Evaluation of a modified co-heating test for in-situ measurements of thermal transmittance of single family houses

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Angela Sasic Kalagasidis, PhD, Emma Brycke, PE, Jannicke Nilssen, PE, Pär Johansson, PhD

ABSTRACT

Within two years after commissioning the energy use for heating and operation of new buildings in Sweden should be verified by measurements. These have to be corrected for energy usage deviating from what has been defined normal during the building design, e.g. excessive venting and hot water use. This is practically difficult since the transmission losses of the building in use cannot be verified due to lack of a standard practical methods for their evaluation. Designers and producers of low-energy houses would benefit of such a method as the design of well-insulated envelopes is an essential quality of these buildings. A recently reintroduced method, the so called co-heating test, could be used for the verification of the overall thermal transmittance of buildings. To test the applicability of the co-heating test in-situ, measurements were performed on two test objects. A two years old low-energy house and a new summer cottage were tested. During the measurements, the latter was placed in a laboratory environment with a stable climate. Air tightness was measured on both houses. The overall average heat transfer coefficients were obtained and compared to theoretical values. This paper describes how the co-heating test has been modified to be used in in-situ conditions. Findings from both the measurements and following analyses are presented. The results obtained indicate that there is a clear potential for further simplifications of the co-heating test in future.

INTRODUCTION

The co-heating test is an experimental method for in-situ evaluation of a building's overall thermal conductance (W/K), also called the overall heat loss coefficient (HLC). This value describes the insulation level of a building envelope, which is one of the most influential parameters in the energy use for heating of a building. A measured value of HLC is needed when it is not possible to make reliable predictions of the building's energy use by simulations, or to verify the building simulations' results. Aging and deterioration of buildings in use may cause permanent changes of building envelopes that cannot be quantified by available building simulation software due to their inherent limitations. The same applies for varying workmanship standards and on-site invented solutions during the production of buildings. Therefore,

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the co-heating test can be used both as a diagnostic tool for the buildings in use and as a quality control method of the building's design and construction processes. The latter could be of particular interest for designers and constructors of low-energy houses, where such a test could be a certificate of their particular expertise. A similarity can be drawn with a blower-door test thanks to which the air tightness of a building envelope is reported as an evidence of a building's particular quality.

After the co-heating test was introduced in the late 1970's (Sonderegger and Modera, 1979), a vast number of modified co-heating tests have been developed with the aim of achieving a better accuracy and repeatability of the test. The interested reader may refer to Bauwens and Roels (2014) for an overview of existing co-heating methods. Yet, the co-heating test still remains as a challenging task for practical applications. In this work we would like to further clarify some issues that should be taken into account when preparing and executing the test. Based on two field studies, we show how the test can be simplified and shortened.

Basics of the co-heating test

The co-heating test involves heating of the indoor environment to a constant temperature by an electrical heater over a period of time. Continuous recording of the heating output, the ambient conditions, and processing of data reveals the HLC. Besides electrical heaters with sufficient heating power and data loggers (for electrical power input, indoor and outdoor temperatures), fans may be needed to mix the indoor air to a uniform temperature. While the test is in progress, the building should be unoccupied, intentional ventilation, domestic appliances and other heat sources inside the building should be shut down, and solar radiation through windows should be prevented.

The stationary heat transfer through the building envelope establishes a theoretical basis of the test. The heating temperature should be high enough to ensure that the heat flow through the building envelope during the test is transferred from the inside to the outside, to avoid the need for a cooler. From the data collected, the HLC of a building can be found by regression analysis of daily mean heating power input, Q_h [W], and the daily mean inside to outside temperature difference, ΔT [K]

$$Q_h = HLC \cdot \Delta T \tag{1}$$

With relatively simple equipment it is possible to conduct a co-heating test in any type of buildings. However, difficulties associated with assuring stationary ambient conditions, separation of transmission heat losses from other heat transfer processes through the building envelope, as well as the need to have an unoccupied building can make the test both time consuming and expensive. These are discussed briefly below.

Conditions for a successful co-heating test

The reliability of the co-heating test depends largely on the stationarity of ambient conditions and on how well the transmission heat losses can be separated from other heat losses and gains through the building envelope. It is important to subtract infiltration losses from the measured power supply from the heater so that Q_h in Equation (1) encloses only the transmission losses through the building envelope. The air leakage characteristics of the building should be measured by a blower door or tracer gas techniques (Bauwens and Roels, 2014). This also implies that an adequate air infiltration model of the building should be established in order to utilize the results of the air leakages tests. Therefore, wind data (wind direction and speed) during the co-heating test should be recorded.

