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Technologieentwicklung eines anwender-freundlichen TEG-basierten U-Wert Messgerätes

Identifizierung und Evaluierung bisheriger und neuer Anwendungsbereiche für thermoelektrische Generatoren (TEGs)

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Für den Inhalt und die Schlussfolgerungen sind ausschliesslich die Autoren dieses Berichts verantwortlich.

Zusammenfassung/ Résumé/ Abstract

A. Zusammenfassung

Schwerpunkt des vorliegenden Projekts war die technologische Weiterentwicklung der Sensorik, die beispielsweise auch für das U-Wert Messgerät bereits genutzt wurde sowie die Erstellung eines Konzepts für ein neues Messgerät. Etliche Bestandteile des Messgeräts bzw. der Technologie wurden hinsichtlich beispielsweise verbesserter Robustheit optimiert. Auswertungen von Anwender-Feedback und eigenen Messungen führten dazu, ein Spezifikationsheft für ein neues, kabelloses (wifi) U-Wert Messgerät zu entwickeln, das mehrere, gleichzeitige Messungen zulässt.

Weitere Anwendungsfelder für TEGs wurden innerhalb und außerhalb des Gebäudebereiches identifiziert. TEGs können beispielweise die Wirkungsweise von Phase-Change Materialen (PCM) messen und somit das Gesamtsystem (z.B. Glasfassaden in Bürogebäuden), in das sie integriert werden, optimieren. Zusätzlich ist es möglich mit der TEG-Technologie den Wärmefluss und somit auch die innere Temperatur einer Batterie zu bestimmen. Daraus lassen sich, im Vergleich mit anderen Methoden, relativ schnell und einfach Rückschlüsse bezüglich der Lebensdauer oder des Alterungszustandes der Batterie ziehen.

B. Résumé

Pendant le projet, la technologie sous-jacente de l'appareil U-value (pour déterminer le coefficient U / Coefficient de transfert thermique) a été perfectionné et un concept pour un nouveau dispositif a été développé. On a aussi élaboré un concept pour un nouveau, meilleurs instrument. On a optimalisé plusieurs éléments de l'instrument existant, par exemple pour le faire plus robuste. Basé sur une analyse du feedback des utilisateurs et des propres mesures on a défini les spécifications pour développer un nouvel appareil sans câbles qui peut faire plusieurs mesures en même temps.

Autres application dans le secteur de bâtiment pour les TEG technology ont été identifié pendent le projet. Par exemple les TEG peut être utilisé pour mesurer l'effet des PCM (Phase-Change Materials). Basé sur ces mesures on peut optimiser par exemple une façade d'un bâtiment qui a intégré les PCM. En plus, on peut utiliser les TEG pour mesurer le flux de chaleur et la température dans une batterie. Avec cette méthode on peut faire plus vite des déductions sur la condition (longévité) de la batterie.

C. Abstract

During the project the underlying technology of the U-value device was further developed and a concept for a new device was developed. Several parts of the current device and the technology got optimized in regards to its robustness, user-friendliness, etc. Based on own research and user feedback, we could develop a specification concept on which we will now further develop an enhanced measurement device. According to that, the new device will enable the user to do simultaneous measurements at multiple spots and this wireless.

Additional application fields of TEGs were found inside and outside of the building sector. For example, TEGs can measure the mode of action of phase-change-materials (PCM). For instance, these materials are used within new building elements/systems (i.e. glass façade systems) and are constantly getting further developed in research laboratories. Furthermore, we showed that with our TEG technology it is possible to determine the inner temperature of a battery by measuring the heat flux. Hence conclusions can be drawn regarding the lifetime or the state of health of the battery.

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1. Ausgangslage / Starting position

In modern society people are spending most of their time indoors, sitting in their homes or working in their offices. It is therefore not surprising that a lot of energy is consumed for indoor purposes. Buildings represent around 40% of the primary energy consumption in most countries (IEA, 2015). A significant part of this energy is linked to space heating or cooling (Global Energy Assessment, 2009). Better isolated buildings could therefore lead to a large reduction in energy use. Several studies show that energy efficiency in buildings has a large saving potential and ambitious goals are set to reduce energy use in the building sector (Kneifel, 2010) (Boyano, Hernandez, & Wolf, 2013).

Today, still large parts of today's buildings have been constructed based on low insulation standards. Since these low insulation standards lead to large amounts of wasted energy and substantial financial costs for buildings owners and occupants, more and more of these buildings are improved by retrofitting and renovation. A growing attention for retrofitting and renovation, both in the industry and in the academic world, has led to a wide range of improvement options (Kneifel, 2010).

However, until now, activities in this field are hardly based on in-situ and up-to-date quantitative data (Fumo, 2014). Data on e.g. U-values are approximated with simulation models, using laboratory test data or thermographic images (Tadeu, 2015) (Tzifa V. , Papadakos, Papadopoulou, Marinakis, & Psarras , 2014) (Murray, Walsh, Kelliher, & O'sullivan, 2014). Research has already shown that calculated U-values tend to underestimate the actual thermal transmittance due to deterioration and the influence of site-specific conditions (Asdrubali, D'Alessandro, Baldinelli, & Bianchi, 2014).

greenTEG has further developed an alternative measuring method to determine in-situ U-values, using a heat-flux sensor and two temperature sensors. With this technology a non-invasive measurement of 72 hours, with a minimum difference between the inside and outside temperature of only 5 degrees, is required to be conform with ISO 9869 - 2014 standards. With this technology it is possible to solve problems regarding the uncertainty of thermal losses and transmittances, which is an added value for many incumbent players in the energy efficiency building market. However, although it has been proven that this measuring method delivers reliable quantitative data, it is still rather vague to what extent and in which way the method can be of value in the building industry and beyond (other industries besides the building industry).

In our understanding the absence of precise data on U-values of building elements is currently a barrier to an enhanced understanding of the thermal system within a building, and by that, a barrier for an optimal choice of correct renovation options. Precise in-situ measurement of U-values could therefore help to reduce costs for building owners and contribute to higher energy efficiency standards within the building sector, or also be used as a quality control tool. Scientific literature is supporting this by showing that current methods to define in-situ insulation quality have limited accuracy. This is linked to both types of buildings, historic buildings as well as new efficient buildings (Asdrubali, D'Alessandro, Baldinelli, & Bianchi, 2014) (Adhikari, Lucchi, & Pracchi, 2012). Furthermore, it is assumed that better data would contribute to higher energy efficiency standards (Desogus, Mura, & Ricciu, R, 2013) (Biddulph, et al., 2014) (Vollaro, et al., 2014).

2. Ziel der Arbeit / Project goals

The aim of this project was divided into 3 parts.

The first goal was to evaluate different application areas for the U-value device within the building industry and to develop a hardware concept, which includes first steps of assessing the demand (potential customers) and potential partners (hardware suppliers) for a new prototype which is wireless and can be used as a multi-channel readout device.

Second, other possible application areas of heat flux sensors and TEG technology should be assessed within the broader building sector, i.e. for Phase Change Material (PCM).

The third aim was to identify and evaluate potential application areas for TEG technology outside of the building sector, i.e. in the battery (storage) sector.

In regards to these goals and intermediate technology improvements, appropriate publication concepts should be developed and directly or later on implemented in order to receive additional valuable stakeholder feedback.

3. Vorgehen / Method

Our project work for the **first part** (U-value measurement based on TEGs technology) exists of two main aspects. Firstly, an overview and analysis of different evaluation methods, which are today used to define and assess insulation quality. This was added with (field) case studies, which have been conducted to assess the performance of the heat flux method in different situations. Secondly, we deep dived into the improvement and redesign of the U-Value device and its underlying technlogy based on ongoing stakeholder feedback loops.

Furthermore, in the **second part**, the benefits of heat flux measurements for potential users within the broader building industry have been reviewed. Based on this initial assessment, the additional value of heat flux measurements in the building sector was critically examined. We conducted research about the general application of heat flux sensors for Phase Change Materials (PCM). In regards to this application area, we conducted a field test with a PCM developer in order to gain insights about the use of heat flux sensors within the PCM application area.

Our project work for **part three** (TEGs used as battery thermal monitoring application) started with a literature and patent research. Discussions with industry insiders and research institutes were held to understand the fundamental issues in regards to battery safety, life prediction and life elongation. During this phase, first R&D partners and other stakeholders were contacted. Later on, experiments for two of the most promising application areas were conducted. Based on these experiments, the insights gained from battery health estimation and lifetime prediction allowed us to prepare an interactive presentation of these results for the international battery fair in Stuttgart (“World of energy solutions”), and beforehand even showcase some earlier insights at the EST Karlsruhe and the Sensor & Test in Nuremberg.

4. Ergebnisse / Research work and results

4.1 U-value measurement based on heat flux technology in the building sector

In this first subchapter of the review of our research work and results we will focus on our results linked to the building sector. We will start this chapter with an assessment of available U-value evaluation methodologies.

4.1.1 Assessment of available U-value evaluation methodologies

In order to build our project upon a proper assessment of different **application areas of U-value evaluations within the building area,** we reviewed in a first step of this project, which competitive methods are currently used in the industry to obtain data about heat fluxes and U-values of building elements. This literature review helped us to find out what current methods are offering and which problems or needs they address by (in-situ) U-value measurements. Background information on the heat flux method, which greenTEG uses, can be found in Appendix A: ISO 9869 Summary. The following methods, which are widely applied to determinate insulation quality (in different situation and for different purposes), have been assessed:

- Thermography
- Calculation model
- Temperature based method

4.1.1.1 Thermography

One of the most frequent used methods to assess building insulation quality is thermography (Pearson, 2011). Thermography is defined as “the science of acquisition and analysis of thermal information from non-contact thermal imaging devices”. It refers to the process of capturing the intensity of the infrared radiance emitted from a certain object (M'Sirdi, Namaane, Howlett, & Jain, 2012). This is done via a thermographic camera, which converts the radiance data into a two-dimensional image that shows the temperature variations over the surface of the object (Balaras & Argiriou, 2002). For reliable data, the emissivity of the surface has to be set correctly taking into account the specific conditions during the measurement (Balaras & Argiriou, 2002). Thermography has many fields of application which include medical imaging, chemical imaging, electrical faults and process monitoring (Willis, 2008) (Lahiri, Bagavathiappan, Jayakumar, & Philip, 2012).

Thermography is also an established measurement method in the construction industry (Nardi, Sfarra, & Ambrosini, 2014). It is widely used during energy audits to detect thermal bridges, discontinuity of insulation quality, air leakage and moisture sources (Pearson, 2011). A thermal image can be used as proof of a problem or as support of other data obtained during the audit. It may help to exactly locate the source of a problem, which allows for low-cost repairs of the building envelop instead of extensive renovation work (Nardi, Sfarra, & Ambrosini, 2014). Moreover, a scan during the construction phase or before purchase may detect any anomalies in the insulation quality which otherwise would have remain unseen (Balaras & Argiriou, 2002).

Conducting thermographic surveys and analyzing the results requires expertise from the auditor (Pearson, 2011). A right calibration of the measurement device is crucial for the reliability of the images. The emissivity of the observed surface is crucial in that matter. Emissivity highly depends on the type of material, the emissivity of a normal brick or painted wall differs a lot from the emissivity of metallic material (Balaras & Argiriou, 2002). In addition, other factors as emissivity, distance, ambient temperature, relative humidity and wind speed have to be considered during calibration to reduce the chance of misleading results (Young, 2014). The interpretation of the images can be quite difficult and requires knowledge about the specific conditions as well. To assure that the thermographic survey is conducted by someone with sufficient skills, knowledge and experience, an international certification standard is established.

The quality of the thermographic survey depends on few other factors as well. The quality of the thermographic camera is one of these factor (Pearson, 2011). The available cameras on the market differ widely in image resolution, thermal sensitivity and usability features. The mid-range cameras, available from €5000,- to up to €10000,-, are most used during an energy audit since these are suitable for reporting purposes (Pearson, 2011). Besides the quality of the camera, weather conditions may also significantly influence the outcome. Wind, temperature difference between inside and outside, recent rain and solar radiation all influence the outcome to a greater or lesser extent (Pearson, 2011). The impact of these weather conditions is smaller when an internal survey is conducted instead of an external survey (Energy.gov, 2012). However, sometimes an external survey might be useful, for instance to compare one building part to the other. In that case, it is even more important to avoid rain or wet walls, clear sky, solar radiation and wind during the measurement (Pearson, 2011).

Thermography during energy audits is mostly used as a qualitative test measure of thermal performance, though sometimes efforts are made to quantify certain parameters (M'Sirdi, Namaane, Howlett, & Jain, 2012). Several companies in the industry claim that with their products and specialized software a quantification of energy losses, heat fluxes or even U-values can be obtained (IRT Surveys , n.d.) (FLIR, 2009). These claims are challenged by other stakeholders in the industry which state that only in specific conditions some values might be estimated in a reliable way (Thermalvision, 2014) (Westerhold, 2012) . In several academic papers thermographic U-value measurements are conducted which show that it might be possible to get reliable results. The relative deviation in U-value with respect to calculated and heat flux measured ones could often be kept within the 20% range (Nardi, Sfarra, & Ambrosini, 2014) (Tzifa V. , Papadakos, Papadopoulou, Marinakis, & Psarras, 2014) (Fokaides & Kalogirou) (Albatici, Tonelli, & Chiogna, 2015). However, from these papers it can be concluded that these measurements are complex and require very specific conditions and that they are therefore not easy to apply during a typical building assessment. The International Organization for Standardization (ISO) has not established any standardization for U-value measurements using thermographic (Thermalvision, 2014).

4.1.1.2 Calculation model

Assessing the thermal performance of a building envelope can be done by analyzing the thermal properties of the materials it exists of since the combination of these materials determine the total thermal characteristics (Al-Hamoud, 2005). The U-value of a building envelope depends therefore on the thermal conductivity and the thickness of the constituent layers of this envelope (Biddulph, et al., 2014). The thermal conductivity of solids varies widely depending on e.g. porosity, density and structure of the materials, which is the reason of the large differences in insulation qualities of building envelopes (Gustaffson, 1991). Since the thermal conductivity of insulation materials is very low, the characteristics and thicknesses of these type of materials determine for a large part the U-value of the building envelope (Al-Hamoud, 2005).

