Different User Behavior's Impact on Simulated Heating Demand in Energy Efficient Buildings

Hans Bagge
Lund University
Building Physics
Lund, Sweden
hans.bagge@byggtek.lth.se

Dennis Johansson
Lund University
Building Services
Lund, Sweden
dennis.johansson@hvac.lth.se

***Abstract*—To design a building that fulfills requirements regarding low energy use, it is crucial to perform energy simulations of the building in question during the design process and the simulations must be representative of the building during operation. All countries within the European Union will require new buildings to be nearly zero energy buildings beginning in 2019. In nearly zero energy buildings and passive houses, the user related energy uses, household electricity and domestic hot water heating, make up about 80 % of the total energy use since the use of space heating is low. The building's heating demand is affected by the occupants' use of domestic hot water and household electricity. Increased use of domestic hot water increases the heating demand, while a high use of household electricity can reduce the heating demand. Different user characteristics will result in different heating demand in the same building, and in low energy buildings, different user characteristics will have a relatively higher impact compared to less energy efficient buildings. There is a lack of studies that analyze resulting energy use of dwellings based on distribution of measured user related input data. The aim of this paper was to annually measure household electricity and domestic hot water volume in 562 apartments, present the measured distributions and analyze the influence on the apartment heating demand of energy efficient buildings and typical buildings by use of simulations of the building physics and the building services. The results show that, in order to predict the energy use of energy efficient residential buildings, with a reasonable accuracy, the different users' characteristics regarding household electricity and domestic hot water must be taken into account. Furthermore, to determine the impact that different users will have on a building's heating demand, the analysis must be based on the actual building and the result should be given as a distribution rather than as a single figure.**

Keywords - space heating; household electricity; domestic hot water; user behavior.

I. INTRODUCTION

To design a building that fulfills requirements regarding low energy use, it is crucial to perform energy simulations of the building in question during the design process and the simulations must be representative of the building during operation [1]. Research on the agreement between predicted and actual use of space heating in residential buildings in Sweden shows that measured use of energy for space heating during operation exceeds the predicted energy use by between 50% and 100%, even in low energy buildings [1][2][3][4].

Karlsson et al. [5] stressed the importance of accurate input data for the energy simulations of buildings. The building users' behavior is very important in low energy buildings and is the hardest to model according to [5]. Low energy buildings have well insulated building enclosures and efficient ventilation heat recovery systems which lead to small transmission and ventilation heat losses. During a large part of the year, internal heat gains from people, household electricity and solar heat gains balance the heat losses with a zero heating need as a result.

The use of household electricity is influenced strongly by the building users' behavior and is a major internal heat gain. Household electricity is defined as all electricity, not used for heating and ventilation, used in an apartment or a house. Domestic hot water is the hot water from taps in an apartment or a house. A large variation has been measured in equal apartments by [6]. Example of reasons for this variation can be occupancy levels and shower habits.

All energy uses in a building are part of the buildings energy balance and, for example the heat gains from a higher use of household electricity should result in a lower use of heating given that the heating control systems work as intended. Different user characteristics will result in different heating demand in the same building, and in low energy buildings, different user characteristics will have a relatively higher impact compared to less energy efficient buildings.

The users' relatively larger impact on the building's performance in today's and tomorrow's buildings must be taken into account during design and management [7]. The users' impact on the building performance has usually been described by different categories of users, for example families with children or single elders. Bagge [8] proposed to describe the different users' lifestyle and impact by statistical distributions of user related parameters and combinations of parameters for the reason that it is unknown who will live in an apartment or a house over time. A vast majority of residential buildings are certainly not built for a specific category, but for a cross section of the population leading to an urgent need for a statistical approach on users' variation. Energy use in buildings is commonly regulated. For example in Sweden, there are requirements on the sum of heating and non household electricity [9]. Heating is the sum of space heating for keeping the interior at desired temperature and domestic hot water heating. Non household electricity is used for ventilation and purposes outside apartments. A building's heating demand is affected by the occupants' use of domestic hot water and household electricity. Increased use of domestic hot water increases the heating demand, while a high use of household electricity can reduce the heating demand.

Various combinations of high and low uses of household electricity and hot water may be more or less favorable for achieving a low heating demand depending on building characteristic such as insulation standard and efficiency of ventilation heat recovery.