Varying outdoor conditions, particularly sunny and windy periods, disturb the co-heating test by forcing a building into non-stationary thermal balance with the surrounding. To illustrate this, the heat demand in a model building has been calculated by a building simulation tool and plotted against both outdoor air temperature and solar-air temperature in Figure 1. For this purpose, a transient energy balance model of the building has been constructed in Matlab / Simulink (www.mathworks.com) using a building physics toolbox (www.ibpt.org), and the building's thermal characteristics have

been simplified to one-capacity model as described in ISO 1370. As can be seen in Figure 1, there is no unique linear correlation between the heat supply and the outdoor air temperature, regardless the time step (hourly or 24 h average). On the other side, a clear and unique linear correlation exists between the heat supply and solar-air temperature, which takes into account solar radiation on the building, sky radiation, wind, etc. In order to measure the solar-air temperature, additional measuring equipment should be added to the basic measuring kit (electrical heater, indoor and outdoor temperature loggers, and wind data loggers) such as pyranometers and pyrgeometers.

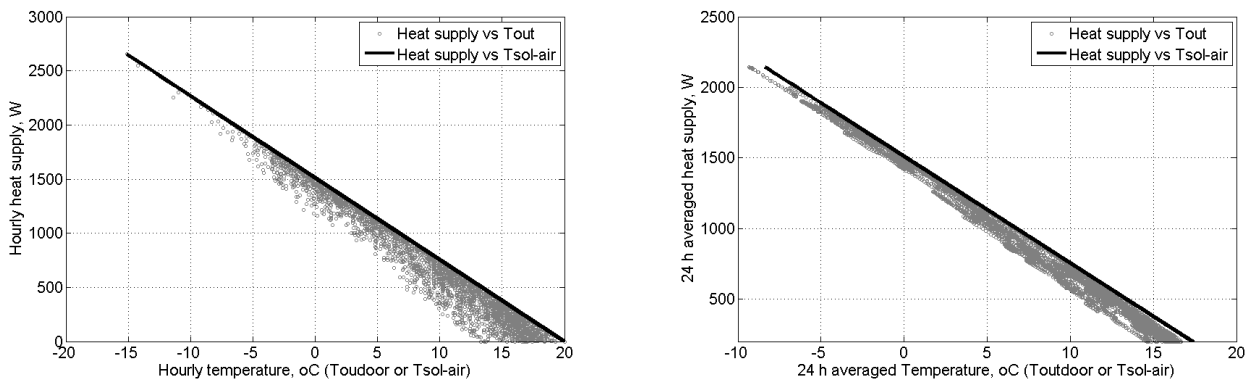

Figure 1 To the left: heat supply to a model building plotted against outdoor air temperature and against equivalent air temperature; all hourly values. To the right: the same results plotted as 24 h averaged. The results are obtained by an in-house made building simulation software (www.ibpt.org), where the building's thermal characteristics have been simplified in accordance with recommendations in SS-EN ISO 13789:2007. The indoor temperature in the building is kept constant at 20 °C (68 °F).

The importance of excluding tenants from the measurements is illustrated in Figure 2, which shows the measured heating power supply during a heating season in 16 identical and occupied single-family houses. These houses were designed according to the Swedish low energy house standard FEBY09 (FEBY, 2009) and built in 2012 in the neighborhood Vallda Heberg, outside Gothenburg, in the south-west of Sweden. To give the reader a reference, the FEBY09 standard limits the total annual energy demand for heating, cooling and ventilation to 65 kWh/m^2 (20.6 kBtu/ft^2) heated floor area (60 % of the national requirements at that time) at the indoor temperature 21 °C (70 °F). To fulfill this requirements, the thermal transmittance (U-Value / U-Factor) of the exterior walls and windows in the tested houses is designed to 0.11 W/m^{2}K (R-52 ft^2·°F·h/Btu) and 0.7 W/m^{2}K (R-8 ft^2·°F·h/Btu) respectively, while the air leakage characteristics is 0.25 ACH at 50 Pa pressure difference. Although all 16 houses in Figure 2 have the same design value of the heat loss coefficient, HLC = 112.7 W/K, the heating power supply varied largely between them during the heating season as a consequence of different users and their preferences on indoor environment (Jimmefors and Östberg, 2014).

TWO REASONS TO SHORTEN THE CO-HEATING TEST

Based on the literature, the length of the co-heating experiment varies between different methods from days to weeks (Bauwens and Roels, 2014). Weekly periods are too long for practical applications because adequate solutions for the relocation of the tenants may not be available. It would be easier if the test could be performed over a course of a day or two, as there is a fair chance for the tenants to spend that time at another location. The results from Figure 1 suggest that there is no reason for prolonging the test more than a day or two. More measured data will not improve the accuracy of the test unless they are correlated to the correct temperature, solar-air instead of air temperature, and there is a proper air leakage model.