If these different thermal properties and the corresponding thicknesses are identified correctly, the U-value of the building envelope can be calculated in a very simple way. The thermal resistance of one layer (the inverse of the U-value) can be calculated by dividing the thickness of the layer by the thermal conductivity of the material. Adding together these resulting thermal resistances and the surface resistances leads to the total thermal resistance. The U-value of the building envelope can be calculated by taking the inverse of this thermal resistance. A basic U-value calculation can be made using the following formula (BFE, 2002).

$$U = \frac{1}{R_{si} + \sum_i \frac{\lambda_i}{d_i} + R_{so}}$$

Equation 1: U-value calculation based on the calculation model

Where R_{si} is the inside surface resistance and R_{so} the outside surface resistance [m^2K/W]. λ_i stands for the thermal conductivity [W/mK] and d_i for the thickness of a certain layer [m]. The most commonly used values for the inside surface resistance (R_{si}) and the outside surface resistance (R_{so}) are, respectively, 0,13 m²K/W and 0,04 m²K/W (BFE, 2002). Thermal conductivities of all different kind of building materials, including brand specific materials, can be found in large databases such as the NIST Data Gateway.

A calculation of the U-value of a building envelope as described above is often referred to as a steady state U-value calculation (Dwyer, 2012) . One can find in the internet many U-value calculators that provide such an estimation of the U-value of a wall if the constituent materials and their thickness are filled in (e.g. ChangePlan, EcoWho, Vesma, thermalcalconline, u-wert.net). The quality of these online tools differ mostly depending on the quality and amount of data linked to the embedded building materials of the specific database. For a more precise and professional approach software tools have been developed which can be purchased for prices ranging from approximately €50,- to €200,- (e.g. Xtratherm, BuildDesk, IES-SV). They tend to have a more detailed database of building materials including data on certified insulation material of different fabricants. Some of these software tools take into account the specific heat values and density of each element in addition to conductivity and thickness (Dwyer, 2012). These tools apply dynamic models in which temperature patterns are included so more realistic data on thermal behavior and energy losses can be obtained (Booth, 2010). Since temperature patterns are included as well, more realistic data can be calculated. Furthermore, also professional energy consultants offer to calculate dynamic U-value assessments on the basis of the information which is available of a given building (Abbey consultants, Hibec, Comfort Solutions). However, most of the calculation tools are just to provide steady state calculations according to the guidelines formulated in the standard ISO 6946.

With the ISO 6946 the ISO has established a standard for calculations of thermal resistance and thermal transmittance for building envelopes. The method applies to components and elements consisting of thermally homogeneous layers (which can include air layers). This international standard also provides guidelines how to deal with building envelopes containing inhomogeneous layers (Tipperary Energy Agency, 2011). The upper resistance limit and the lower resistance limit has to be determined after which the average of the two lead to the total thermal resistance. In addition, correction terms to include the effect for air gaps and metal fasteners are mentioned in ISO 6946. This standard does not apply to doors, windows, floors and for cases in which insulation is bridged by larger metal elements such as fasteners. The guidelines to calculate the thermal transmittance of doors and windows are described in detail in ISO 10077 --Thermal performance of windows, doors and shutters -- and ISO 13370 -- Heat transfer via the ground—which includes a calculation method for ground floors.

ISO 6946 is an international standard on which many other national calculation standards, such as DIN 4108 (Germany) or SIA 180 (Switzerland), are based on. Requirements on the overall energy rating of buildings obligate building experts to calculate U-values according to these directives. These requirements are detailed in energy efficiency regulations in Switzerland, but also in other European countries such in Germany (Energieeinsparverordnung (EnEv)) or in the UK (Standard Assessment Procedure (SAP)). In most countries it is required to perform an energy assessment for new or renovated buildings in line with these energy efficiency regulations. Performing U-value calculations is therefore obligated in most cases (Rodríguez-Soria, Domínguez-Hernández, Pérez-Bella, & Coz-Díaz, 2014).

Performing U-value calculations based on material characteristics is currently the standard for determination of U-values. It is widely applied by many stakeholders in the building industry such as architects, engineers and energy assessors (Tipperary Energy Agency, 2011b). Which calculation model is applied differs according to the type of user and the level of detail that is required for a certain analysis.

4.1.1.3 Temperature-based method

The temperature-based method (TBM) is a way to perform a quantitative in-situ U-value measurement by only applying temperature sensors. It requires one outside and one inside air temperature sensor and three thermocouple wired probes, which have to be mounted to the observed wall (KIMO, 2011). With the output of these temperature sensors, the U-value of the wall can be derived. Like the heat flux method (HFM), the U-value calculation is based on the following formula (Spohn, 2008).

$$U = \frac{\mathrm{Q}}{\mathrm{T_{in}} - \mathrm{T_{out}}}$$

Equation 2: U-value calculation with temperature based method

Where T_{in} and T_{out} are, respectively, the inside temperature and outside temperature in Kelvin and Q is the actual heat flux through a wall (W/m^2). The U-value itself is expressed in W/m^{2}K. The inside temperature (T_{in}) and the outside temperature (T_{out}) are measured by the two air temperature sensors. With the TBM Q cannot be measured directly as it is done when the HFM is applied. In this case, the value of Q is determined by using the following formula (Spohn, 2008):

$$Q = \frac{T_{in} - T_{wall}}{R_{si}}$$

Equation 3: Heat flux calculation with the temperature based method

Where T_{in} is the inside temperature and T_{wall} is the temperature of the wall in Kelvin, and R_{si} is the boundary layer resistance between the inside wall surface and the inside air (m^{2}K/W). Surface temperature sensors are used to measure the T_{wall}. The boundary layer resistance (R_{si}) is not measured but derived from standard values for building elements taking into account the local conditions. A commonly used value for this boundary layer resistance (R_{si}) is 0.13 m^{2}K/W (ISO 6946 : 2007) (Testo, n.d.). The user needs to be aware that the boundary layer resistance can only be estimated and can therefore significantly differ from the actual in-situ value. By using such an estimated value for the boundary layer resistance of the inside surface (R_{si}) the formula for the heat flux (Q) can be filled in. All parameters are known and the U-value can be calculated according to Equation 1.

A few companies offer a complete toolset to measure the U-value based on TBM within the price range of 850 CHF and 1050 CHF (e.g. Testo, KIMO). These sets include read-out software and a data logger to analyze the measurement results. They often offer additional parameters to measure such as air humidity, pressure and material moisture (Testo, 2014a) (KIMO, 2011). There are no guidelines established on how to perform such a temperature-based U-value measurement, neither by ISO nor by any other standard setting organization. However, manufacturers of the equipment state that the temperature difference should be at least 15 °C to 20 °C degrees Celsius (Testo, n.d.) (KIMO, 2011) (Spohn, 2008). Moreover, direct solar radiation would disturb the measurement and should therefore be avoided. The minimum duration of a reliable measurement is nowhere mentioned, however, the product descriptions of the products claim instant U-value measurements. The few measurements described in case studies mention that stable values were recorded after a measurement time of 60 to 90 minutes (Testo, 2014b).

4.1.1.4 Heat flux-based method

A heat flux through a material is caused as soon as a temperature difference between the opposite sides is present. Heat flows 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 (ambient) 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. The ISO 9869 determines the following equation for calculation the U-Value:

$$U = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} (T_{ij} - T_{ej})}$$

Equation 4: U-value calculation using the heat flux method

Hereby q equals the heat flux, T_{ij} minus T_{ej} is the difference between the outside and the inside temperature and n is the number of measurement points.

Currently, different manufacturers of measurement devices rely on the ISO 9869 norm, such as Ahlborn, and Hukseflux. According to the norm the device has to consist of at least one heat flow meter (HFM) and two temperature sensors (inside and outside). HFMs should be thin, with a low thermal resistance. Additionally, the HFM should be surrounded by heat conductive material to minimize disruptive factors. The calibration factor of a new type of heat flow meter shall be evaluated on various materials through an absolute test method.

Suitable surface temperature sensors are thin thermocouples and flat resistance thermometers. These sensors must be suitable for the measurement circumstances and if necessary shielded against external influences such as solar radiation. They have to be calibrated for several temperatures in the relevant range (generally between -10°C to 50°C).

For the measurement the sensors shall be mounted in such a way to ensure a measurement result which is representative of the whole element. The HFM shall be mounted in the inside of the building and the temperature sensors has to be located in immediate surroundings inside and outside. The outer temperature sensor should be protected from rain, snow, solar radiation, thermal heat or ventilation. To record accurate results the minimum test duration is 72 hours (3 days) if the temperature is stable. Otherwise, the duration should be extended up to 7 days. The data acquisition process should not be interrupted. To get a detailed analysis of the data at least one or two measurements per hour should be done (ISO 9869-1:2014).

Figure 1 shows the procedure to conduct a U-value measurement. In the following abstract we give a short overview how to set up and conduct a valid U-value measurement.

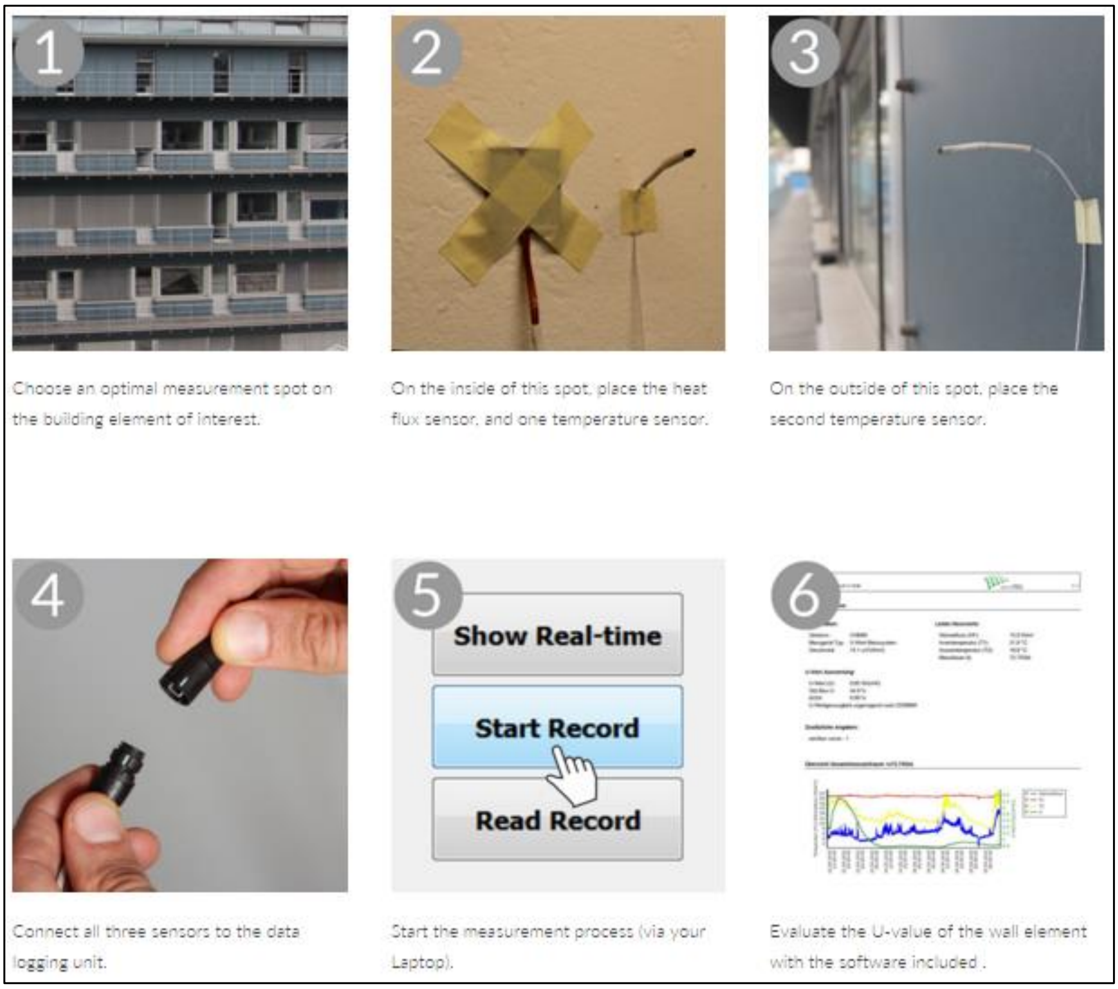


Figure 1: Six steps to conduct a U-value measurement with the heat flux method (source: greenTEG AG)

After identification of the optimal measurement spot (step 1), the inside sensors and the outside sensor should be mounted (step 2 and 3). Now the sensors need to be connected to a data logger (step 4) which then has to be started (step 5). Finally, after a certain period (preferably 72 hours according to ISO 9869), the U-value can be evaluated via a readout software (step 6).

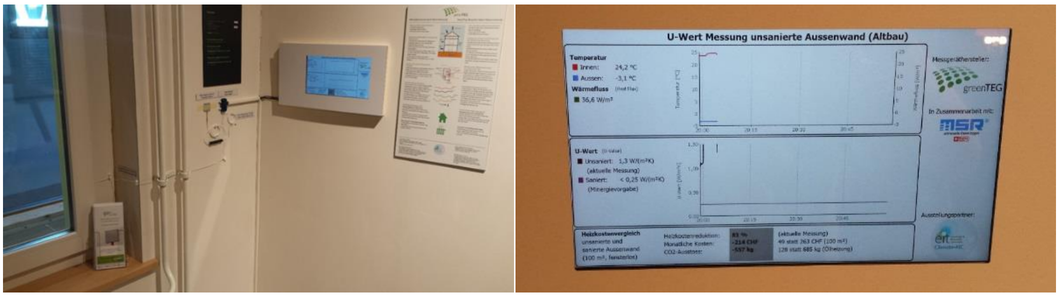


Figure 2: Long time U-value measurement at Umweltarena Spreitenbach according to ISO Norm 9869

The above Figure 2 shows a long time U-value measurement at the Umweltarena Spreitenbach in Switzerland. A U-value device was installed at a not renovated outer-facing wall for demonstration purposes (stable "outside" temperature conditions of 0°C). This is important, as being part of an exhibition raises awareness, especially among other cleantech stakeholders. Furthermore, to showcase that a long term monitoring based on the TEG technology can be successfully implemented into a building concept, could be further used as an entry point for smart home application or any other future prototyping for the use TEG sensors as a "home monitoring" application, i.e. within the NEST environment at EMPA Dübbendorf.