All countries within the European Union will require new buildings to be nearly zero energy buildings beginning in 2019. In order to make accurate predictions and decisions regarding future buildings, it is important to have a good statistical description on energy related user characteristics and its impact on buildings energy use and not only use average values of guessed or measured user related parameters.

There is a lack of studies that analyze resulting energy use of dwellings based on distribution of measured user related input data. The aim of this paper was to annually measure household electricity and domestic hot water volume, which by definition are totally user influenced, in 562 apartments, present the measured distributions and analyze the influence on the apartment heating demand of energy efficient buildings and typical buildings by use of simulations of the building physics and the building services taking into account the user of the building.

The paper is organized as follows. Section II presents the methods used and has four subsections A. Measurements, B. Simulated buildings and apartments, C. Parametric study and D. Simulation tool. Section III presents the measurement and simulation results and discusses these. Section IV presents the conclusions.

II. METHOD

The measured use of household electricity and domestic hot water in 562 apartments were used as input data in simulations of total heating demand of apartments in order to study the effect of different users. Parametric studies were performed to study the effect of different window area, ventilation heat exchanger efficiency, the average heat transmittance of the building and the location of the apartment within the building on the total heating demand taking into account the 562 different users.

As defined in the introduction, heating refers to the sum of space heating and domestic hot water heating. Space heating is the heating supplied by the heating system to the interior and the ventilation supply air, that means excluding domestic hot water heating. Household electricity is in practice completely used within the apartments, and is the only electricity used within the apartments [10]. There are also other internal heat gains such as solar radiation or occupant heat gain that is handled by the simulation program.

A. Measurements

As a basis for individual billing, household electricity and domestic hot water was measured during 2012 in 562 one bedroom apartments in buildings located in Karlstad, Sweden at latitude 59.39°, and built between 1932 and 2007 with a large portion built in 1980 and in the period 1961-1965. To obtain the domestic hot water heating, the measured domestic hot water volume was multiplied by 55 kWh/m³ based on [11]. The distribution of the uses and their average values are presented as well as the actual relationship between the measured parameters in the studied apartments. Each measured apartment's use of household electricity and domestic hot water describes a user which means that in this study, 562 users are described.

B. Simulated buildings and apartments

The 562 combinations of use of household electricity and domestic hot water heating were used as input data in a simulation model of two different apartments in two different buildings. Building 1 had building technology representing a typical Swedish building designed during 2014 in accordance with the Swedish building code [9]. Building 2 had building technology representing a Swedish passive house [12].

In each building, the heating demands of one bedroom apartments, at two different locations in the building, were simulated. In both buildings, one of the apartments, Apartment 1, was located in the center of the building with adjacent apartments on two sides, above the ceiling and below the floor. That means that the apartment was going all way through the cross section of a floor of the building with half of the exterior surfaces facing north and the other half south. The other apartment, Apartment 2, was at the eastern gable and on the top floor meaning that exterior surfaces also included the eastern wall and the roof. The eastern wall did not include any windows. The outdoor climate data were obtained from Meteonorm [13] for Karlstad, the same city as measurements were from. Figure 1 presents the hourly outdoor temperature during the normal year. The normal year average outdoor temperature is 6.4°C.

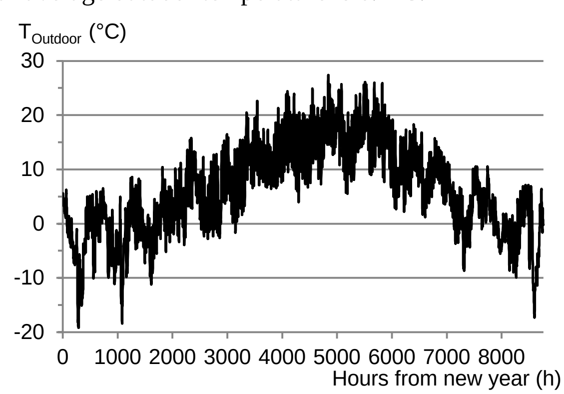

Figure 1. Hourly outdoor temperatures in Karlstad according to the data used in the simulations.