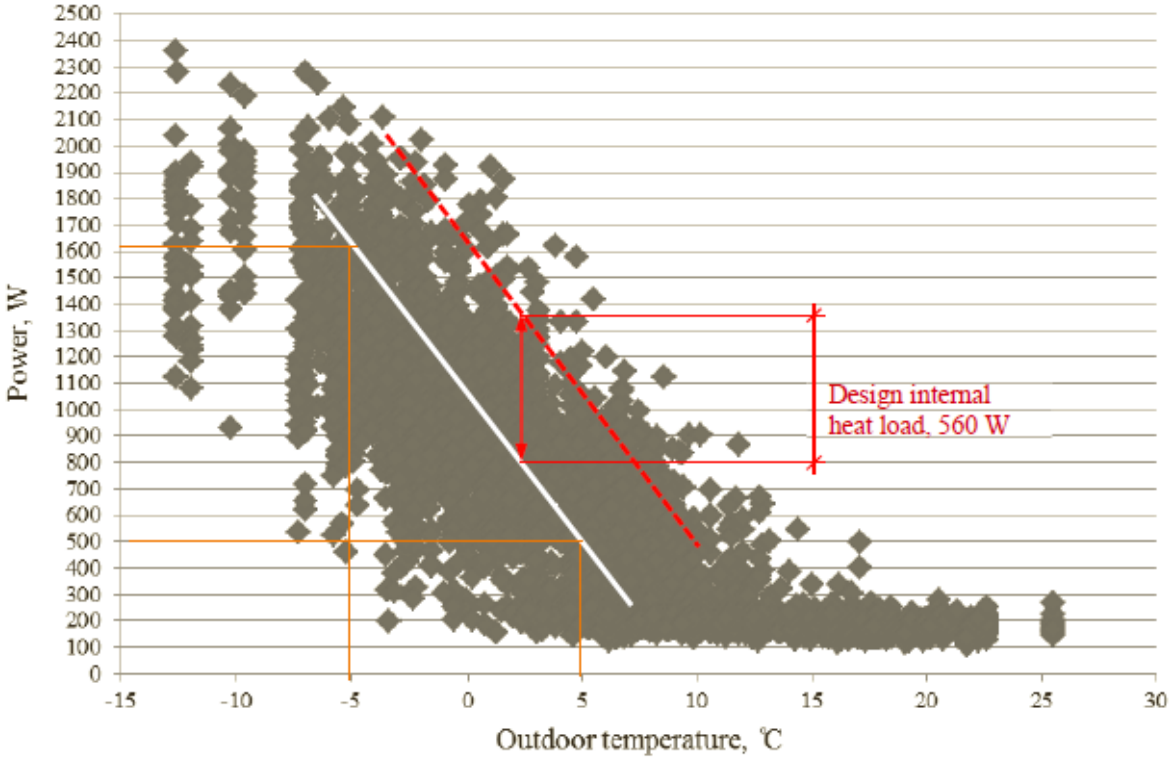

Figure 2 Daily averaged heating power supply measured in 16 identical and occupied houses during 2013. All houses fulfill the passive house standard FEBY09 (FEBY, 2009). The white line represents a designed *HLC* = 112.7 W/K of the building envelopes. The distance between the white and the red line represents the designed internal heat gains (Jimmefors and Östberg, 2014).

Another way to shorten the co-heating test is to keep the indoor temperature at the same (average) level as in normal use of the building. While raising the indoor temperature may be needed to assure a positive temperature difference between the indoor and outdoor environment, it should be definitely avoided whenever possible. Each change of the indoor temperature leads a building into non-stationary thermal balance with the environment. Thermal inertia of the building will determine the time that is basically wasted on waiting until the building reaches a new steady state. Theoretically, assuming a lumped model of the building, the difference between the steady state and the current average temperature in the building is about 13.5 %, if the waiting time is equivalent to two time constants of the building (Hagentoft, 2001).

FIELD TESTS

The major hypothesis in this work is that the heat loss coefficient of a house can be obtained from short-term co-heating tests, without changing the indoor air temperature. To test the hypothesis, two field tests were performed. The first test was conducted on a single-zone building, i.e. a summer cottage, and under stable ambient conditions. The second test was conducted in a community building in Vallda Heberg neighborhood. This is a multi-zone building in real climate conditions. The testing procedures and major findings are summarized below.

First test object: Summer cottage

The co-heating test under almost ideally stable ambient conditions was conducted in a simple building during February 2015 in an experimental hall at Chalmers University of Technology. The ambient temperature was around 19 °C (66 °F) throughout the test, without solar radiation and wind (see Figure 3). The building, a summer cottage (Friggebod in Swedish), was constructed by students of Architecture as a part of their spring-term course, after which it was sold and profits were given to charity. It was a single-zone building, with the floor area approximately 10 m² (108 ft²), with one window and one door. The building envelope was timber-framed and insulated. The overall thermal transmittance of the building, including thermal bridges, is estimated to 0.47 W/m²K (R-12 ft²·°F·h/Btu) by detailed calculations (Brycke and Nilssen, 2015).

Figure 3 To the left: the summer cottage from the outside, during a blower door test. To the right: the interior of the summer cottage during the co-heating test.

All ventilation openings were sealed to exclude the ventilation heat losses during the test. A Blower door measurement was also performed. Sensors for logging the temperature and relative humidity were placed both inside the building and outside, at different heights. Inside the object, 4 devices were placed on tripods with a vertical distance of 0.5 m between them. They were placed in a suitable location where the influence of direct heat from the radiator should be as low as possible. Outside the building 4 sensors were placed along a vertical line with approximately 0.8 m distance between them. Further details can be found in (Brycke and Nilssen, 2015).

