gSKIN® Application Note: U-Value Measurement Case Study

The overall energy consumption for housing is responsible for 35% of global energy consumption on average. In Europe, roughly 3'100 TWh (or 266 Mtoe) are spent in energy for housing every year. A large part of today's housing stock has been constructed before 1980, using low insulation standards. These low insulation standards lead to large amounts of wasted energy, and cause substantial financial costs to the building owners. To reduce these costs, the insulation of affected buildings can be improved through retrofitting and renovation. Due to the large saving potential, the market for retrofitting is growing and various attractive solutions are offered. However, to this day, the activities are not based on quantitative insulation data (i.e. U-Value) of complete buildings and building elements since these values exist commonly only for the individual building components. The absence of U-Values of complete building profiles hinders the determination of existing conditions, justification of investments and validation of completed improvements.
This case study shows the three methods available for collecting information about insulation quality. It shows that only one of these methods allows a user to gain quantitative and meaningful information. Furthermore, the case study describes the method and applies it to a typical Swiss residential building constructed in 1948.

Available Methods

Today, the insulation quality of building envelopes is measured using three different approaches:

1. **Thermography (i.e. infrared imaging)**
   This approach shows the thermal radiation of an object and produces an image showing spots with higher and lower radiation. Thermography helps to understand the overall quality of a building envelope and to identify thermal bridges and parts with inhomogeneous insulation. However, it does not produce quantitative data (e.g. U-Value in W/m^2K) that can be used to interpret the insulation quality.

2. **Multiple temperature measurements**
   This approach is based on three or more temperature measurements inside and outside of a building element. By synchronizing these measurements, it is possible to calculate the heat flux indirectly, and thus deriving the U-Value of a building element. While this method generates quantitative data, it is hardly usable for in-situ measurements. To apply this method, a minimum temperature difference of 10 °C between the inside and outside temperature is required. Such temperature differences hardly occur in most regions, and are most likely not achieved continuously throughout the year.

3. **Heat flux method**
   A heat flux through a material is caused as soon as a temperature difference between the opposite sides is present. Heat is flowing from the warmer part to the colder part. The heat flux method uses this effect and measures heat flux as well as the warm and cold temperatures directly. With this data, it is possible to calculate the U-Value of any building material in-situ. The method for U-Value measurements is described and standardized in ISO 9869, ASTM C1046 and ASTM C1155. This is the only method which delivers reliable quantitative information about a building envelope.

The above short description shows why methods 1 and 2 are less suitable for the establishment of meaningful quantitative insulation quality data (i.e. U-Value). The following paragraphs describe how the heat flux method is applied according to ISO 9869 and which results it generates.

The equipment

In order to make the measurements, this case study used the gSKIN® U-Value Kit (KIT-2838C). The Kit enables users to make measurements according to ISO 9869, ASTM C1046 and ASTM C1155. It contains all the required components:

- 2 temperature sensors
- 1 heat flux sensor
- 1 datalogger

The datalogger has an adjustable measuring frequency, battery for up to 1 month of measurements, and memory for up to 2 million data points.

The Kit automatically records the following parameters:

- Heat flux through the building element in W/m^2
- Inside and outside temperatures in °C

From the recorded data file, the software included in the gSKIN® U-Value Kit, creates these results with the press of one button:

- Graphs of the heat flux and temperature measurements (see Figures 4, 5, and 6 for examples).
- Calculation of the U-Value

The method step by step:

1. Heat Flux Sensor placement
   - Install the heat flux sensor on the indoor surface. Ensure that the sensor is protected from direct heating, convection, and solar radiation.
   - For mounting the heat flux sensor, use heat conductive paste. Apply adhesive tape additionally to fix the sensor to the wall.
   - Optional: Use thermography to help identify representative/interesting spots for the heat flux sensor placement on your building element.
   - Optional: Cover the heat flux sensor with the same material as its surrounding material.
   - Optional: Use several sensors to obtain an average value for highly inhomogeneous building elements.
   - Additional information is available in the "Application Note: Building Physics".
2. Temperature sensor placement
   - Place two sensors at opposite sides of the wall at the position where the heat flux sensor is placed.
   - For U-Value measurements, make sure that the ambient air temperature is measured (i.e. by measuring the temperature 2-10 cm away from the wall).
3. Data acquisition (according to ISO 9869)
   - Minimum measurement duration: 72 h
   - Requirement to end the measurement: the U-Value does not deviate more than ± 5 % from the value obtained 24h earlier.
   - Typical recording frequency: 1 data point per 0.5 – 1 h (this case study uses 1 data point per 10 minutes)
4. Data Analysis
   - Using the gSKIN® U-Value Kit software, the measurement data is analyzed automatically. If preferred, the measurement data can also be extracted.
   - The U-Value is obtained from the mean values of the heat flux through the building element and ΔT. To calculate the U-Value, the following formula must be used:

$$U\text{-}Value = \frac{\sum_{j=1}^{n} \varphi_j}{\sum_{j=1}^{n} \Delta T_j} \qquad [W/(m^2K)]$$

where n is the total number of data points,
φ is the heat flux in W/m^2,
ΔT is the temperature difference between outside and inside in °C.

The measurement subject

The building measured was constructed in 1948. Since then, the house was renovated on several occasions. The renovations relevant to this case study are the renovation of the ceiling in 1979, and the renovation of the ground floor in 1999, where the insulation was renewed and adapted to the standards of the respective time period. Three spots were chosen for measurements:

A Outer wall facing south-east
Material: cinder brick, 25cm thick, built in 1948, not renovated since
Element separating the living room from the outside

B Floor on the ground level
Material: Concrete, 20cm thick, ceramic floor tiles on ground floor, renovated in 1999
Element separating the ground level from the unheated cellar

C Ceiling on first floor
Material: wood, thickness unknown, renovated in 1979
Element separating the stair case from the unheated attic

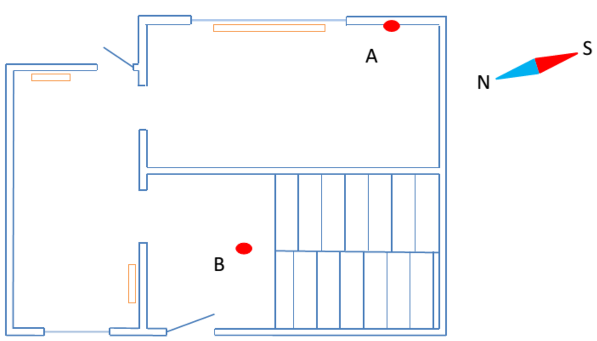

Figure 1. Ground floor: positioning of the measurement spots A and B.

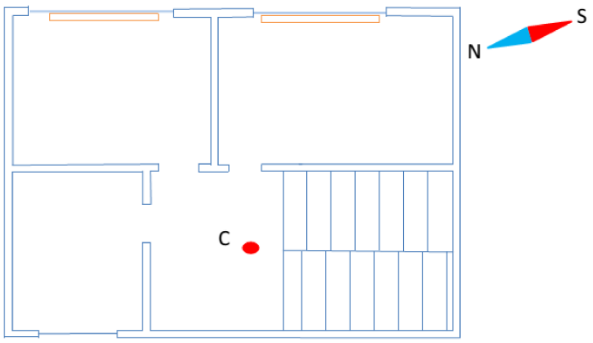

Figure 2. First floor: positioning of the measurement spot C.

The exact spots were chosen to avoid unwanted influences from heaters, lateral convection and radiation (e.g. the sun). The sensors were placed with a minimum distance of 1 m from heating sources. However, to show possible negative effects on measurements, an unfavorable setting was chosen as well (see discussion of measurement spot C below).

Spot A – Outer wall Spot B – Ground floor Spot C – Ceiling

Figure 3. Sensor mounting with detailed view (on bottom part) on the three spots.

Results

The following section shows the temperature and heat flux evolution over the measurement period obtained at each spot individually. The graphs are interpreted to give the reader a feeling for various possible effects of a measurement.