Copyright (c) IARIA, 2014. ISBN: 978-1-61208-371-1

Building 1 had exterior walls with a U-value of 0.18 W/(m²·K), roof with U-value of 0.13 W/(m²·K) and windows with a U-value of 1.3 W/(m²·K). Building 2 had exterior walls with a U-value of 0.1 W/(m²·K), roof with U-value of 0.08 W/(m²·K) and windows with a U-value of 0.8 W/(m²·K). Thermal bridging was estimated by adding 20 % to the described transmission losses for all building components. Mechanical supply and exhaust ventilation with heat recovery was used, 75 % temperature efficiency. The apartments had a heated floor area of 60 m² and a ceiling height of 2.4 m^2. The apartments north and south facades were 18 m^2 respectively and the eastern façade was 19.2 m^2 in the gable apartments. 60 % of the window area was facing south and 40 % of the window area was facing north. The ventilation airflow was 25 l/s and the leakage airflow was 0.04 $l/(s \cdot m^2)$ and 0.013 $l/(s \cdot m^2)$ referring to exterior surface area for Building 1 and Building 2 respectively. The apartments were heated to 22 °C and the occupancy was 0.03 persons/m² based on actual measurements of occupancy in the city of Karlstad [14]. The solar heat gain coefficient of the widows was set to 0.4.

Energy simulations in practice are commonly based on one-zone calculations. The same approach was chosen in this study to match sector practice.

C. Parametric study

In order to study different building technology characteristics impact on the heating demand with the different user scenarios, a parametric study was carried out. Window area was varied from zero to 45 % of heated floor area in steps of 5 %. Ventilation heat recovery temperature efficiency was varied from 50 % to 95 % in steps of 5 %. When the window area was varied, the ventilation heat recovery temperature efficiency was set to 75 %. When the ventilation heat recovery temperature efficiency was varied, the window area was set to 25 % of heated floor area. For each step, the heating demand was calculated with the 562 different user scenarios which results in the same number of different heating demands for each of the four different apartments studied. Statistics regarding the heating demand are presented for each step for each of the studied apartments respectively. The presented statistics are minimum, 10, 25, 50, 75 and 90 percentile and maximum as well as average values of total heating demand. That means that a total of 45120 simulations of heating demand were carried out to obtain the results of the parametric study.

D. Simulation tool

Code was developed in the Delphi programming language to simulate the energy use hourly over a normal year explicitly by help of the power balance shown in Figure 2 [15][16] to handle user scenarios and parametric studies effectively. ROOM is the simulated zone. P_{trans} is the transmitted heat through the envelope, P_{cap} is the heat from a first order heat capacitor with the temperature t_{cap} and a heat capacitance of 15000 J/(m²·K). P_{solar} is incoming shortwave solar radiation that heats the room and P_{vent} is the power needed to change the temperature of the supply air, t_{sa}, 19°C, to the temperature of the exhaust air, t_{ex}. It is assumed that the room temperature, t_{room}, is 22°C and can rise to 27°C and is the same as the exhaust temperature. P_{int} refers to the load from people and household electricity that both were assumed to be constant during the year based on the measurements.

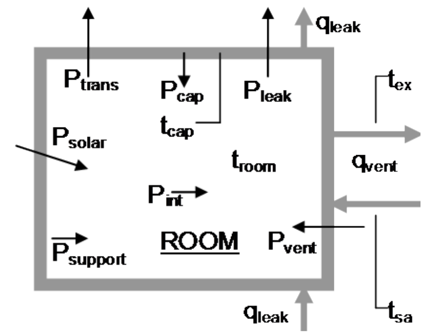

Figure 2. Power balance used in the simulation tool for the building. Quantities are given in the text.

$P_{support}$ is the energy needed to keep the room in balance at the desired t_{room}. Since no cooling system was used, $P_{support}$ could not be negative. Air heating after the heat recovery of the heating recovery ventilation is included but not shown in Figure 2. Also no air cooling was included. The SFP value of the air handling unit was set to 2 kW/(m³/s). Freezing protection of the heat recovery is modelled by keeping the exhaust air above freezing temperature.

III. RESULTS AND DISCUSSION

All measured calculated and simulated energy results are annual with the area referring to heated apartment floor area. The abbreviations HEL is used for household electricity and DHW for domestic hot water heating. As defined, Heating is the sum of Space heating and DHW.

Figure 3 shows the distribution of the annual use of HEL and DHW respectively. Average annual use of HEL was 26.7 kWh/m^2 and average annual DHW was 21.4 kWh/m^2. The median values are by definition the 50 percentile, directly readable in the figure. The highest use of HEL was 100 kWh/m^2 and the highest use of DHW was 104 kWh/m^2.