The house was not heated before the test. Due to a relatively high temperature in the test hall, the indoor temperature in the house was raised to about 30 °C (86 °F) to assure sufficient temperature difference during the co-heating test in respect to the ambient temperature. An electrical radiator was placed in the middle of the room in order to spread the heat uniformly. The data from the power/energy-meter and the temperature sensors were logged hourly. The measurements lasted for about a week. A fan was used to mix the indoor air only during the last 7 hours of measurements, to evaluate possible effects on the results.

Results from the test are presented in Figure 5. The ambient temperature during the test was rather stable and the small variations that are visible in the figure were caused by occasional openings of the exterior doors at the test hall. The indoor temperature during the test was somewhat higher than intended, i.e. 31.7 °C (89.1 °F) on average, due to a coarse regulation of the thermostat at the radiator. There was clear temperature stratification which did not decrease after the fan was turned on (the last 7 hours).

From the measured data, the average thermal transmittance of the building envelope U_m [W/m²K] was found as

$$U_m = \frac{Q_h}{A \cdot (T_{in} - T_{out})} \quad (2)$$

where A [m²] is the total area of the building envelope, T_{in} and T_{out} [°C] average indoor and outdoor temperature over a period of interest, and Q_h [W] average electric power supply from the radiator. The air infiltration losses were deducted from Q_h.

The average test-based U_m values were found for both the whole measuring period (7 days) and for the six selected shorter periods (5-10 h), as summarized in Table 1. The average test-based U_m value from all test periods is 0.44±0.008 W/m²K (12.9±0.23 ft²·°F·h/Btu). The results from the short periods diverge for not more than 2.3 % from the U_m value found over the whole test period. We can conclude that a stable outdoor environment and indoor temperature provide good conditions for successful use of the co-heating test, regardless the length of the test. One can notice a slight increment of U_m during the periods 1-3 and then decrement during the periods 4-6, which coincide with the increment and decrement of the relative humidity inside the house (Figure 4 and Figure 5). The house was finished just before the measurements, so the drying of the built in moisture very likely occurred during the test. Finally, the difference between the test-based U_m values and the theoretical one are in the range 4-9 %, which is considered acceptable. However, it should be kept in mind that the accuracy of the theoretical value is not known.

Table 1 Measured average heat transfer coefficient in the summer cottage

Interval	Period of Logging Start	Period of Logging Stop	Average Um [W/m²·K] [ft²·°F·h/Btu]	Deviation from the theoretical value [%]	Deviation from the whole period averaged value [%]
Whole period	2015-03-24 09:00	2015-03-30 08:00	0.44 (R-12.9)	-6.4	-
1	2015-03-24 23:00	2015-03-25 09:00	0.45 (R-12.6)	-4.3	2.3
2	2015-03-26 02:00	2015-03-26 09:00	0.45 (R-12.6)	-4.3	2.3
3	2015-03-27 01:00	2015-03-27 06:00	0.44 (R-12.9)	-6.4	0.0
4	2015-03-27 23:00	2015-03-28 05:00	0.44(R-12.9)	-6.4	0.0
5	2015-03-28 23:00	2015-03-29 05:00	0.43(R-13.2)	-8.5	-2.3
6	2015-03-29 23:00	2015-03-30 07:00	0.43 (with fan) (R-13.2)	-8.5 (with fan)	-2.3 (with fan)