Spot A – Outer wall

Figure 4 shows the measurement results of spot A. The outside temperature fluctuates in a range from -1 to 3°C, with the lowest points during the night before sunrise. The inside temperature would fluctuate with the outside temperature, but is compensated by the heating system. The heating system is turned off during the night, and the lowest temperature is reached shortly before the heating is turned on again. Both temperatures have a 24h cycle. The time lag between the temperatures results in a non-constant temperature difference across the wall and thus fluctuations of the heat flux. The largest heat flux is observed during the afternoons when the outside temperature starts to drop and the inside is heated according to the heating cycle. The outlier at 10:04 on 14.12.2013 is caused by ventilating the room (i.e. opening window), which leads to a decrease of the inside temperature, and thus a lower heat flux.

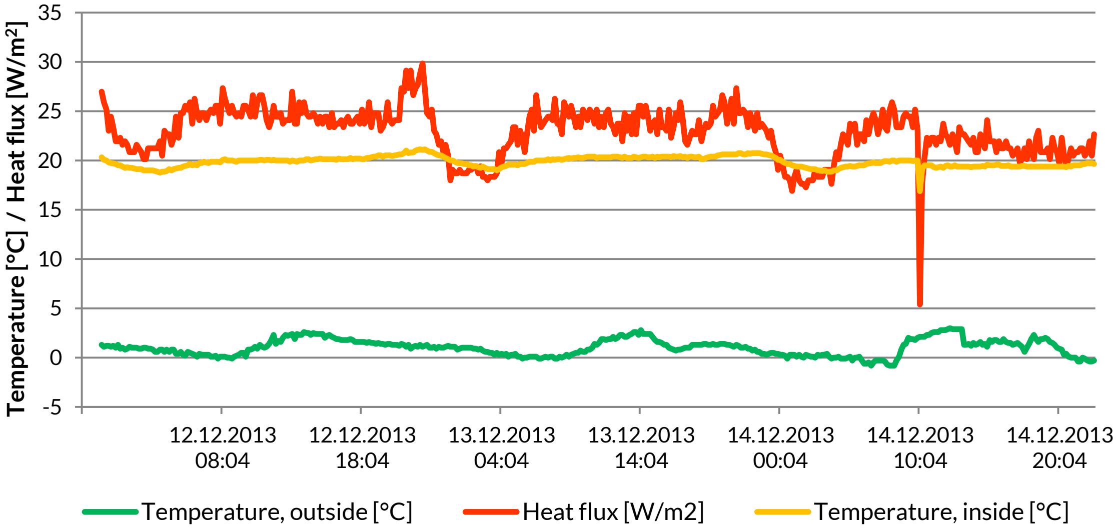

Figure 4. Temperature and heat flux of spot A. This graph was created using the software included in the measurement device.

Spot B – Ground floor

The temperature and heat flux measurements are very stable for an extended period of time during the weekend when the building is not occupied. Starting at 09:30 on 03.02.2014, both temperatures start to decrease as the doors to the basement and ground floor are opened. Then, the inside temperature recovers to its initial level, with several drops as the door is opened and closed again. The outside temperature (i.e. the temperature in the cellar) does not increase as a window is left open for the remainder of the measurement. The heat flux is stable until both temperatures start changing, and then fluctuates with respect to changes of the inside temperature. In order to calculate an accurate U-Value, the temperature difference has to be bigger than 5°C. In this measurement, the difference is mostly below 5°C, and thus the data should not be used for U-Value calculation.