4.1.1.5 Advantages and disadvantages of the heat flux method for U-value measurement

The following table (Figure 3) summarizes the pros and cons of the heat flux method.

Advantages	Disadvantages
• No layout of building element needed • Not based on any assumptions • Best price / performance (accuracy) ratio compared to others • Temperature difference between outside and inside can be low • Most accurate measurement methodology (especially at low U-values)	• No large scale measurements possible • ISO conform measurement takes 72 hours • Not yet a current standard to assess U-value • Heat capacity of the wall influences measurement

Figure 3: Advantages and disadvantages of the heat flux method

4.1.2 Improvement of the current U-Value device

Figure 4 shows an overview of how we further approached this part of the project. **First**, we analyzed where we needed to enhance our existing analytical guidelines for stakeholders interested in U-value measurement, especially in regards to better explaining the (often unknown) ISO standard and deriving new building specific case studies and manuals. **Second**, we reviewed where to improve the underlying technology and measurement concept and executed these incremental enhancement steps. **Third**, we started to steer the redesign process of the U-Value device, with which we aim to create a new product which will be built upon the existing device but will benefit from the learning loop during the recent months (i.e. during the BFE project and other ongoing innovation projects).

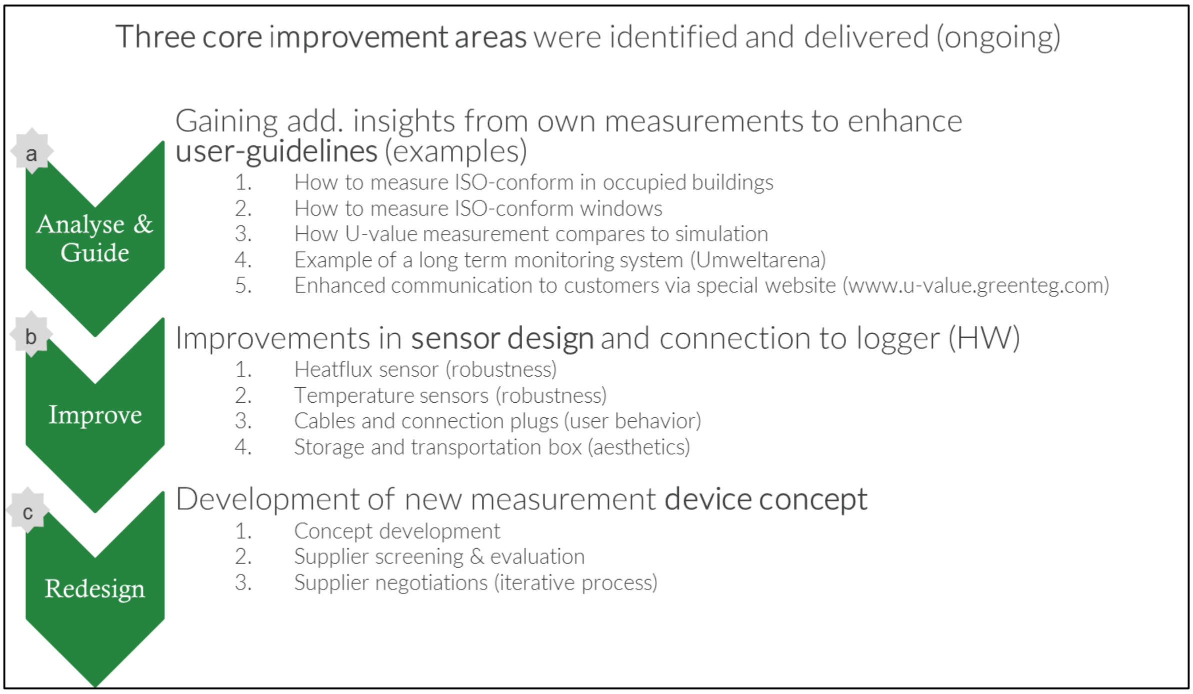


Figure 4: Procedure of developing a user-friendly TEG-based U-value measurement device

The first step "Analyse & Guide" (a) was used to summarize the ISO-conform measurement procedure, we focused here on deriving a standard guideline for occupied buildings and for windows. Furthermore, we developed additional special guidelines after having analyzed stakeholder's feedback and our own results from measurements. These guidelines and recommendations are shown in Figure 5. In Appendix B: Case Studies you can find the German published version of these articles which are so far in particular posted via our homepage and newsletter

	Occupied building	Window
→ Problem	1. User influences the measurement with venting / heating. 2. Solar radiation and climate changes may disturb outside temp. sensor 3. HFS installation on plastered walls often difficult	• Solar radiation disturbs measurement
→ Solution	1. Briefing of residents / extend measurement time 2. Cover of the outside temp. sensor 3. Attach thermal pad between wall and HFS	• Measure during nights • Protect HFS with aluminium foil

Figure 5: Special guidelines and installation recommendations

The left picture of Figure 6 shows the setup of a U-value measurement at a window. The aluminum foil is attached between window and heat flux sensor in order to reflect any potential radiation. Nevertheless, ISO conform measurements can only be conducted during the night. In general, windows are responsible for 10 to 20% of the heat losses in a building during winter time (Axel-Lute, 2009). The thermal performance of a given window glass can vary a lot. The U-value may range from 5 W/m²K for single glazed windows to 0.7 W/m²K for triple glazed windows (VFF-BF, 2014). This means that a lot of energy and costs can be saved by replacing a poorly insulated and outdated window with a window according to the latest standards. However, the exact thermal performance of the glass within a window is hard to examine which makes analyzing the cost-effectiveness of replacement difficult. In-situ measurement data can therefore be of great value. As with other building envelopes, reliable in-situ measurements of glass can be conducted using heat flux meters. However, as the thermal behavior of glass differs from that of walls, a different measurement approach is required, such as adding the mentioned aluminum foil or only conduct measurements during night (ISO 9869-1:2014).

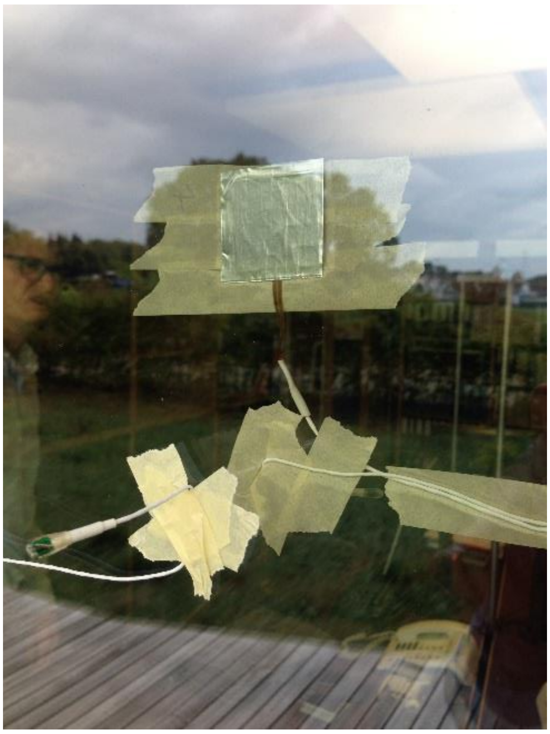


Figure 6: Measurement setup of a window measurement (left) and a wall measurement (right)

The picture on the right in Figure 6 shows the inside setup of a wall measurement. In the top left corner the heat flux sensor and one temperature sensor can be seen. Furthermore, the data logger can be recognized in the bottom of the picture. In order to compensate irregularities at the wall a thermal pad is added between sensor and surface. In general, buildings represent around 40% of the primary energy consumption in most countries and in Europe alone, roughly 3,100 TWh are consumed in buildings every year. A large part of this energy use is due to heating and cooling which means that better insulated buildings could have a huge impact on the overall energy consumption. Still, a lot can be gained in this field since a large part of today's buildings have been constructed before 1980 using low insulation standards. These low insulation standards lead to large amounts of wasted energy and as a result, substantial financial costs to building owners and occupants. To reduce these costs, 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 only commonly exist for the individual building components. The absence of U-values for complete building profiles hinders the determination of existing conditions, justification of investments and validation of completed improvements. Therefore, there is a large need to measure U-values of building elements empirically in order to obtain reliable and precise data on up-to-date U-values at a specific location. The whole setup of a wall measurement can be watched online on our installation video at YouTube(https://www.youtube.com/watch?v=I671gfYb9ko&feature=youtu.be).

To make it clearly understandable for interested stakeholders, we summarized these insights in a simple user manual, which can be downloaded on our websites (available in German and English). Furthermore, many stakeholders were interested in the ISO 9869 guideline but did not had access to it. Therefore, we summarized all important points in 2-page summary (see Appendix A: ISO 9869 Summary).

Furthermore, we identified in which conditions it is recommendable to make a measurement instead of a calculation or simulation to find out the right U-value. We carefully reviewed why there could be differences between calculated and measured U-values.

Three scenarios we reviewed in more detail:

1. Old house without plans
2. Old house with plan
3. Newly build house

In all three cases, a measurement is possible. If there is no plan available, the simulation or calculation is based on assumptions, which could lead to high differences in comparison to measurements. If plans are available (case 2 and case 3) the difference should not be big. A higher U-value in measurement at an old house could highlight that the insulation got worse after decades. A difference between the U-values at a newly build house could highlight that incorrect installation of insulation material has caused problems. Figure 7 illustrates the outcome of this analysis.

	1. Old house without plans	2. Old house with plans	3. Newly build house
Measure	☑	☑	☑
Simulation/ Calculation	? > *only assumed values*	☑/?	☑
Result	**High difference**	**Same** / **Different** (insulation got worse)	**Same** (unless incorrect installation)
Value added through U-Value measurement	**Range often too high with calculation**	**Insulation gets worse after decades → verify**	**Only if questionable installation**

Figure 7: Application cases of measurements and calculations

In order to inform the public and interested stakeholders with a lean, simple and enhanced web presence, we created a subpage, which only addresses stakeholders in the building sector and is available in German and English. A screenshot of the homepage is shown in Figure 8.

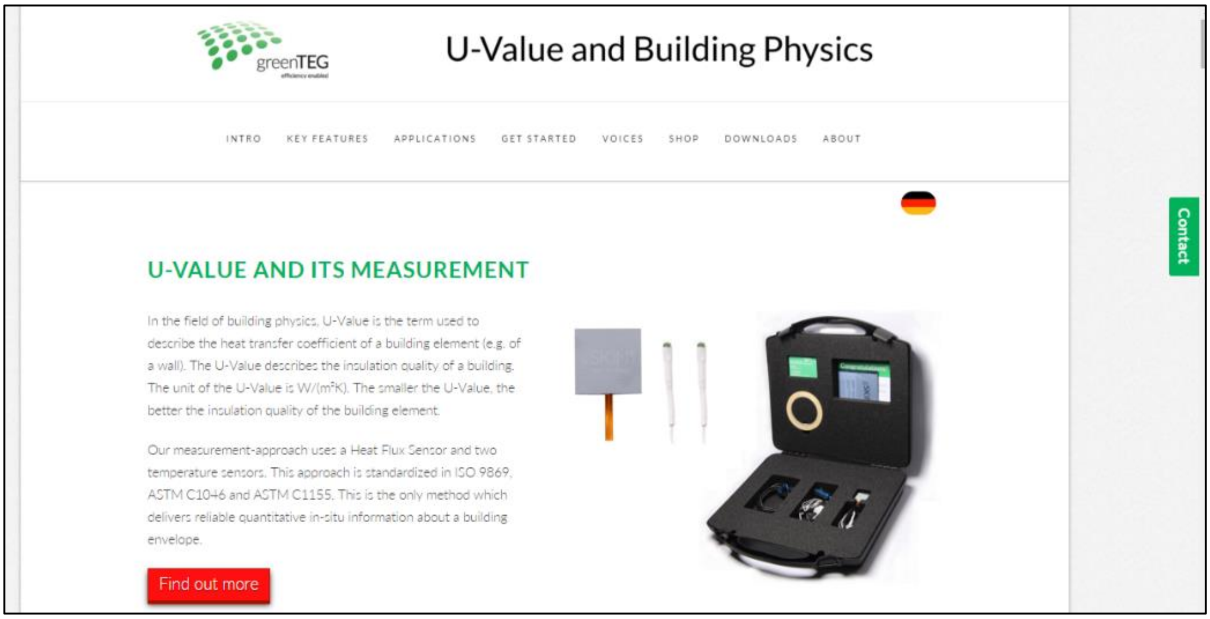


Figure 8: Screenshot of the new subpage "U-value and Building Physics"

During the second process step (b) we focused on improvements in sensor design and connection to the data logger. Before elaborating on these points, we will give a short introduction to the general underlying technology and physics.

Heat flux technology

Heat Flux is the rate of heat energy that passes through a surface. Depending on the exact definition of heat flux, its unit can be expressed as either W/m^2 or W. In Figure 9 different types of heat fluxes are illustrated. Heat fluxes can have their origin in conduction (HF through solids), convection (HF through liquids and gases) and radiation (HF through electromagnetic waves).