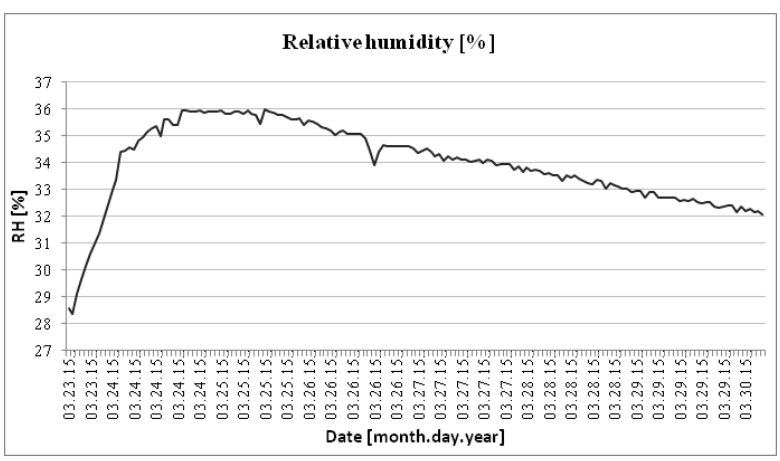

Figure 4 Relative humidity inside the summer cottage during the co-heating test

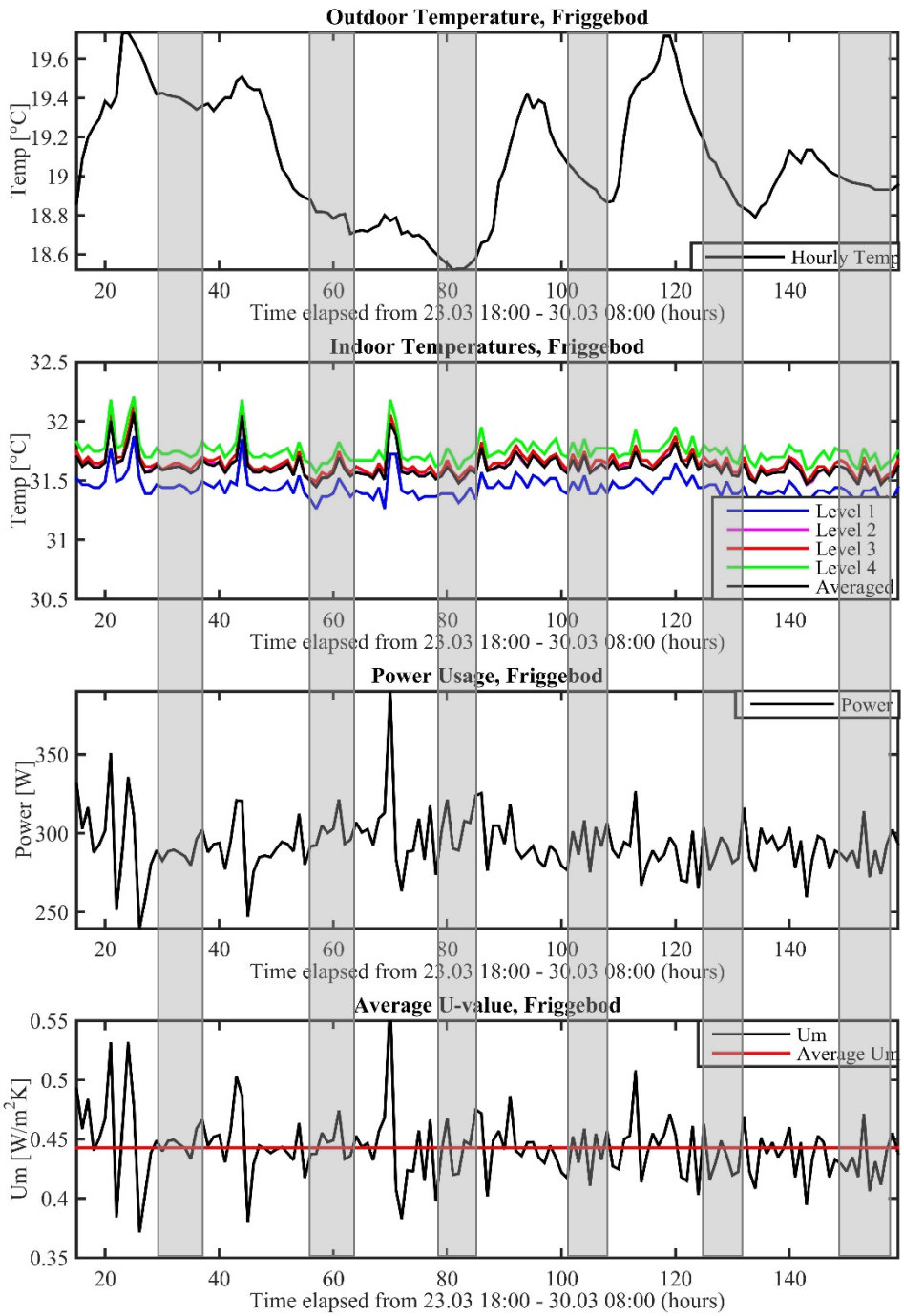

Figure 5 Results of the co-heating test in the summer cottage (Friggebod): top: ambient temperature in the test hall; second from the top: indoor temperature: level 1 at 0.5 m (1.6 ft) from the floor, all other levels offset by 0.5 m (1.6 ft); third from the top: power usage by the electrical radiator; bottom: estimated thermal transmittance of the building envelope. Shaded areas indicate six short-time periods for the estimation of the average thermal transmittance of the building envelope (Equation 2 and Table 2).

Second test object: The community building in Vallda Heberg

The second co-heating test was performed in a multi-zone building, located in Vallda Heberg neighborhood residential area outside Gothenburg, and under normal weather conditions. This is a rentable house for the residents in the neighborhood (the same as for Figure 2) and as such it was found suitable because it was possible to keep it both uninhabited and unventilated during the test, and all domestic appliances were turned off. The building has a floor area of approximately 200 m² (2 100 ft²) divided on two floors, as shown in Figure 6.