Figure 4 shows DHW as a function of HEL, a regression line and its coefficients are given. There is a rather weak correlation with a coefficient of determination of 0.14. In Figure 4, an apartment with low use of household electricity, about 11.5 kWh/m^2, had the highest use of domestic hot water, and an apartment with high use of household electricity, about 63 kWh/m^2, had a domestic hot water use close to zero which indicates the weak correlation. This implies that it is not straight forward to define a typical user of HEL and DHW. Hence, the actual distribution of combinations needs to be taken into account.

Figures 6 and 8 present statistics regarding the simulated total heating demand for different window areas in the apartments in Building 1 while Figures 7 and 9 present corresponding statistics for the apartments in Building 2. When the window area increases, the total transmission losses increases due to the higher transmission losses through

Copyright (c) IARIA, 2014. ISBN: 978-1-61208-371-1

a window compared to a wall. However, a larger window area can result in more solar heat gains.

Figures 10 and 12 present statistics regarding the simulated total heating demand for different ventilation heat recovery temperature efficiencies in the apartments in Building 1. Figures 11 and 13 present corresponding statistics for the apartments in Building 2. In Figures 6 through 13, maximums are given in the figure caption and percentile curve types are presented in Figure 5.

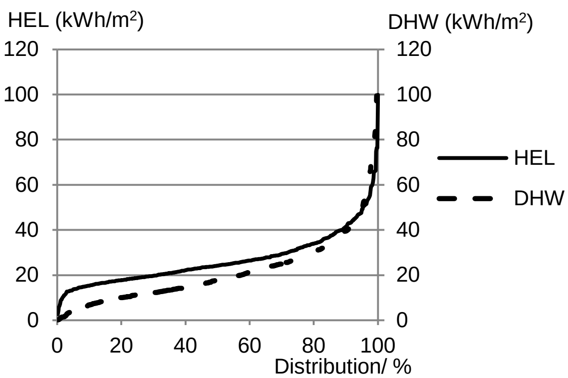

Figure 3. Duration of annual use of household electricity (HEL) and domestic hot water heating (DHW).

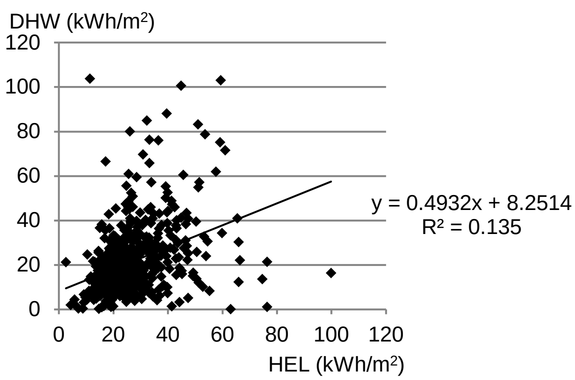

Figure 4. Use of annual domestic hot water heating (DHW) as a function of the use of annual household electricity (HEL).

Figure 5. Curve types used in Figures 6 through 13.

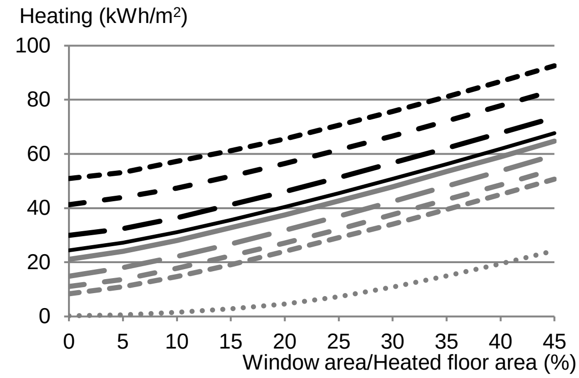

Figure 6. Annual heating, Apartment 1 in Building 1. Maximums: 111, 115, 119, 125, 130, 135, 141, 146, 152 and 158 kWh/m^2.

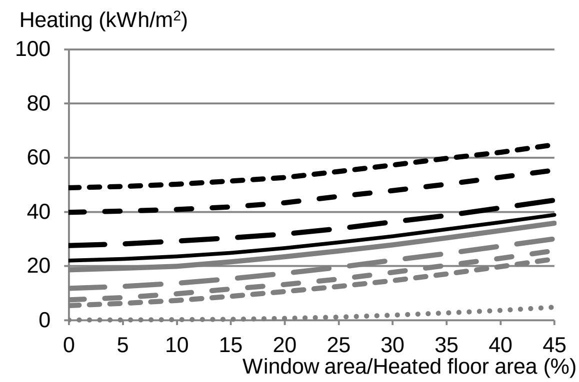

Figure 7. Annual heating, Apartment 1 in Building 2. Maximums: 105, 107, 108, 111, 113, 116, 118, 121, 124 and 127 kWh/m^2.