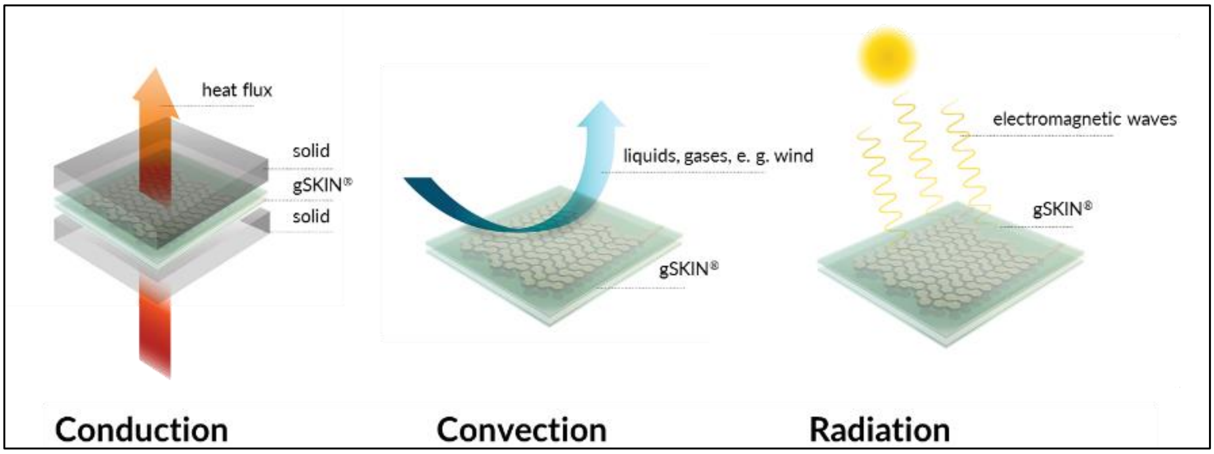


Figure 9: Different types of heat flux

1. **Conduction** is heat flux through liquids and gases. Heat flux sensors can measure conductive heat flux. Examples of conductive heat flux are:
    - Touching a hot cup of coffee.
    - Thermal influences in precision instruments.
    - Measurement of heat output from chemical reactors
2. **Convection** is heat flux through liquids and gases. Heat flux sensors can measure convective heat flux. Examples of convective heat flux are:
    - Feeling much colder when it is windy
    - Feeling much colder in water of 25°C than in air of 25°C
    - Sensing principle in heat flux based mass flow sensors

3. **Radiation** is s heat flux through electromagnetic waves. Heat flux sensors can measure radiative heat fluxes. examples of radiative heat fluxes are::
    - Feeling hot when standing close to fire.
    - Measurement of solar power.

Heat Flux Sensors are based on the Seebeck effect. When heat passes through the sensor, the sensor generates a voltage signal. This voltage signal is proportional to the heat passing through the sensor. An illustration is shown in Figure 10.

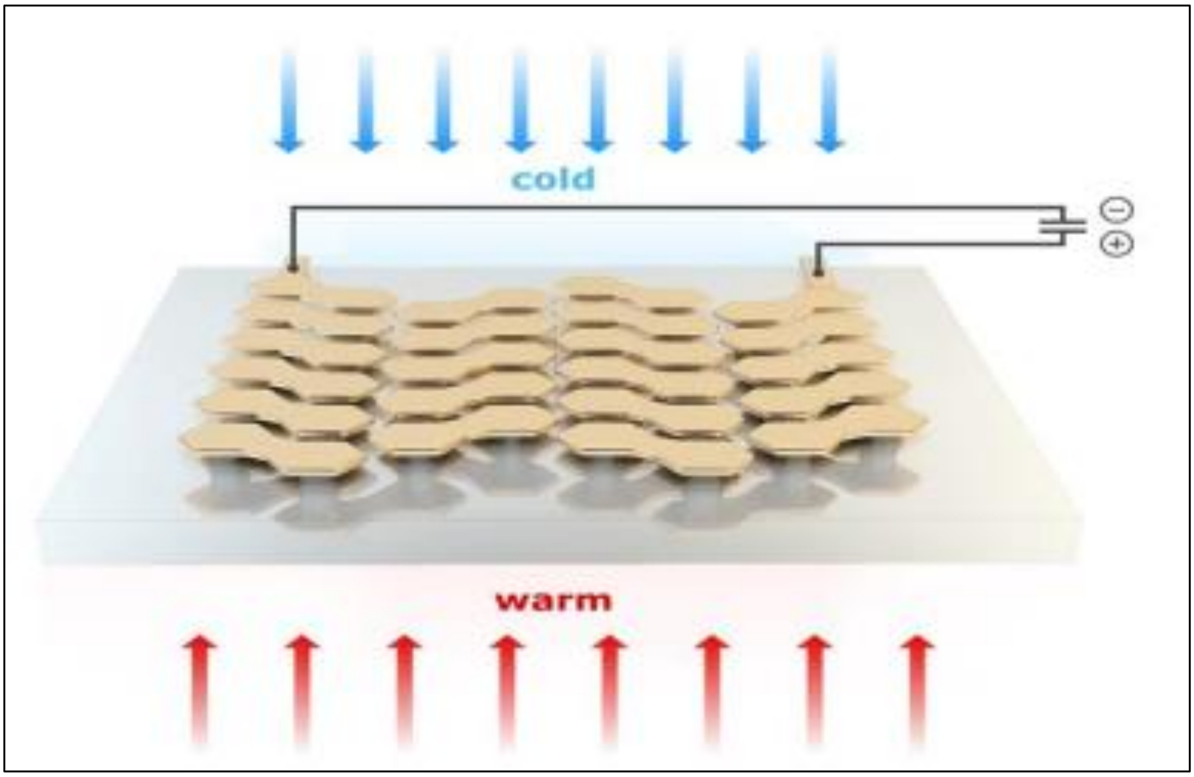


Figure 10: Illustration of the Seebeck effect

Figure 11 shows the roughly saying 6-step production process and the layers of the heat flux sensor developed and produced at greenTEG.

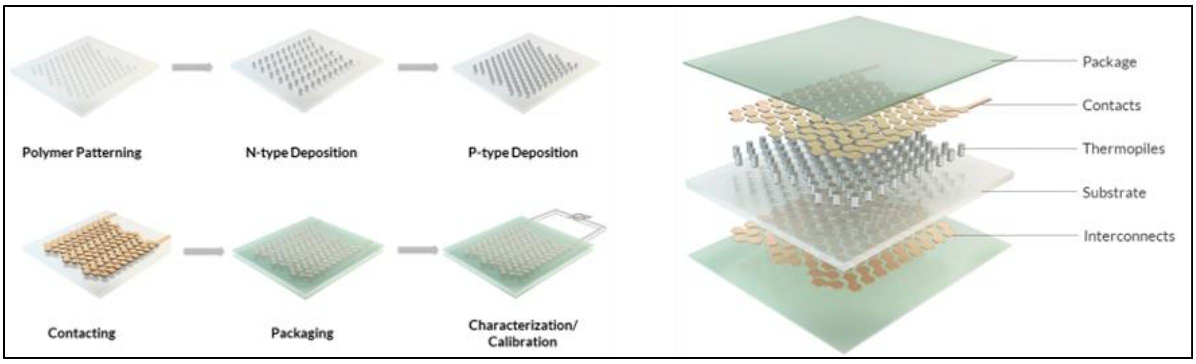


Figure 11: Production process and layers of gSKIN heat flux sensor

As mentioned before, greenTEG´s Heat Flux Sensors are highly sensitive Seebeck sensors. The sensitivity of a Seebeck sensor depends on the thermocouple material quality used in the sensor and the number of thermocouples used. A thermocouple consists of two separate thermopiles (n-type and p-type). The thermopiles in the Heat Flux sensors are based on BiTe (Bismuth Telluride). These thermopiles are highly integrated in the sensor substrate, which leads to high sensitivity sensor modules.

Further details on this production process are confidential.

Technology improvements

Several improvements regarding the sensors were conducted. The loose cables at the heat flux sensor got replaced by a flex print cable and the silicon embedding process got optimized. Both improvements were identified to increase the robustness and stability of the heat flux sensor (see number 1 in Figure 12). In addition, for increasing the robustness of the temperature sensors, we identified the opportunity to add a shrink tube around these sensor heads (see number 2). Furthermore, the plugs were bonded because users tended to untwist these, which sometimes led to a reconnection of the plug and the cable (see number 3). In order to improve the handling and the transportation of the U-value device, the old carton box got replaced by a tailored plastic box (see number 4). All major changes are summarized in the table in Figure 12.

Product-Part	Improvement	Before	After
1. Heat Flux Sensor	- Flex print cable / PCB mounting and changes in silicon embedding / cutting process → Cable can't break easily anymore		
2. Temperature Sensor	- Adding of shrink tube → Protection against breaking		
3. Plugs / Connection	- Bonding → Customers can't untwist		
4. Transportation Box	- Replacement of carton box → Easier to carry and more protection		

Figure 12: Sensor and other design improvements

The last process step was to design (c) and development of a new measurement device (HW) concept. In order to further evaluate and build a (confidential) concept on how to improve the current hardware for developing a multichannel, wireless and display enabled device, we used the knowledge gained in the previous work steps to better understand potential application areas for existing and future user groups. A first draft of the new measurement device system is shown in Figure 13.

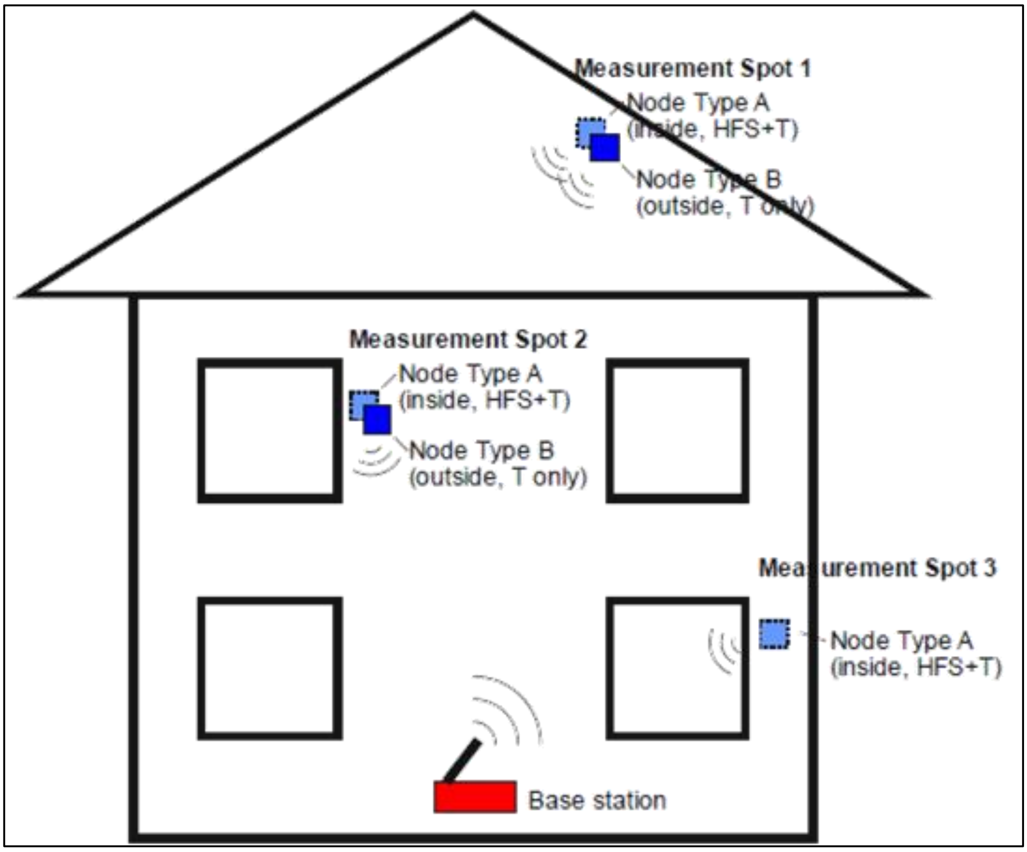


Figure 13: Scheme for U-Value Kit 2.0

Existing and potential users and stakeholders have mentioned, that if they want to measure multiple building elements at the either same time, they have to get many U-Value Kits, which is rather expensive, or measure one after another, which is rather time consuming. Therefore, the need to develop a device, which can measure at multiple spots simultaneously, was clearly given. In Figure 13 three different spots are illustrated: one in the ground floor, one in the first floor and one at the roof. In order to avoid that cables are being mixed up, all sensors are connected wireless to a base station, which is located in one central spot. Many technical barriers, such as how the signal overcomes the distance, how to account for different materials between base station and knot, how to assure that every knot receives its own energy supply, and other initial customer responses were further verified in distinguished customer interviews, and are already or will need to get solved. At this time, no additional data and insights can be shared publicly.

After this underlying "groundwork", we developed a specification sheet for potential suppliers. We started searching these via web, fairs and networks. Finally, we reviewed a selected group of potential suppliers during emailing and phone calls. This analysis was followed by an internal, iterative update and review round. After several discussion rounds with a long list of potential suppliers, we are now further discussing with only 2 suppliers a detailed development roadmap.

4.2 Other possible application areas of heat flux sensors within the broader building sector

4.2.1 Heat flux sensors in Phase Change Materials (PCM) – general application

Nowadays development of novel materials including PCM relies on precise calorimetric measurements. Additionally understanding heat capacities and microstructural changes is of great importance. greenTEG' s insights of the market show significant demand for the technology with use of heat flux sensors. Therefore, we reviewed possible market applications. Figure 14 shows the basic principle behind the PCM Technology. When temperature rises (during the day), the material absorbs heat energy and it melts. Now the PCM is in a liquid stage and as temperature falls (during the night), the PCM solidifies and releases heat energy back into the environment.

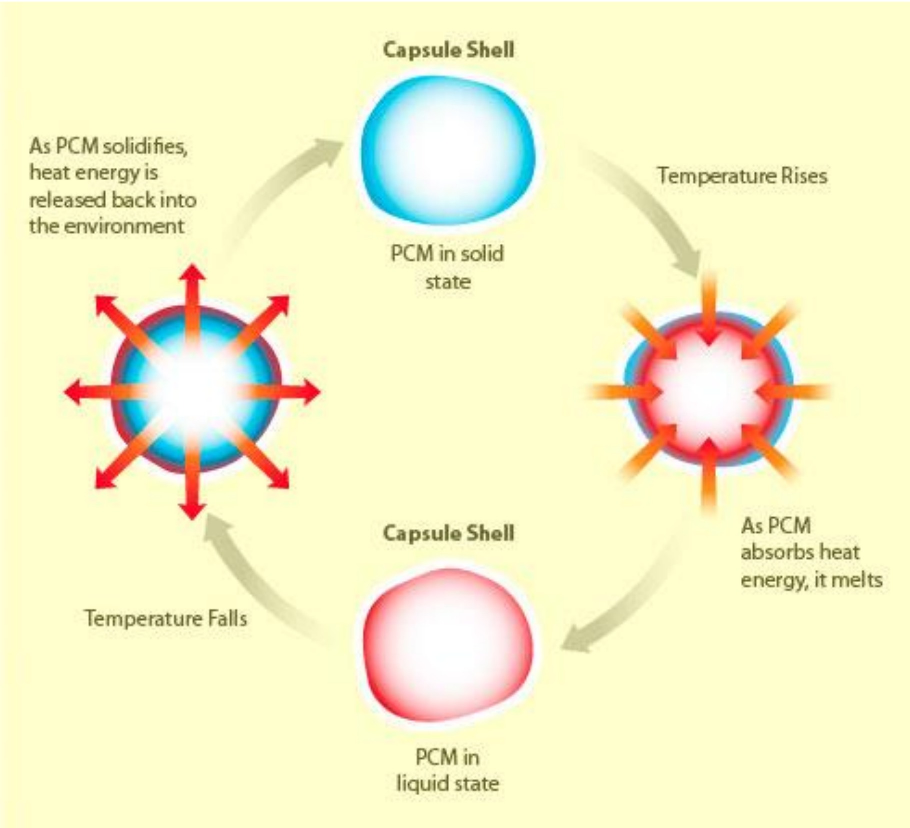


Figure 14: Basic Principle of Phase-Change-Materials (PCM) (Ticsay, 2010)

Heat flux measurement is important in understanding and optimizing PCM and other thermal storage materials. PCMs are nowadays very well characterized by the powerful method of Differential Scanning Calorimetry (DSC). However, the characteristics of the phase change material itself in the specific application can be different. For optimal integration in the application, the characteristics need to be known. With heat flux sensors, calorimetric measurements directly at the application become feasible.