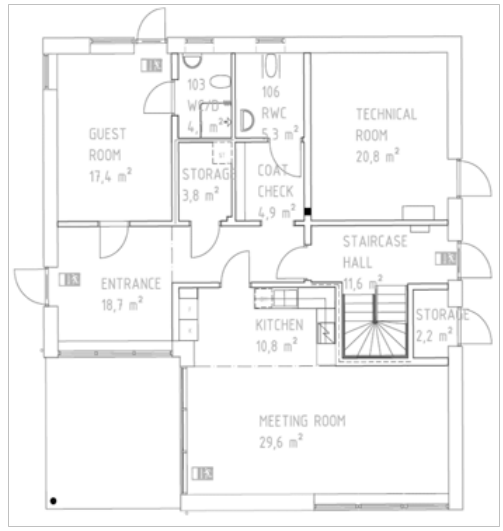

Figure 6 The community building in Vallda Heberg neighborhood and the layout of the ground floor.

The community building is much larger than an average single family house, and would require several electric heaters for the co-heating test. Due to financial reasons, it was decided to use the existing hydronic heating system, i.e. radiators placed below windows, since it was already equipped with energy and power meters. This was further motivated by the lack of reported results from co-heating tests where the existing heating system in the house was used.

The co-heating test was performed at two different occasions in March and April 2015, which were chosen based on the building's availability (i.e. the building was fully booked on other occasions). The ventilation system was turned off, and all visible openings in the building envelope were closed or sealed. The air leakage characteristics was determined from a Blower door test. Temperature loggers were distributed evenly in the building, mainly at a height of 1.5 m (4.9 ft) above the floor level, and typically in the centerline of the non-exterior walls. Rooms with a higher ceiling height such as those on the 2nd floor and the kitchen were equipped with temperature loggers at two levels, to account for possible temperature gradients. All windows were covered by aluminum foil to block the solar irradiation through windows. Only the outdoor air temperature was logged during the test as it was estimated that the solar radiation would be of modest intensity in this period of the year. Further details about the test can be found in Brycke and Nilssen (2015).

Results from the co-heating tests from both test periods are presented in Figure 7 and Figure 8 respectively, and summarized further in Table 2 and Table 3. As a basis for comparison, a theoretical thermal transmittance of the entire building envelope was estimated to 0.19 W/m²K (R-30 ft²·°F·h/Btu) (HLC=94.2 W/K, total area of the building envelope 496 m² (5 300 ft²)) by detailed calculations, where both thermal bridges and air infiltration losses have been taken into account. Further details are provided in Brycke and Nilssen (2015). The test-based average U_m values were found in the same manner as presented in the test on the summer cottage. Besides the average values over the entire measuring periods of 4 and 5 days respectively, the values from shorter periods, mostly night times, were also calculated.

Table 2 Measured average heat transfer coefficient in the community building. Test 1

Interval	Period of Logging Start	Period of Logging Stop	Average Um [W/m²·K] [ft²·°F·h/Btu]	Deviation from the theoretical value [%]	Deviation from the whole period averaged value [%]
Whole period	2015-03-10 23:00	2015-03-13 11:00	0.17 (R-33.4)	-10.5	-
1	2015-03-10 23:00	2015-03-11 06:00	0.19 (R-29.9)	-1.6	25.3
2	2015-03-11 22:00	2015-03-12 08:00	0.21 (R-27.0)	12.1	3.5
3	2015-03-12 23:00	2015-03-13 07:00	0.18 (R-31.5)	-7.4	10.0
Periods 1, 2 and 3			0.19±0.02 (R-29.9±0.31)	1.0±10.0	12.9±11.2

Table 3 Measured average heat transfer coefficient in the community building. Test 2

Interval	Period of Logging Start	Period of Logging Stop	Average Um [W/m²·K] [ft²·°F·h/Btu]	Deviation from the theoretical value [%]	Deviation from the whole period averaged value [%]
Whole period	2015-04-15 12:00	2015-04-20 09:00	0.18 (R-31.5)	-4.2	-
1	2015-04-16 02:00	2015-04-16 07:00	0.20 (R-28.3)	4.2	8.8
2	2015-04-17 02:00	2015-04-17 07:00	0.18 (R-31.5)	-6.3	-2.2
3	2015-04-18 02:00	2015-04-18 07:00	0.18 (R-31.5)	-5.3	-1.1
4	2015-04-18 22:00	2015-04-19 06:00	0.15 (R-37.9	-23.2	-19.8
5	2015-04-19 22:00	2015-04-20 02:00	0.17 (R-33.4)	-12.6	-8.8
Periods 1-5			0.17±0.02 (R-33.4±0.39)	-8.6±10.1	-4.6±10.6

The average test-based U_m value from all shorter periods in test 1 is 0.19±0.02 W/m²K (R-29.9±0.31 ft²·°F·h/Btu) (Table 2), and in test 2 0.17±0.02 W/m²K (R-33.4±0.39 ft²·°F·h/Btu) (Table 3). These differences are in the range 10 ± 10 %. Approximately the same range of difference is found when the short-term test-based U_m values are compared to the theoretical one. The average test-based U_m values for the entire periods are in a similar absolute range. It should be emphasized again that the accuracy of the theoretical U_m value cannot be estimated, although standard procedures have been followed.

