apartment buildings, the losses from the developed power model are slightly higher than those from the IDA-simulations. This may be mainly because the developed model does not take the effect of thermal mass into consideration. Concrete structures are able to store heat effectively, which reduces the power demand required from the heating system. In the building-level IDA-simulations, thermal mass is taken into account.

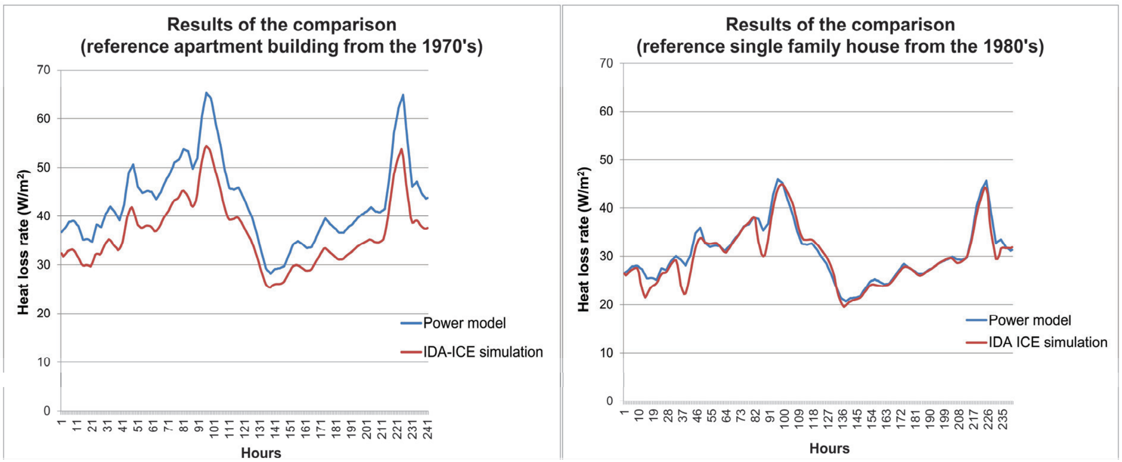

Figure 4. The modeling results of an apartment building from the 1970's (on the left) and a single family house from the 1980's (on the right) obtained from the IDA-ICE and the developed power model.

After the comparison, the developed model was used to calculate the heat loss rate in the 2010 Finnish residential and service-building stock (Figure 5). The model includes the distribution of heating systems for different building types and age categories; thus the results are presented following that categorization.

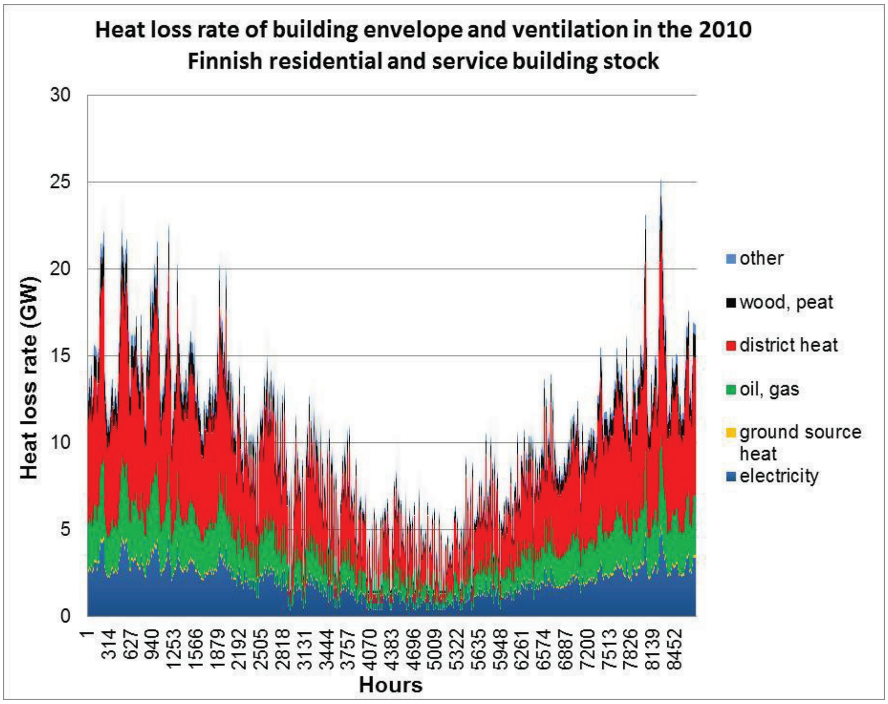

Figure 5. The heat loss rate in the Finnish residential and service-building stock throughout the year when implementing 2012 test reference year weather data in the model.

The results show that the peak heat loss rate in the modeled building stock, when applying the 2012 reference year weather data, is approximately 25 GW. Power demand consists mainly of buildings utilizing electricity, oil or district heating to cover their heating energy demand. Other heating systems/fuels can be considered marginal. Modeling results of this sort can be used, for example, to study the impacts of different demand responses and building-stock renovation measures on greenhouse gas emissions or power demand. It should be noted that the heat loss rate is not equivalent to the actual power needed from the heating systems because the thermal loads from inhabitants, electric devices, heat distribution, sun and wind or specifics of the heating systems are not taken into consideration.

4. Discussion and conclusion

There may be a need for a paradigm change to emphasize the power perspective instead of focusing merely on annual energy consumption when considering energy efficiency issues of building environments. The new paradigm could enable a more systematic approach to decision-making regarding the energy system as a whole.

The model presented in this paper is a step towards more complex analysis of power for building stock. Finnish building stock was used as an example to demonstrate the model, but this type of modeling could be performed also in other buildings stocks.

One reason to model the building stock's power use is that data about buildings' power use and its distribution are difficult to obtain. Electricity meters measure the total energy consumption continuously in buildings, but do not usually report the sources of consumption separately. In the future, this model could be utilized, for example, for studying various dimensions of demand responses or the effects of renovation measures in the building stock.

There are also several limitations of this study. The model is based on theoretical calculation methods. There are numerous assumptions that affect the results. The model has been simplified and does not take into account all of the factors that can affect the heat loss rate. The model has been tested doing building-level simulations with another modeling tool and their results compared for separate buildings because the other model was not designed for building-stock-level inspections. The results were similar; however, the model has not been validated with real-life data.

Further research is needed for additional model development. New features could be integrated into the model and the results compared to real power consumption data, at least in some special cases. The model could also be tested by utilizing building stock and weather data from other countries.

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