Additionally, to further review specific market applications for our TEG technology, we reviewed existing PCM literature and identified the following **advantages of heat flux sensors** for PCM system analytics:

- It is possible to integrate thermal storage characterization directly into R&D and monitoring applications, as well as determining the thermal conductivity of material.
- The small sized heat flux sensors with low thermal resistance can be integrated into heat exchanging systems and measurement setups to measure the heat flow into and from any system of interest.
- Already in the range of today's application possibilities is the use of the U-Value device to characterize thermal storage capabilities and release characteristics of materials and walls vs. air and other media with high thermal transfer coefficient.

To set a foot in the market we reached out to potential PCM R&D customers and stakeholders in order to gain additional insights and to review their level of interest. Besides customers who used our sensors to display efficiency gains in their PCM installations, we have already sold sensors to research institutions as well as industrial companies and their R&D departments. By serving this new segment of clients, we have realized that we need to develop own detailed research results and publish them in order to gain new customers and increase the trust in our system.

4.2.2 Heat flux sensors to monitor PCM performance in existing building – insights from a case study

For getting new research results and “in situ” data, we teamed up with GLASSX to gain additional insights from long-term measurement during a field project. The already obtained results are very promising and showing valuable insights into the PCM facade system. The research aim of this field project is to show the advantages of a PCM façade and the monitoring capabilities of heat flux sensors. The whole measurement was carried out between 3rd of September 2015 to 2nd of October 2015 (4 weeks).

Measurement set-up:

The measurement of the heat flux and temperature was conducted at the south side of the building. Four U-Value measurement devices were installed at the PCM window and the regular window (2 at each, one at the bottom, one at the top), located next to each other. Each of the measurement set-ups included:

- 1 Heat Flux XO sensor
- 2 temperature sensors
- 1 data logger

For each set-up, the heat flux sensor was mounted on the inside of the window using regular adhesive tape. One of the two temperature probes was mounted in close proximity to the heat flux sensor. The second temperature probe was mounted on the outside in roughly the same position as the heat flux sensor. In addition, each of the heat flux sensor was covered with aluminum foil in order to minimize the influence of sun radiation on the measurement results. The whole setup was connected to the data logger which recorded simultaneously the outside temperature (T2), temperature inside (T1) and the heat flux (HF).

Figure 15: Marché International AG building and outside view of the measurement set-up; source: (Hellwig) left picture, (greenTEG, right picture)

First insights/results:

The results of the measurements provide great insight into the technology and behavior of the PCM. As the main constituent of PCM is water - during sunny days the material absorbs the energy and gradually melts. Most of the time the PCM is semi-molten during the measurement period. At the temperature of about 26 to 27 ºC PCM is fully molten and at about 25 ºC it becomes solid. These temperature differences are usually really hard to account for but during our measurement it was possible to show the transition temperature of the PCM.

During the night, when temperatures drop, the material solidifies and releases the heat into the room. The results show that for PCM the heat flux is mostly negative, which means that there are almost no heat loses (during the day and night). The negative heat flux is higher during the night.

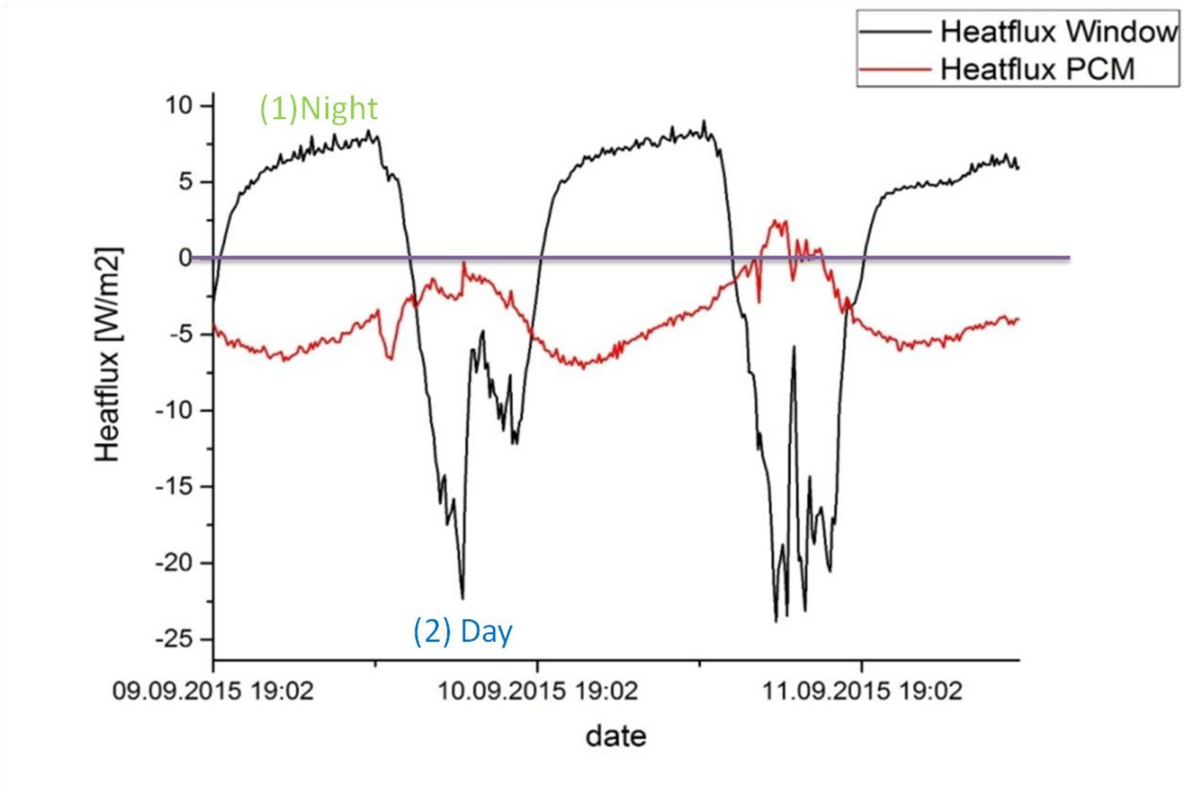


Figure 10: Results of the heat flux measurement for the PCM (red) and regular window (black)

The figure above clearly shows the results in heat flux for the PCM (red) and for the regular window (black). During the night (1) the regular window releases the heat into the outside while the PCM releases the energy into the room. During the day (2) the window allows for the heat to flow into the room, while PCM stores the energy and releases it later during the night. At some points the values of the heat flux slightly change. The variations can be accounted for the ventilation of the room or the presence of office workers pursuing their works tasks nearby.

The carried out measurement leads to the following conclusions:

- The PCM window provides better insulation capabilities than in comparison with a regular window.
- The installation of PCM windows can lead to considerable energy savings in a building.
- Heat Flux sensors allow accurate measurements of heat fluxes in different types of materials including PCM and regular glass.
- While conducting the heat flux measurement, it is important to take into account human factors, heating times and influence of sun radiation.

The additional goal is to publish this study in scientific and practitioner-oriented journals in the beginning of 2016.

4.3 Other applications: Heat flux sensors in battery cell systems

Nowadays, Li-Ion batteries are getting more and more important as a source for energy storage. Latest since the market entry of Tesla, the automotive industry relies on that storage system. In addition, the energy sector perceives Li-ion battery as one of the most interesting solutions for grid capacity variation problems.

Nevertheless, disadvantages of batteries are also well known. The charging process is often taking too long and the capacity is drastically decreasing after a certain amount of charging cycles.

It is well known that the lifetime of a battery strongly depends on its inner temperature. The temperature is increasing by the charging and discharging process. Hence, the limiting factor for the charging speed is the increase of the inner temperature. The determination of the inner temperature of a battery with the common methods is either not reliable or needs complex equipment and time-consuming processes.

greenTEG was able to show, that when using heat flux sensors on the surface of the battery (see Figure 17), thermal phenomenon, occurring in the battery, can be determined fast and easily.

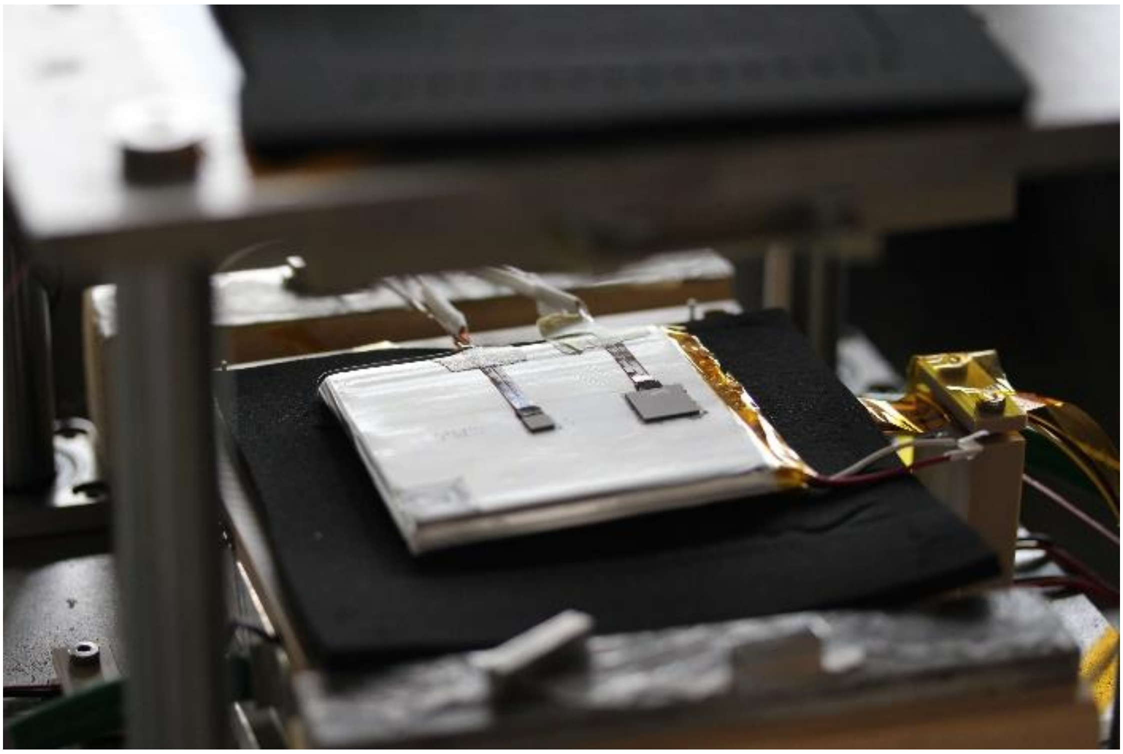


Figure 16: View on experiment setup with 2 heat flux sensors and temperature sensor

For example, the battery was charged and discharged by 1C (1 x Charge with 2 A h). Temperature and heat flux at the cooled battery surface were recorded (see Figure 17). While the temperature signal is constant, a well-defined heat flux signal was obtained. From this signal, the inner temperature of the battery can be determined.

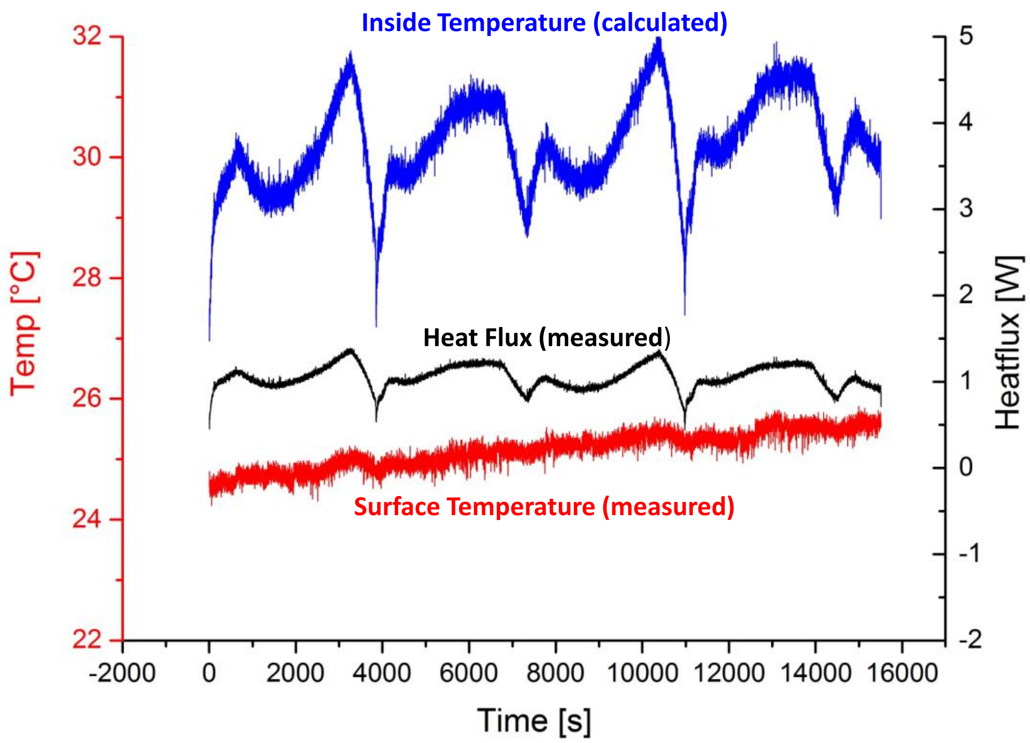


Figure 17: Measured heat flux and battery surface temperature during several charging and discharging cycles for the determination of the inner temperature of the battery.