There were some notable differences between the conditions during these tests in the community building and the one performed on the summer cottage. Namely, the temperature difference inside the community building differed between the zones, and changed over the time (see Figure 7 and Figure 8). The reason for the latter could be found in un-precise control of the indoor temperature as provided with the hydronic heating system, but also because of the sunny periods during the measurements. Besides, the outdoor temperature varied both on average and in the amplitudes. Nevertheless, the accuracy of the short-term test-based U_m values is found acceptable, as it is in the range of accuracy of the theoretically estimated values.

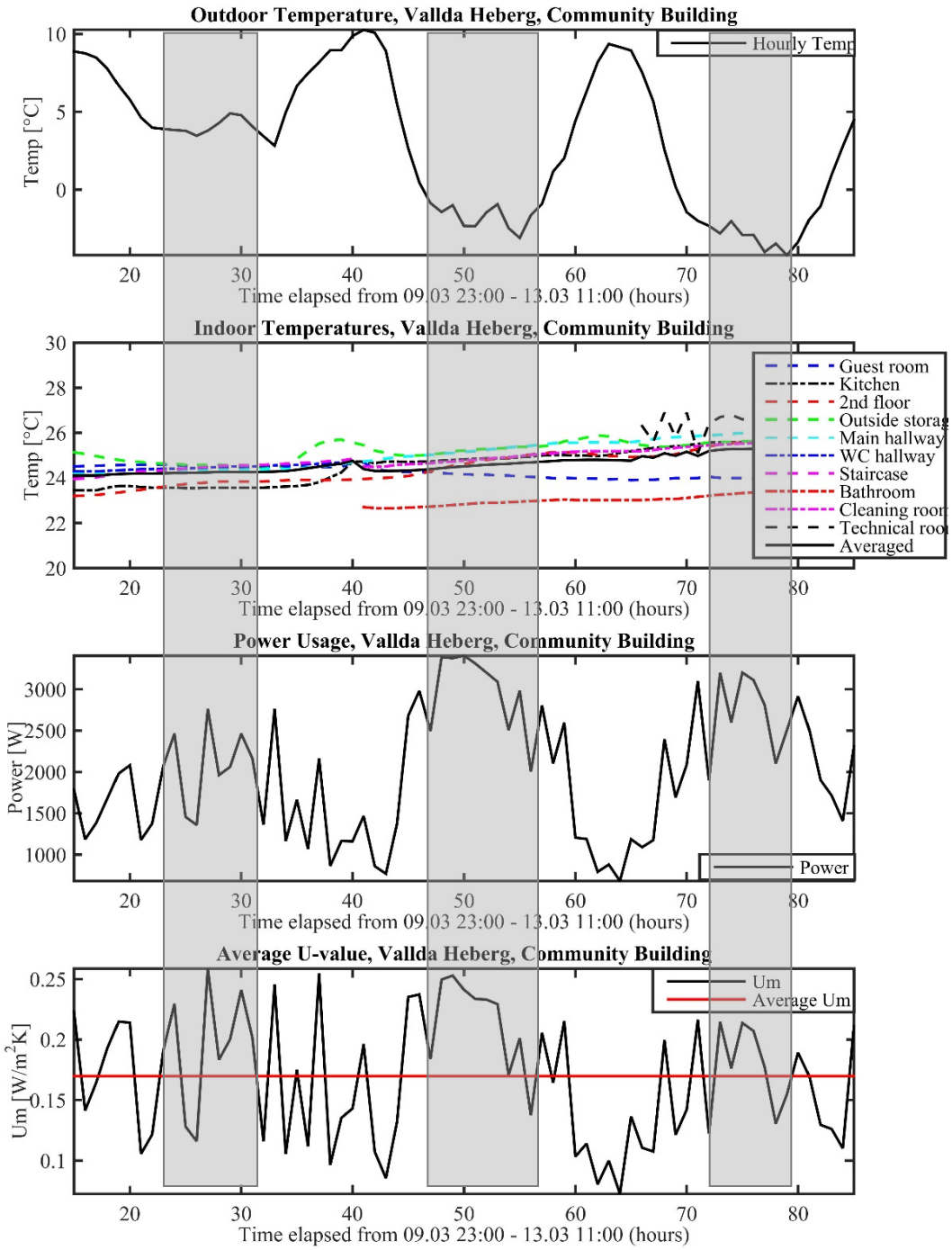

Figure 7 Results of the co-heating test 1 in the community building: top: ambient temperature; second from the top: indoor temperature; third from the top: power usage by the electrical radiator; bottom: estimated thermal transmittance of the building envelope. Shaded areas indicate three short-time periods for the estimation of the average thermal transmittance of the building envelope (Equation 2 and Table 2).