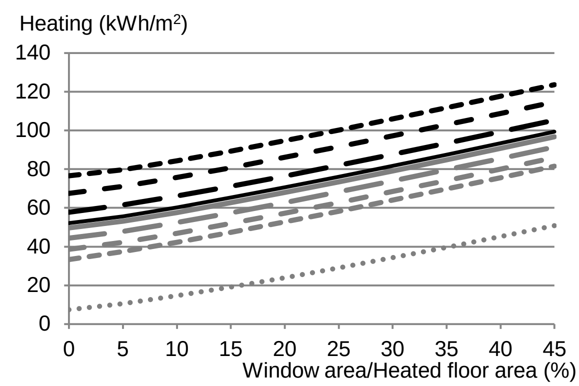

Figure 8. Annual heating, Apartment 2 in Building 1. Maximums: 146, 148, 153, 157, 163, 168, 174, 179, 185 and 191 kWh/m^2.

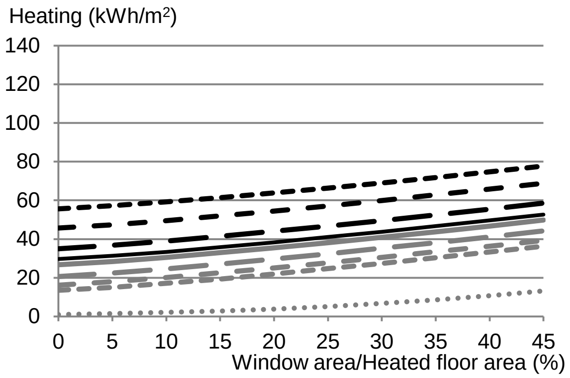

Figure 9. Annual heating, Apartment 2 in Building 2. Maximums: 119, 120, 122, 125, 127, 130, 133, 136, 139 and 142 kWh/m^2.

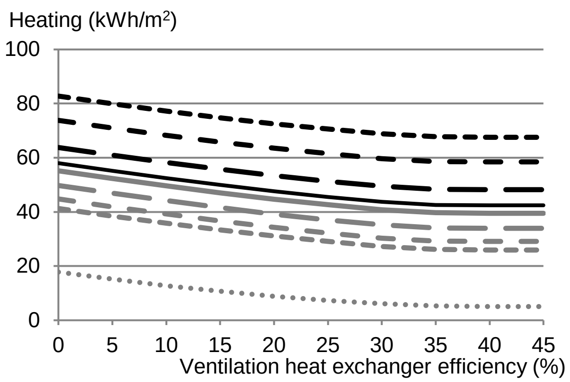

Figure 10. Annual heating, Apartment 1 in Building 1. Maximums: 148, 145, 143, 140, 137, 135, 133, 132, 132 and 132 kWh/m^2.

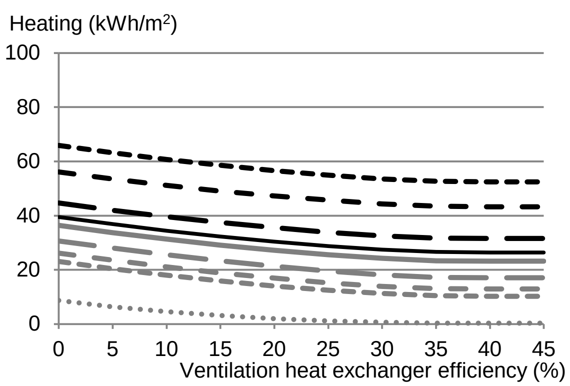

Figure 11. Annual heating, Apartment 1 in Building 2. Maximums: 127, 125, 122, 120, 118, 116, 114, 113, 113 and 113 kWh/m^2.

The results show that the heating demand increases with raised window area and decreases with raised ventilation heat exchanger temperature efficiency. In Building 1, the average heating demand increased 43 kWh/m^2 in Apartment 1 and 47 kWh/m^2 in Apartment 2 when 45 % window area was used compared to zero. In Building 2, the corresponding increase was 17 kWh/m^2 in Apartment 1 and 23 kWh/m^2 in Apartment 2.