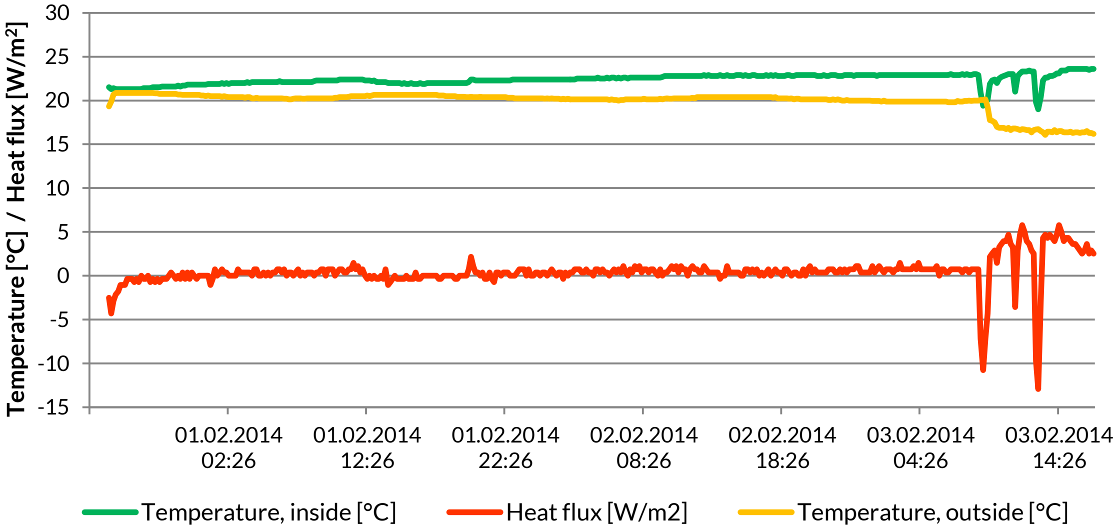

Figure 5. Temperature and heat flux graph of spot B. The outside temperature corresponds to the temperature in the cellar This graph was created using the software included in the measurement device.

Spot C - Ceiling

While the inside temperature is in the range of 19 – 23°C, the outside temperature (i.e. temperature in the attic) moves in a slightly larger range of 3 – 11°C. The inside temperature changes are mainly driven by the night/daytime cycle of the heating system, the temperature in the attic is mostly influenced by weather changes. The exposure to mild outside temperatures and sunlight, increase the temperature in the afternoons of 19.12.2013, 20.12.2013 and 21.12.2013. The low frequency modulations of the heat flux are caused by the asynchronous temperature changes (i.e. inside vs attic temperature). The high frequency modulation (i.e. fast signal fluctuations) is most probably caused by air circulation in the staircase. As the heat flux sensor was placed at the top of the staircase, warm air rising to the top might cause turbulences at the heat flux sensor surface, which lead to a disturbance of the measurement. The chosen spot is therefore not an optimal location for the U-Value measurement, and one might consider making a new measurement on a more suitable spot on the ceiling.

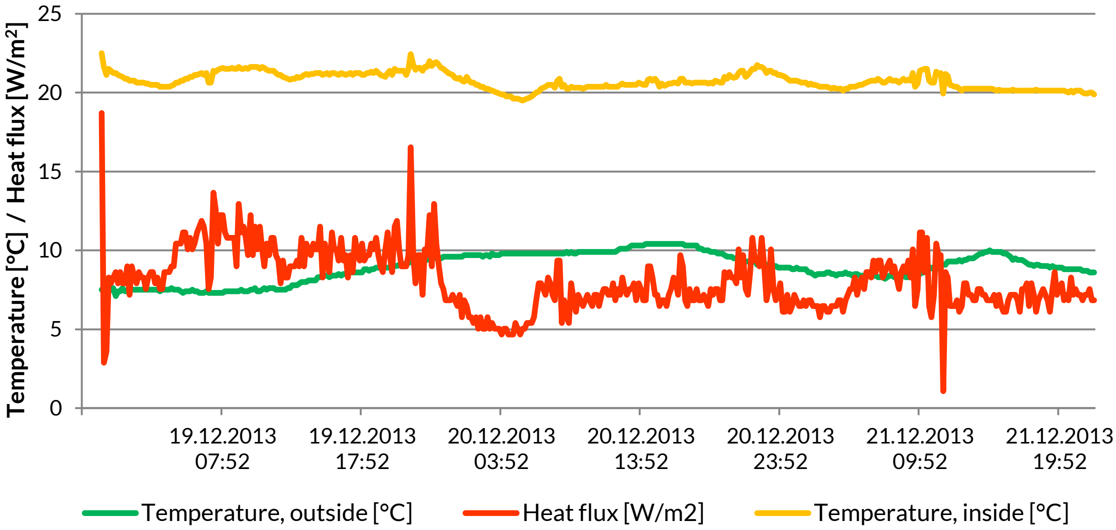

Figure 6. Temperature and heat flux graph of spot C. The outside temperature corresponds to the temperature in the attic. This graph was created using the software included in the measurement device.