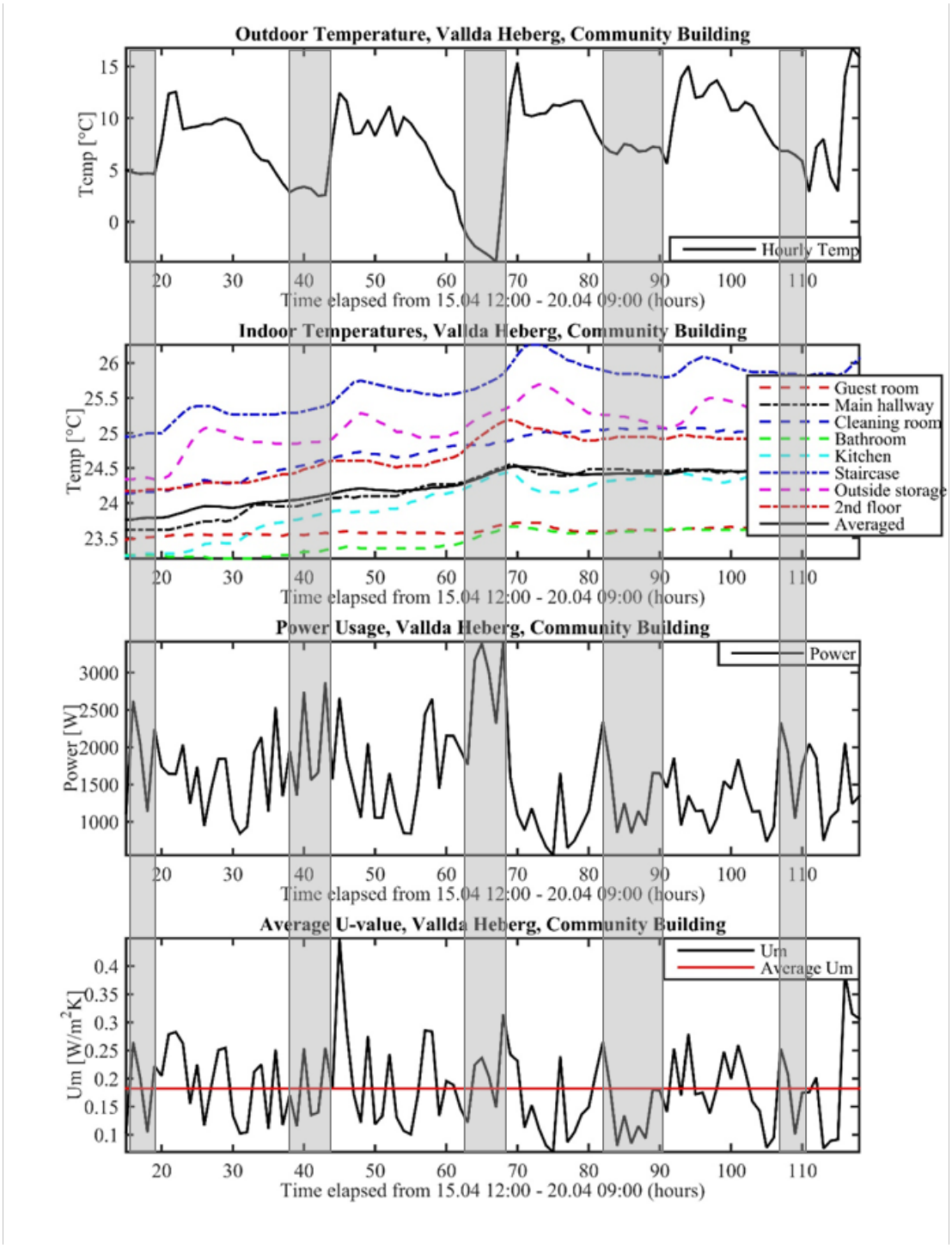

Figure 8 Results of the co-heating test 2 in the community building: top: ambient temperature; second from the top: indoor temperature; third from the top: power usage by the electrical radiator; bottom: estimated thermal transmittance of the building envelope. Shaded areas indicate five short-time periods for the estimation of the average thermal transmittance of the building envelope (Equation 2 and Table 3).

CONCLUSIONS

This study has investigated the usability and reliability of a modified co-heating test, which is both shortened to a couple of hours (night time) and conducted without changing the indoor air temperature. Both simplifications are motivated by theoretical analyses which suggest that a large number of data does not necessarily improve the accuracy of the test. On the contrary, substantial time is wasted if the indoor air temperature is changed during the measurements.

These hypotheses have been tested in two field tests, where the first one was conducted under stable ambient conditions in a simple single-zone building, and the second one under realistic ambient conditions in a complex multi-zone building. The results from the first test differed up to 2-3 % from the theoretically estimated overall thermal transmittance of the building envelope. The difference between the measured and theoretical value in the second test was about 10 ± 10 %, which is considered acceptable since the uncertainties in estimating the theoretical values could be in the same range.

The results from the field tests indicate that the suggested modifications of the co-heating test are reasonable. The test could be performed with basic equipment composed of a heater, energy and electric power meters, and temperature loggers. Besides, the air flow characteristics of the building should be measured and a building air leakage model should be established in order to differentiate between infiltration and transmission losses. Moreover, it was shown that the test could be performed using the existing hydronic heating system in a building. Finally, the results indicate that it is sufficient to conduct the test under several night-time periods during cold months.

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