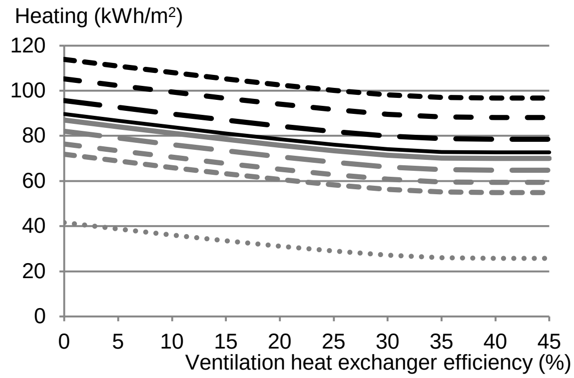

Figure 12. Annual heating, Apartment 2 in Building 1. Maximums: 181, 179, 176, 173, 170, 168, 166, 165, 165 and 165 kWh/m^2.

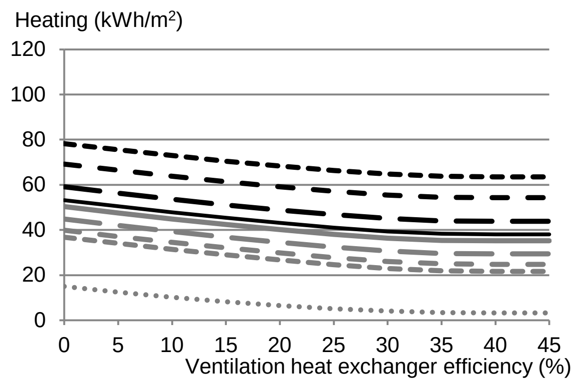

Figure 13. Annual heating, Apartment 2 in Building 2. Maximums: 143, 140, 137, 135, 132, 130, 128, 127, 127 and 127 kWh/m^2.

The difference between the 95 percentile and the 5 percentile of heating demand in Figures 6 through 13 represents the resulting span of heating demand taking into account 90 % of the users excluding the 5 % low and high extremes. The average difference between the 95 and 5 percentile of heating demand was about 42 kWh/m^2 for all studied window sizes in both buildings both apartments. In Building 1's Apartment 1, the span in heating demand, taking into account the middle 90 % of the users, is about the same as the average increase in heating demand when having 45 % window area compared to zero while the span is slightly lower than the heating demand increase in Apartment 2. In the more energy efficient passive house type Building 2, the span in heating demand was more than twice as high compared to the average increase in heating demand when having 45 % window area compared to zero in Apartment 1 and almost twice as high in Apartment 2. The above mentioned analysis compares the heating demand at a very large window area, 45 % of heated floor area, to the heating demand at no window area. It is not likely to have apartments with no windows due to daylight requirements. The difference in heating demand between all other studied window percentages will be smaller while the difference between the 95 and the 5 percentile of heating demand is about the same for all studied window sizes. The different user behaviors have a higher impact on the heating demand compared to different window areas and this increases with increasing energy efficiency regarding building enclosure and ventilation heat exchanger efficiency.

In Building 1, the average heating demand decreased 16 kWh/m^2 in Apartment 1 and 17 kWh/m^2 in Apartment 2 when 95 % temperature efficiency of the heat recovery was used compared to 55 %. In Building 2, the corresponding decrease was 13 kWh/m^2 in Apartment 1 and 15 kWh/m^2 in Apartment 2. The average difference between the 95 and 5 percentile of heating demand was about 42 kWh/m^2 for all studied efficiencies in both buildings both apartments. The span in heating demand was about three times higher than the average decrease in heating demand when having 95 % efficiency compared to 55 %. The difference in heating demand between all other studied temperature efficiencies will be smaller while the difference between the 95 and the 5 percentile of heating demand is about the same for all studied efficiencies. The different user behaviors have much higher impact on the heating demand compared to different ventilation heat exchanger temperature efficiencies.

As expected, the heating demand increases with raised window area and decreases with raised ventilation heat changer efficiency. However, different user behavior can have a much higher impact on the heating demand compared to different window sizes and heat exchanger efficiencies. Since today's buildings are, and tomorrows buildings will be even more, energy efficient, the user related energy uses will be an even larger part of the buildings energy balance. As important as it is to accurately model the physical properties of the building enclosure and the building services in simulation tools, as important is it to take different users' behavior into account.