Another problem in the battery business is the state of health (SOH) determination. This parameter is urgently needed for displaying information of how long the battery can be used until it needs to be recharged. In addition, the information of how long the battery will live can be determined by knowing the state of health. This is important for its second use (second life, often not within the automotive sector).

Studies have shown that it might be possible to determine the SOH by the entropy profile based on charging and discharging of a battery. However, this method requires large stationary battery calorimeter. greenTEG was able to show, that this entropy profile can also be recorded with simply placing the heat flux sensor to the tow electrodes of the battery. Figure 18 shows an entropy profile measured by a heat flux sensor while charging and discharging of a polymer-based battery. The black vertical lines indicates Li-phase transitions in the electrodes, which will shift up on aging of the battery.

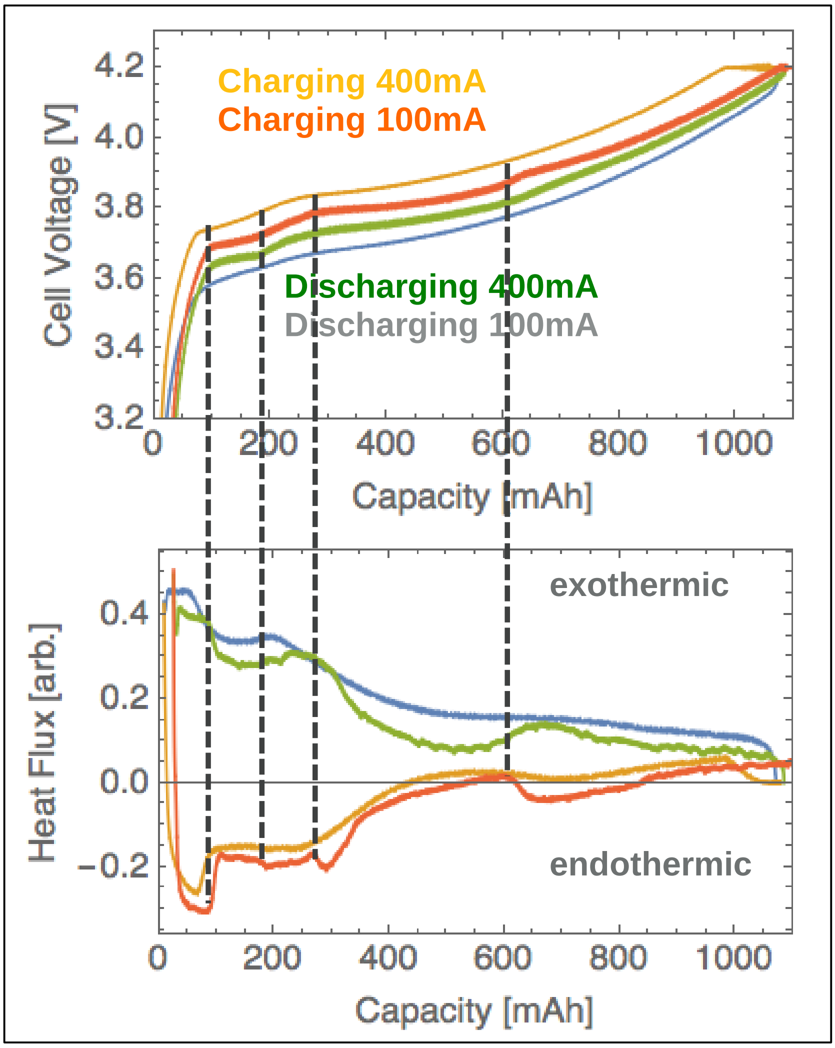


Figure 18: Heat flux entropy profile measured by a heat flux sensor up on different charging and discharging currents of the battery.

Based on these initial activities within a new industry sector, we are already confident that due to the already received interest form automotive manufacturers and suppliers as well as from many research institutes dealing with thermal battery investigations, the TEG technology can be further applied and customized to this new industry segment.

4.4 Publication of project results

In order to publish project results, decided that it would be best to funnel publication activities not into “mainstream” print / online publishing but into fostering our presence at fairs where we reach out to R&D experts and potential OEM customers in fields broader than the building sector (but including this sector as well).

We therefore fostered our presence at the following fairs:

- Sensor & Test Nürnberg
- EST Karlsruhe
- World of Energy Solutions Stuttgart

Figure 19: greenTEG fair booths (top left corner: Sensor & Test Nuremberg; bottom left corner: EST Karlsruhe; right side: World of Energy Solutions Stuttgart)

Sensor & Test is a measurement and sensor fair. It provides a comprehensive overview of system expertise for measuring, testing, and monitoring tasks in all industries. greenTEG focused on finding different heat flux application in the industry as well as partners to further collaborate with for the U-Value KIT 2.0 development.

EST Karlsruhe is a platform for internationally renowned scientists and entrepreneurs from the energy sector. At the EST 2015 experts from all over the world discussed the topics of renewable energies, energy efficiency and systems, storage & networks over three days. Employees from greenTEG carried out live U-value measurements and got into contact with people from building sector as well as research and development experts from fields such as battery or PCM.

World of Energy Solutions is a leading international conference and trade fair for the convergence of energy generation, storage systems and mobility solutions. It addresses all players involved in the manufacturing of battery and energy storage systems for mobile and stationary implementation. greenTEG showed the application of heat flux sensors in the battery area and additional contacts in this segment were established.

The traditional reach out of project results can only be scattered around the sub-streams, i.e. relaunching the U-Value Kit website in German and English language and raising awareness among newly identified key customer markets. In a similar approach, we intensified our communication in the field of PCM and battery. We summarized our findings from the case studies, guidelines and own measurements (winter 2014/ spring 2015) in short articles for journals.

A list of examplatory articles can be found in Appendix C: Publications as well as examples from the English-language internet journal scitechnews and the German language journals Baubiologie and Umweltperspektiven.

5. Diskussion / Würdigung der Ergebnisse / Erkenntnisse // discussion / results / findings

For measuring the U-value greenTEG applies the so called heat flux method, which utilizes two temperature sensors and one heat flux sensor to measure in-situ the U-value of a given building envelope. This methodology is standardized according to ISO 9869 (Thermal insulation – Building elements In-situ measurement of thermal resistance and thermal transmittance: 2014; Appendix A: ISO 9869 Summary).

To get a solid understanding of the full potential of this method next to other established U-value evaluation methodologies, literature research in regards to three other methods was completed. The top three **competitive U-value evaluation methodologies** are:

1. Thermography, sometimes used to derive the U-value from thermal images. But in most cases used as a qualitative view on a given building, i.e. to detect thermal bridges
2. Calculation method, which uses general databases and layout plans to calculate the U-value. This is the most common method as it is the fastest one to conduct a rough building envelope energy efficiency assessment
3. Temperature based method, which uses temperature sensors and assumptions to evaluate the U-value. This method has cost advantages due to lower costs of temperature sensors, but lacks in terms of accuracy and cannot rely on a proven ISO documented measurement setup.

In summary, the advantages of the heat flux method are that no layout plans of the measured building element is needed and no assumptions need to be made. In addition, the price/ performance (accuracy) ratio is best compared to other competitive methods. Furthermore, the temperature difference between outside and inside can be low and it is overall the most accurate methodology, especially at low range U-values.

To **improve the underlying technology** and specs of the U-Value device we followed a three step approach:
First, insights from own measurements and user feedback were used to enhance **user-guidelines**. For example, a new manual, adapted to the ISO 9869 norm, was written bilingually. Many field pilots were conducted within the building and general insulation market sector to review the different application areas of the U-value and heat flux measurement technology. Furthermore, an individual website for U-value measurements was launched to inform stakeholders about the technology.
Second, the **sensor design and logger connection technology** was improved. Hereby changes in the cable connection, PCB mounting / silicon embedding and cutting process of the heat flux sensor were made in order to increase its stability and robustness. Moreover, to increase the robustness of the temperature sensor a shrink tube was added to this. Connectors were bonded and the carton transportation box was replaced by a tailored, professional plastic box.
Third, a **concept for the next generation of** the U-Value device and its **underlying technology** was developed based on findings from previous process steps. According to our research and investigations, a new device should be able to do simultaneous measurements at multiple spots and have a wireless connection (i.e. using Zigbee technology) between sensors and the base station. According to these findings, features of the current device were summarized within a confidential specification sheet. At the same time, a supplier search was started and first discussions were held.

We identified as main problems for a faster user uptake of the new heat flux enabled U-value device technology (in the building industry) mainly three interconnected issues:

a) The general laws of thermodynamic are very complex and their application in an easy to handle end-user device is a very challenging task
b) Even the ISO norm 9869 does not specify or nor guides users for specific questions in regards to mounting of the sensors, handling of different types of surfaces, etc.
c) In regards to the general laws of thermodynamic (see a)), especially in the case of walls with high heat storage capacity, systems react very slowly. By combining this with daytime solar radiation, this leads to even more complex measurement setups and interpretation challenges and is therefore preventing the development of faster measurement cycles (which would be, for example, 1/40 of the current time needed, which is instead of 72h less than 2h)

Next to the application of heat flux sensors for the U-value measurement device, the project aim was to find other application areas. Here, the *first* focus was set on other building relevant areas, where the usability of heat flux sensors for Phase-Change-Materials (PCM) was evaluated. In this context, heat flux sensors can be integrated in R&D and monitoring applications, into heat exchanging systems or can be used according to the already existing U-value measurement device to characterize thermal storage capabilities. Regarding the last application area, a field-test over four weeks with a PCM façade developer was conducted with promising results. This case study shows that greenTEG's sensors are able to identify the thermal storage capabilities of PCMs very well.

To further identify use cases of our TEG technology in this nascent PCM market, we struggled so far mainly with the early development status of the PCM market itself. As many PCM application areas still need to find their suitable (end-) customer areas themselves, adding ("expansive") measurement equipment is in some cases not yet perceived as necessary within the industry, although reliable measurement technologies could boost the credibility of the performance enhancements due to PCM.

Furthermore, another application area, outside the building sector was reviewed in regards to battery cell systems. The lifetime of a battery strongly depends on its inner temperature. Common methods to measure this parameter are either not reliable or need complex equipment and time-consuming processes. Furthermore, the battery industry nowadays uses large stationary battery calorimeters to determine the State of Health (SOH). For the battery industry, our initial insights are as following: First, greenTEG's research has shown that thermal phenomena inside a battery can be determined fast and easily when mounting a heat flux sensor on the surface of a battery. Second, an entropy profile can also be recorded with simply placing the heat flux sensor to the tow electrodes of the battery, which can be used to determine the SOH.

To further identify use cases of our TEG technology within this huge market, these above mentioned application areas need to be further researched within our own R&D labs as well as with other academic and industry partners. As the field of battery technology and market access of nascent technologies, especially for the automotive industry, is already heavily regulated mostly due to safety and security reasons, this needs to be further addressed with strong partners with access to the relevant stakeholders.

In order reach out to R&D experts in building as well as non-building areas, greenTEG visited several fairs. Products and research results were presented at Sensor & Test Nürnberg, EST Karlsruhe and World of Energy Solutions Stuttgart. Furthermore, besides many articles and short text passages linked to the U-Value device and its underlying technlogoy, a journal article about the PCM field pilot was started and will be soon published.

6. Schlussfolgerungen, Ausblick, nächste Schritte nach Projektabschluss / outlook and next steps

It can be concluded that there is a market for greenTEG's U-Value device and its underlying core technology, the TEGs. There is a distinct group of users, mostly so called early adopters, who uses the TEG technology mostly for U-value measurements. Furthermore, there is also a certain potential for greenTEG's technology in other application areas such as PCM or battery monitoring.

In order to gain additional insights for applying the U-value measurement technology with end-users such as energy consultants, building physics and insulation material manufacturers, further research and in-field application of the technology is needed. For example, we need to better showcase and defend about the value-add coming from heat flux measurements of historic buildings where little insights in regards to the building envelope material and its consistency is available. For doing this, the most suitable solution for the future are conducting more field tests and linking their results to comparisons with material databases ("Bauteilkatalog") and rough estimations based on the year the building was build (i.e. often used for GEAK assessments). By adding and aligning reputable partners for these tasks into a sort of consortium or task group, the heat flux technology applied for certain use cases in the building sector could soon realize a higher penetration rate and a wider use by experts within the industry.

In the direct future, we will further work on entering new markets and continuing penetrating current markets. It is still necessary to firstly continue the product development process and secondly to increase marketing activities by e.g. writing case studies for this purpose. Publishing the new PCM case study in journals and online channels will be one of these distinct marketing steps. Moreover, the development of the new U-Value device is going to be finished in the soon future and after fully functioning prototype used for early adopter user testing, an enhanced U-value device "2.0" will be brought to market maturity. For this new device, which would have also a function to shorten measurement cycles by abandoning certain ISO norm criteria but still measuring U-values and heat fluxes with a certain confidence interval, new user groups such as sales force personal for insulation material developers and manufacturers could be also an interesting market.

7. References

Adhikari, R. S., Lucchi, E., & Pracchi, V. (2012). 28th International PLEA Conference on vertical walls in the historical buildings vertical walls in the historical buildings. Paper presented at the Proceedings. *28th International PLEA Conference on Sustainable Architecture + Urban Design: Opportunities, Limits and Needs - Towards an Environmentally Responsible Architecture.* PLEA.

Albatici, R., Tonelli, A. M., & Chiogna, M. (2015). A comprehensive experimental approach for the validation of quantitative infrared thermography in the evaluation of building thermal transmittance. In *Applied Energy* (pp. 141, 218-228).

Al-Hamoud, M. (2005). Performance characteristics and practical applications of common building thermal insulation materials. Building and Environment.