Table 1 summarizes the measurement results. For each building element, the expected U-Value for the respective time period, as found in literature, is taken as a reference value. Comparing the results and reference U-Values from literature, the following interpretations are drawn.

Spot A – Outer wall
While the U-Value of the wall is good compared to the standard at the time of construction, it is very poor compared to today's standards. Renovating the outer wall would improve the insulation substantially. As the large total heating costs show, insulation improvements could help save a significant amount of costs.

Spot B – Ground floor
As mentioned previously, in the interpretation of the data of spot B, the temperature difference is not great enough to allow accurate U-Value calculation. Due to the insufficient temperature difference, the measured U-Value (0.19 W/m^{2}K) is unreliable. In comparison with the reference values, this observation is further affirmed. This measured U-Value cannot be used for any further processing.

Spot C – Ceiling
The renovation in 1979 did not improve the insulation quality as much as it could have based on the technology for this period. While the insulation quality of the ceiling is much better than the quality of the measured outer wall, it should also be improved to save costs.

	Spot A Outer wall	**Spot B Ground floor**	**Spot C Ceiling**
Average ΔT [°C]	18.84	2.52	11.83
Average heat flux [W/m^2]	22.88	0.48	8.08
Measured U-Value [W/m^{2}K]	1.21	0.19 [1]	0.68
U-Value of reference element [W/m^{2}K]	1.70 [2]	0.35 [3]	0.45 [4]
Achievable U-Value through renovation [W/m^{2}K]	0.25	0.2	0.20
U-Value for new construction [W/m^{2}K] [5]	< 0.15	< 0.2	< 0.1
Area [m^2]	50 [6]	38	42
Total heating energy per day [kWh]	27.46	0.44	8.14
Total heating costs per month [EUR] [7]	140.03	2.23	41.54

[1] This U-Value is not accurate. A minimum temperature difference of 5°C is required to make accurate U-Value measurements
[2,3,4] Source: Prof. Dr. Wolff, Kennwerte Aussenbauteile, Ostfalia Hochschule, http://www.energieberaterkurs.de/export/sites/default/de/Dateien_Kennwerte/kennwerte_aussenbauteile.pdf
[2] Reference U-Value of similar building element constructed before 1948
[3] Reference U-Value of similar building element constructed since 1995
[4] Reference U-Value of similar building element constructed 1977 – 1983
[5] "Passivhaus" standard
[6] Area of the wall facing south-east on ground level
[7] Assuming 0.17 EUR/kWh, and 30 days/month

Table 1: Summary of measurement results. Low U-Values indicate materials with high thermal insulation capability (i.e. low U-Values are desired).

Conclusion

The measurements carried out in this study show that the U-Value of a specific building element can be determined without much effort. By determining the insulation quality quantitatively, appropriate conclusions can be drawn. To get a complete overview of the building properties, various different spots should be measured.

However, the three measurements conducted here allow for a first conclusion about the building's condition and a rough estimate of possible measures. Compared to the two other elements (i.e. ground floor, ceiling), the renovation of the outer wall is the option with the biggest energy saving potential. Considering that the biggest part of the outside facing elements (i.e. the outer wall) resulted in the highest U-Value, the overall insulation properties of the building are very poor. Retrofitting the building envelope according to current insulation technology would therefore not only save energy, but lower the heating/cooling costs of the building considerably.

The measurements were recorded in three consecutive steps. Alternatively, multiple Kits can be used to make simultaneous measurements of multiple spots. The measurement standards (ISO 9869, ASTM C1046 and ASTM C1155) allow the consecutive and simultaneous approaches. While the measurement setup time per spot took 10 minutes, the data analysis per spot required 10 minutes, totaling at 20 minutes working time per spot. Adding the 72 hours of measurement time, the overall time frame for the measurement of one spot requires 72.3 hours (~ 3 days).

Document information

Revision History

Date	Revision	Changes
11. February 2014	1.1 (first published)	Completed content
18. February 2014	1.4	Complemented conclusions