The building technique and building services might have actual performance that differs from design values. For example, the thermal transmittance of the building enclosure is to some extent dependent on the quality of the construction work on site. However, according to the results, even relatively large variations in thermal transmittance, exemplified by the difference between Building 1 and Building 2, at 25 % window area and 75 % heat exchanger efficiency, is 17 kWh/m^2 which is less than half of the difference in heating demand taking into account the difference from the middle 90 % of the different users and slightly higher than the difference between the 75 and 25 percentile representing the middle 50 percent of the users.

The results imply that energy simulations of residential buildings should take the variation in user behavior into account and rather than presenting a single figure, present the predicted energy use in a span that represents the variation of the user behavior, for example based on the middle 90 % or 50 % of the users. Based on the performed simulations, the span representing 90 % of the different user behaviors is about 42 kWh/m^2 and the span representing 50 % is about 14 kWh/m^2.

IV. CONCLUSION

Annual use of household electricity and domestic hot water was measured in 562 one bedroom apartments in Sweden. Simulations of annual heating demand, taking into account the 562 different users, show that in order to predict the energy use of energy efficient residential buildings, with a reasonable accuracy, the different users' characteristics regarding household electricity and domestic hot water must be taken into account. Furthermore, to determine the impact that different users will have on a building's heating demand, the analysis must be based on the actual building and the result should be given as a distribution rather than as a single figure.

ACKNOWLEDGMENT

This Research was founded by LÅGAN, SBUF and KBAB.

REFERENCES

[1] H. Bagge and D. Johansson, "Energy use in multi-family dwellings – demands and verification" Proceedings of 5th Nordic conference on construction economics and organization, vol. 1, 2009, pp 185-192.

[2] A. Elmroth, "Energy use in theory and practice" Contribution to the Anthology: More efficient energy use in residential buildings An anthology on future means of control (in Swedish), Swedish Energy Agency, Eskilstuna, Sweden, 2002, pp 66-75.

[3] A. Lindén, "Hammarby Sjöstad – crazy crossbar height" (in Swedish) VVS teknik & installation. The 2006 October issue, Stockholm, VVS forum, 2006, pp 2-5.

[4] A. Nilsson, "Energy use in newly built residential blocks at the Bo01 area in Malmö" (in Swedish) Lund, Building Physics LTH, Lund University, 2003.

[5] F. Karlsson, P. Rohdin, and ML. Persson, "Measured and predicted energy demand in a low energy building: important aspects when using Building Energy Simulations" Building Services Engineering Research and Technology, vol. 28, 2007, pp 223-235.

[6] H. Bagge, L. Lindstrii, and D. Johansson, "User related energy use – Result from mesurements in 1300 apartments" (in Swedish), Sveriges Byggindustrier, FoU-Väst rapport 1240, 2012.

[7] V. Corrado and HE. Mechri, "Uncertainty and sensitivity analysis for building energy rating" Journal of Building Physics, vol. 33, 2009, pp 125-155.

[8] H. Bagge, "Building Performance – Methods for Improved Prediction and Verification of Energy Use and Indoor Climate" Building Physics LTH, Lund University, Sweden. 2011.

[9] The Swedish National Board of Housing, Building and Planning. Building Regulations, BBR, BFS 2011: 26. 2014.

[10] H. Bagge, "Household electricity – measurements and analysis" Proceedings of Building physics symposium 2008 in Leuven, 2008, pp 95-99.

[11] Swedish Energy Agency , http://www.energimyndigheten.se/Hushall/Varmvatten-och-ventilation/Vatten-och-varmvattenberedare/, Accessed 2014-03-14.

[12] Sveriges centrum för nollenergihus, "Kravspecifikation för nollenergihus, passivhus och minienergihus" http://www.nollhus.se/dokument/Kravspecifikation%20FEBY12%20-%20bostader%20sept.pdf. Accesssed 2014-05-24.

[13] Meteotest, "Meteonorm handbook, manual and theoretical background" Switzerland. 2011.

[14] D. Johansson, H. Bagge, and L. Lindstrii, "Measurements of occupancy levels in multi-family dwellings – Application to demand controlled ventilation" Journal of Energy and Buildings, vol. 43(9), 2011, pp 2449–2455.

[15] D. Johansson, "Modelling Life Cycle Cost for Indoor Climate Systems" Building Services LTH, Lund University, Sweden. 2005.

[16] International Organization for Standardization, "Energy performance of buildings – Calculation of energy use for space heating and cooling" EN ISO 13790. 2008.