Asdrubali, F., D'Alessandro, F., Baldinelli, G., & Bianchi, F. (2014). Evaluating in situ thermal transmittance of green buildings masonries—A case study. In *Case Studies in Construction Materials* (pp. 53-59).

Axel-Lute, M. (2009). *Three steps to super-efficient windows*. Abgerufen am 2. April 2015 von Green America: http://www.greenamerica.org/livinggreen/windows.cfm

Balaras, C., & Argiriou, A. (2002). Infrared thermography for building diagnostics. In *Energy and Buildings* (pp. 171-183).

BFE, B. f. (2002). *U-Wert-Berechnung und Bauteilekatalog Neubauten.*

Biddulph, P., Gori, V., Elwell, C. A., Scott, C., Rye, C., Lowe, R., & & Oreszczyn, T. (2014). Inferring the thermal resistance and effective thermal mass of a wall using frequent temperature and heat flux measurements. In *Energy and Buildings* (pp. 78, 10-16).

Boyano, A., Hernandez, P., & Wolf, O. (2013). Energy demands and potential savings in European office buildings: Case studies based on EnergyPlus simulations. In *Energy and Buildings* (pp. 19-28).

Desogus, G., Mura, S., & Ricciu, R. (2013). In *Comparing different approaches to in situ measurement of building* (S. 2613-2620).

Dwyer, T. (2012). *Simple thermal analysis for buildings, The CIBSE Journal CPD Programme*. Retrieved March 26, 2015, from http://www.cibsejournal.com/cpd/2013-01/

Energy.gov. (2012). *Thermographic Inspections*. Retrieved March 6, 2015, from http://energy.gov/energysaver/articles/thermographic-inspections

FLIR. (2009). *Press release: FLIR Reporter Building Software*. Retrieved March 6, 2015, from http://www.flir.com/thermography/americas/us/content/?id=17966

Fokaides, P., & Kalogirou, S. (kein Datum). Application of infrared thermography for the determination of the overall heat transfer coefficient (U-Value) in building envelopes. In *Applied Energy* (S. 4358-4365).

Fumo, N. (2014). A review on the basics of building energy estimation. Renewable and Sustainable Energy Reviews.

Global Energy Assessment. (2009). *Towards a sustainable future*. Retrieved February 23, 2015, from http://www.globalenergyassessment.org/

Gustaffson, S. (1991). Transient plane source techniques for thermal conductivity and thermal diffusivity.

Hellwig, H. (kein Datum). Von http://glassx.ch/fileadmin/_migrated/content_uploads/01_Marche_International_Sued_01.jpg abgerufen

IEA. (2015, November 03). *FAQs: Energy efficiency*. Retrieved February 19, 2015, from http://www.iea.org/aboutus/faqs/energyefficiency/

IRT Surveys . (n.d.). *Analyse & Quantify Thermal Images - IRT Surveys*. Retrieved March 6, 2015, from http://irtsurveys.co.uk/analyse-and-quantify-thermal-images/

ISO 6946 : 2007. (n.d.). Building components and building elements - Thermal resistance and thermal transmittance - Calculation method.

ISO 9869-1:2014 . (kein Datum). Thermal insulation- Building elemnts - In-situ measurement of thermal resistance and thermal transmittance.

KIMO. (2011). *TM 200 U thermometer Special determination of U coefficient*. Retrieved April 9, 2015, from http://www.kimo.se/pdf/FT-TM200-U.pdf

Kneifel, J. (2010). Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings. In *Energy and Building* (pp. 333-340).

Lahiri, B., Bagavathiappan, S., Jayakumar, T., & Philip, J. (2012). Medical applications of infrared thermography: A review. In *Infrared Physics & Technology* (S. 221-235).

M'Sirdi, N., Namaane, A., Howlett, R., & Jain, L. (2012). proceedings of the 3rd International Conference on Sustainability in Energy and Buildings (SEB'11). *Sustainability in energy and buildings.* Berlin: Springer.

Murray, S., Walsh, B., Kelliher, D., & O'sullivan. (2014). Multi-variable optimization of thermal energy efficiency. In *Building and Environment* (pp. 98-107).

Nardi, I., Sfarra, S., & Ambrosini, D. (2014). Quantitative thermography for the estimation of the U-value: state of the art and a case study. *Journal of Physics: Conference Series*.

Pearson, C. (2011). *A BSRIA Guide: Thermal imaging of Building Fabric.* Bracknell: BSRIA.

Rodríguez-Soria, B., Domínguez-Hernández, J., Pérez-Bella, J., & Coz-Díaz, J. (2014). Review of international regulations governing the thermal insulation requirements of residential buildings and the harmonization of envelope energy loss. In *Renewable and Sustainable Energy Reviews* (pp. 78-90).

Spohn, B. (2008). *In Field Determination of Installed R-Value,*. Retrieved April 9, 2015, from Testo: https://trutechguy.files.wordpress.com/2012/10/u-value-probe-presentation1.pdf

Tadeu, A. S. (2015). In-situ thermal resistance evaluation of walls using an iterative dynamic model. Numerical Heat Transfer; Part A: Applications, 67(1).

Testo. (2014a). *Humidity/temperature measuring instrument*. Retrieved April 6, 2015, from http://www.testo.com.cn/resources/media/global_media/produkte/testo_635_1/testo-635-0981-9624.pdf

Testo. (2014b). *U-value measurement on a wall of unknown materials with the testo 635*. Retrieved April 1, 2015, from http://issuu.com/testolimited/docs/u-value_measurement_using_the_testo

Testo. (n.d.). *Temperature probe for calculating U value, application information*. Retrieved April 9, 2015, from http://www.testo.com.cn/resources/media/global_media/probes/temperature/0614_1635__ai__0973_0455_en.pdf

Thermalvision. (2014). *Thermography of buildings (myth no 4)*. Retrieved March 6, 2015, from http://www.thermalvision.ie/2014/09/thermography-of-buildings-myth-no-4/

Ticsay, C. (2010, November 10). *illumin.usc.edu*. Retrieved November 2, 2015, from https://illumin.usc.edu/2/get-that-34just-right34-feel-incorporating-phase-change-materials-into-textiles/

Tipperary Energy Agency. (2011). *Module 3.3: Calculation of U-value Simple construction without thermal bridging*. Retrieved March 26, 2015, from http://tea.ie/wp-content/uploads/2011/09/Module-3.3-Calculation-of-U-value-simple-construction.pdf

Tipperary Energy Agency. (2011b). *Module 3.4: Calculation of U-value Construction with thermal bridging*. Retrieved March 24, 2015, from http://tea.ie/wp-content/uploads/2011/09/Module-3.4-Caclulation-of-U-value-thermalbridging.pdf

Tzifa , V., Papadakos, G., Papadopoulou, A. G., Marinakis, V., & Psarras, J. (2014). Uncertainty and method limitations in a short-time measurement of the effective thermal transmittance on a building envelope using an infrared camera,. *International Journal of Sustainable Energy*.

Tzifa, V., Papadakos, G., Papadopoulou, V., Marinakis, V., & Psarras , J. (2014). Uncertainty and method limitations in a short-time measurement of the effective thermal transmittance on a building envelope using an infrared camera. *International Journal of Sustainable Energy*.

VFF-BF. (2014). *Mehr Energie sparen mit neuen Fenstern*. Abgerufen am 1. April 2015 von http://www.bundesverband-flachglas.de/cms/upload/publikationen/VFF-BFStudie_

Vollaro, R., Guattari, C., Evangelisti, L., Battista, G., Carnielo, E., & Gori, P. (2014). Building energy performance analysis: A case study. In *Energy and Buildings* (S. 87-94).

Westerhold, K. (2012). *Can U Values be measured using a thermal imaging camera?* Retrieved March 6, 2015, from https://www.red-current.com/thermal-imaging-blog/46-can-u-values-be-measured-using-a-thermal-imaging-camera

Willis. (2008). *Thermographic applications and loss control*. Retrieved March 6, 2015, from Willis: http://www.willis.com/documents/publications/services/property/Thermographic Applications.pdf

Young, M. (2014, January 1). *Thermal Imaging in the Investigation of Solid Masonry Structures*. Retrieved March 6, 2015, from www.buildingconservation.com/articles/thermal-imaging/thermal-imaging.html

Appendix A: ISO 9869 Summary

Thermal insulation – Building elements In-situ measurement of thermal resistance and thermal transmittance: Summary of ISO 9869-1 (2014)

Background

The ISO (International Organization for Standardization) Norm 9869 was published in 1967 and got revised and extended in 2014. The norm contains standardized guidelines to determine a reliable and generally accepted U-Value based on the heat-flux method. The main points of the ISO Norm are summarized in the following. The focus will be on chapter 4 "Apparatus", Chapter 5 "Calibration procedure", Chapter 6 "Measurements", Chapter 7 "Analysis of data", Chapter 9 "Accuracy" and Chapter 10 "Test report". For more detailed information additional insights the ISO Norm 9869 should be consulted, directly.

About 4. Apparatus

The device has to consist of at least one heat flow meter (HFM) and two temperature sensors (inside and outside). HFMs should be thin, with a low thermal resistance. Additionally, the HFM should be surrounded by heat conductive material to minimize disruptive factors. Suitable surface temperature sensors are thin thermocouples and flat resistance thermometers. These sensors must be suitable for the measurement circumstances and if necessary shielded against external influences such as solar radiation.

About 5. Calibration procedure

The calibration factor of a new type of heat flow meter shall be evaluated on various materials through an absolute test method. greenTEG calibrates their heat flux sensors in a measurement setup using NIST traceable thermal reference materials. The surface and air temperature sensors are calibrated for several temperatures in the relevant range (generally between -10°C to 50°C). greenTEG's Temperature sensors are factory calibrated. Where direct readout equipment is provided, adequate provision shall be made for calibration of this equipment.

About 6. Measurements

Sensors shall be mounted in such a way so as to ensure a result which is representative of the whole element. The HFM shall be mounted in the inside of the building and the temperature sensors has to be located in immediate surroundings inside and outside. The outer surface of the element should be protected from rain, snow, solar radiation, thermal heat or ventilation. To record accurate results the minimum test duration is 72 hours (3 days) if the temperature is stable. Otherwise, the duration should be extended up to 7 days. The data acquisition process should not be interrupted. To get a detailed analysis of the data at least one or two measurements per hour should be done.

About 7. Analysis of the Data

With the average method the average heat flux is divided by the average temperature difference.
Formula:

$$U = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} (T_{ij} - T_{ej})}$$

U= Thermal transmission coefficient
q= Density of heat flow rate
T_i= Inside temperature
T_e= Outside temperature

For elements with low heat capacity (< 20kJ/[m^2], e.g. window)
it is recommended that the analysis is carried out only on data acquired at night. Measurements should be started one hour after sunset and finished before sunrise. The test may be stopped when the results after three subsequent nights do not differ by more than ± 5 %. Otherwise, it shall be continued.
For elements with high heat capacity (> 20kJ/[m^2], e.g. wall structures) the analysis shall be carried out over a period which is an integer multiple of 24 hours, at least 72 hours. The test shall be ended when the U-value obtained at the end of the test does not deviate by more than ± 5 % from the value obtained before. In the case that these criteria are not fulfilled, the measurement should be continued or restarted.

About 9. Accuracy

Variations, which can be caused by calibration deviation, slight differences in the thermal contact between the sensors and the surface or temperature variations within the space and differences between air and radiant temperatures, can be about 5%. The variation caused by the additional heat resistance of the sensor can be about 2 % - 3 %. Additional errors can be caused by the variations over time of the temperatures and heat flow. Consequently, the measured U-value may deviate by a maximum of 14% from the actual U-value (after taking into account all possible sources of errors).

About 10. Test report

The test report must contain data on the element which was measured, data on the measurements itself and data on the method of analysis.

The data regarding the measured element must contain information about location, purpose of the test, thickness and type of material. Furthermore, the data on the measurements must include date and time of the beginning and end of the measurement, the interval between records and the temperature measured. Furthermore, the report must contain graphs of the recorded data.

Final note

The paragraphs, which are not mentioned, are not particularly relevant for the execution and were thus not included in the summary. If there is an interest in the additional information, it can be reviewed in the ISO itself.

For further questions do not hesitate to contact us at info@greenteg.com.

Appendix B: Case Studies

gSKIN® Anwendungsbeschreibung: U-Wert Bestimmung bei bewohnten Gebäuden

Einleitung

Zahlreiche Untersuchungen zeigen, dass der U-Wert von Wänden verlässlich über den Wärmefluss berechnet werden kann. Verschiedene Wandaufbauten/-typen mit unterschiedlichem Wärmeverhalten können auf diese Weise gemessen werden. Jedoch darf der Einfluss von externen Effekten auf die Messungen nicht ohne Beachtung bleiben. Da die meisten Messungen in bewohnten Räumen oder Gebäuden stattfinden ist es wichtig, diese Effekte genau zu kennen und mögliche Auswirkungen auf die Messungen zu reduzieren.

Um die Ergebnisse bei unterschiedlichem Verhalten von Bewohnern zu analysieren, wurden zwei Messungen in bewohnten Wohnungen durchgeführt. Die Resultate zeigen den Effekt von wechselnden Temperaturen beim Messen und können repräsentativ ausgewertet werden.

Messaufbau

Das gemessene Objekt ist eine Wohnung aus dem Jahr 1990 welche nicht renoviert wurde. Die Wand an der die Messung durchgeführt wurde ist eine 32 cm starke Betonwand und befindet auf der Nordseite des Gebäudes. Es liegen keine Informationen über das verbaute Isolationsmaterial oder dessen Qualität vor. Die Innentemperatur schwankt durch die Benutzung der Heizung und durch die Öffnung von Fenstern.
Der Wärmeflusssensor und der Innentemperatursensor wurden beide an der Innenseite der Wand angebracht, der Temperatursensor in einem Abstand von 5 cm von der Wand. Der Außentemperatursensor wurde an der Außenseite der Wand gegenüber dem ersten Temperatursensor in einem Abstand von 5 cm von der Wand angebracht. Die Messdauer für beide Messungen beträgt ungefähr 96 Stunden (4 Tage) gemäß ISO 9869.

Ergebnis

Beide Messungen werden in den folgenden Abbildungen wiedergegeben. Die Graphen beinhalten den Wärmefluss, die Innentemperatur, die Außentemperatur und den U-Wert.

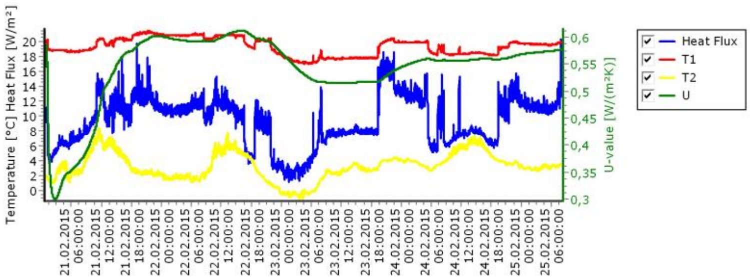


Abbildung 1: Resultat der 1. Wärmeflussmessung (Report auf der Basis von greenTEG Software v1.00.03. 2015)

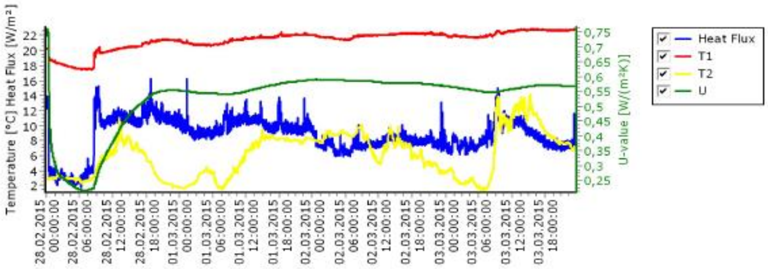


Abbildung 2: Resultat der 2. Wärmeflussmessung (Report auf der Basis von greenTEG Software v1.00.03. 2015)

	U-Wert (W/m²K)	Std. Dev.	dU 24h	Messdauer (h)
Messung 1	0,58	6.7%	3.6%	103
Messung 2	0.57	10.0%	0.32	95

Abbildung 1 weist viele Schwankungen der Innentemperatur auf, die durch die Heizung und das Öffnen von Fenstern entstanden sind. Der Wärmefluss wird stark von der Innentemperatur beeinflusst und reagiert auf plötzliche Temperaturänderungen, er liegt zwischen 3 W/m² und 18/m². Der Einfluss auf den U-Wert bleibt gering, so dass eine Standardabweichung von 6.7% entsteht, die in den letzten 24 Stunden auf 3.6% absinkt und somit mit der ISO 9869 Norm konform ist.

Die zweite Messung weist eine geringere Anzahl an plötzlichen Temperaturunterschieden auf. Nach dem ersten Morgen an dem das Fenster geschlossen wurde und die Temperatur sich angepasst hat, sind nur kleine Temperaturschwankungen zu beobachten, die durch die Heizung ausgelöst wurden. Dementsprechend ist der Wärmefluss stabiler und der U-Wert hat eine Standardabweichung von 0.32% in den letzten 24 Stunden. Die Abweichungen der Außentemperatur scheinen eine Verzögerung von einigen Stunden zu haben, die durch die thermische Masse der Wand entstehen.

Beide Messungen haben nur einen geringen Unterschied im U-Wert aufgewiesen (0.01 W/m²K). Die stark schwankende Innentemperatur hat einen großen Einfluss auf den Wärmefluss, über einen längeren Zeitraum hinweg gleicht sich der U-Wert aber aus. Trotz großer Temperaturschwankungen erfüllen beide Messungen nach 4 Tagen die Vorgaben gemäß ISO 9869.

Fazit

Die Fallstudie zeigt, dass eine Messung gemäß ISO 9869, bei sich ändernden Rahmenbedingungen und in kurzer Zeit, durchgeführt werden kann. Alle Messergebnisse konnten in einer weiteren Messung bestätigt werden. Somit wird deutlich, dass eine Wärmeflussmessung mit dem greenTEG U-Wert KIT in der Regel nicht von alltäglichen Routinen der Bewohner verfälscht werden kann. Schwankungen bei der Innentemperatur haben bei kurzen Messungen einen großen Einfluss auf den Wärmefluss und auf den U-Wert. Der Einfluss sinkt rapide bei längeren Messungen, trotzdem empfiehlt es sich, eine stabile Innentemperatur beizubehalten. Der Einfluss der Außentemperatur ist geringer und zeitlich verschoben auf den Wärmefluss und auf den U-Wert. Für verlässliche Ergebnisse sollte die Messung über einen längeren Zeitraum von 72 Stunden oder einen anderen Multiplikator von 24 Stunden stattfinden.

gSKIN® Anwendungsbeschreibung: U-Wert Bestimmung bei Fensterscheiben

Einleitung

Fenster sind für 10 bis 20% des Wärmeverlustes in Gebäuden in der Winterzeit verantwortlich (Axel-Lute, 2009). Das Wärmeverhalten und die Wärmeleitfähigkeit hängen stark vom verwendeten Glas ab und kann von einem U-Wert von 5 W/m^2K, für einfach verglaste Fenster, bis zu 0.7 W/m^2K, für dreifach verglaste Fenster, variieren (VFF, 2014). Dies bedeutet, dass man durch die Sanierung von alten und schlecht isolierten Fenstern Einsparungen sowohl bei der Wärmeenergie als auch bei den Kosten erzielen kann. Da eine genaue Bestimmung eines U-Wertes bei Fensterglas sehr schwer ist, wird eine genau Berechnung des Einsparpotenzials im Falle einer Sanierung schwierig. Eine in-situ Messung kann jedoch zu einem genauen Ergebnis führen und ist daher von großem Wert. Verlässliche in-situ Messungen können mit dem gSKIN® Wärmeflusssensor durchgeführt werden, jedoch muss wegen dem unterschiedlichen Wärmeverhalten von Glas ein differenzierter Ansatz genutzt werden.

In dieser Fallstudie zeigen wir die U-Wert Messung eines doppelverglasten Fensters in einem Wohnhaus mit einem gSKIN® Wärmeflusssensor. Alle Messungen wurden während der Nacht durchgeführt um einen möglichen Einfluss von Sonnenstrahlen zu annullieren und somit alle Vorgaben zur Glasmessung gemäß ISO 9869 zu folgen. Um den Effekt von Sonnenstrahlung auf den U-Wert zu untersuchen wurden außerdem Messungen während des Tages durchgeführt.

Das Ziel der Fallstudie war es ein genaueres Verständnis vom Wärmeverhalten von Glas und dem daraus resultierenden Einfluss auf U-Wertmessungen zu erhalten. Zusätzlich wird eine detailliertere Bestimmung des U-Wertes, im Vergleich zu einer rein visuellen Einschätzung, möglich, wodurch das genaue Einsparpotenzial und die Amortisationszeit berechnet werden können.

Untersuchtes Gebäude

Die untersuchten Fenster sind Teil eines Wohngebäudes aus den 90er-Jahren und sind 50 cm breit sowie 90 cm hoch. Die Fenster sind doppelt verglast, haben einen PVC rahmen und befinden sich auf der Südseite des Gebäudes. An der Außenseite des Fensters sind in einem Abstand von 10 cm metallische Sonnenblenden angebracht, die nach belieben geschlossen werden können. Da die Sonnenblenden nicht hochgefahren werden können, wurden diese in die Messungen mit eingerechnet. Die Fenster machen insgesamt 8 m^2 der Gebäudewand aus und wurden seit der Erbauung nicht saniert oder renoviert.

Messungsaufbau

Der Aufbau der Messung entspricht den Vorgaben der ISO 9869 Norm. Der Wärmeflusssensor wird an der Innenseite des Fensters angebracht und der Temperatursensor für innen wird daneben in einem Abstand von 3-5 cm von der Oberfläche des Fensters platziert. Der Temperatursensor für außen wird außerhalb des Fensters, gegenüber des ersten Sensors, mit einem Abstand von 3-5 cm zum Fenster platziert.

Alle Nachtmessungen werden ein paar Stunden nach Sonnenuntergang gestartet und am frühen Morgen, kurz vor Sonnenaufgang, wieder beendet (gemäß ISO 9869). Die dritte Messung wurde direkt nach Sonnenaufgang gestoppt was jedoch keinen Einfluss auf die Messergebnisse hatte. Die Messungen während des Tages begangen zum Sonnenaufgang und wurden zum Sonnenuntergang gestoppt. Über den Zeitraum der Messungen gab es keine Aktivitäten im Raum. Alle Messungen wurden mit der greenTEG Software(V1.00.03) ausgewertet.

Abbildung 1: Messsaufbau; Fenster mit metallischer Sonnenblende; Wärmeflusssensor mit 2 Temperatursensoren, einer innen und einer außen, beide ungefähr 3-5 cm Abstand zum Glas.

Auswertung der Daten

Nachtmessung

Die Ergebnisse der drei Nachtmessungen werden in den folgenden drei Abbildung wiedergegeben. Die drei Graphen beinhalten den Wärmefluss, die Innentemperatur, die Außentemperatur und den U-Wert. Alle Parameter sind relativ konstant in allen drei Messungen.

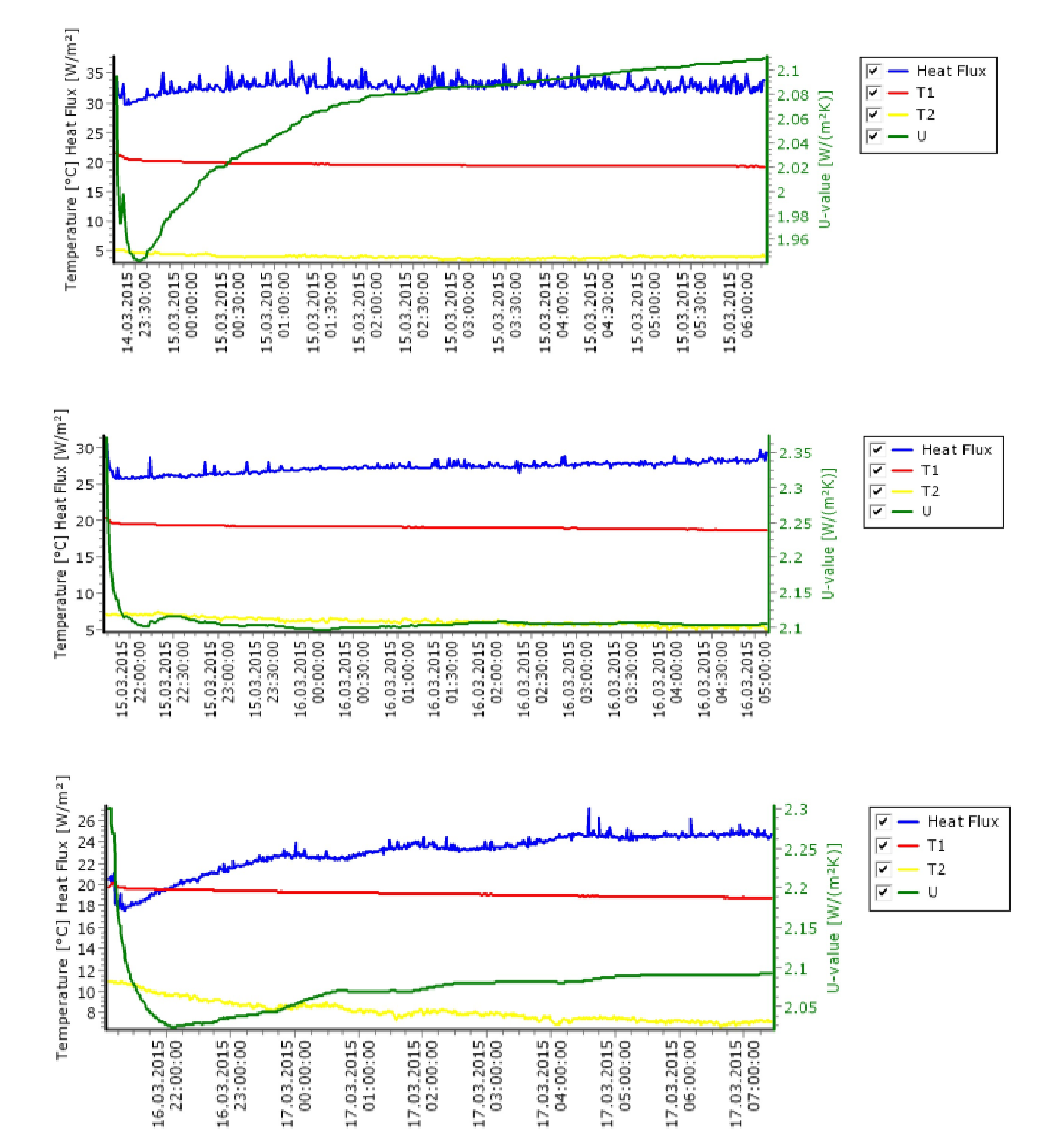


Abbildung 2: Ergebnisse der drei Nachtmessungen, Differenz < 5%, entspricht ISO 9869 (greenTEG Software V1.00.03, 2015)

Die folgende Tabelle zeigt den U-Wert der drei jeweiligen Nächte und die Standardabweichung während der Messzeit. Die durchschnittlichen Werte basieren auf den Messungen während der drei Nächte.

Tabelle 1: Resultat der 3 Nachtmessungen.

	U-Wert (W/m²K)	*Std. Abw.*
1. Nachtmessung	2.11	4.4%
2. Nachtmessung	2.10	1.7%
3. Nachtmessung	2.09	3.2%
Durchschnitt	2.10	3.1%

Die Messungen an den Fenstern während der Nacht haben zu sehr ähnlichen U-Werten geführt die von 2.09 bis 2.11 W/m^2K variieren. Dieser Unterschied ist weniger als 1%, wodurch die ISO 9869 Kriterien von < 5% erfüllt sind. Die Standardabweichung der U-Werte während einer Nacht beträgt im Durchschnitt 3,1% und ist somit niedrig und wenig volatil. Wie in Abbildung 2 zu sehen, kann eine Messung von wenigen Stunden schon aussagekräftige und genaue Daten für den U-Wert wiedergeben.

Tagmessung

Die folgende Abbildung zeigt die Ergebnisse der Tagmessung. Es sind starke Fluktuationen sowohl bei dem Wärmefluss, Außentemperatur als auch beim U-Wert erkennbar.

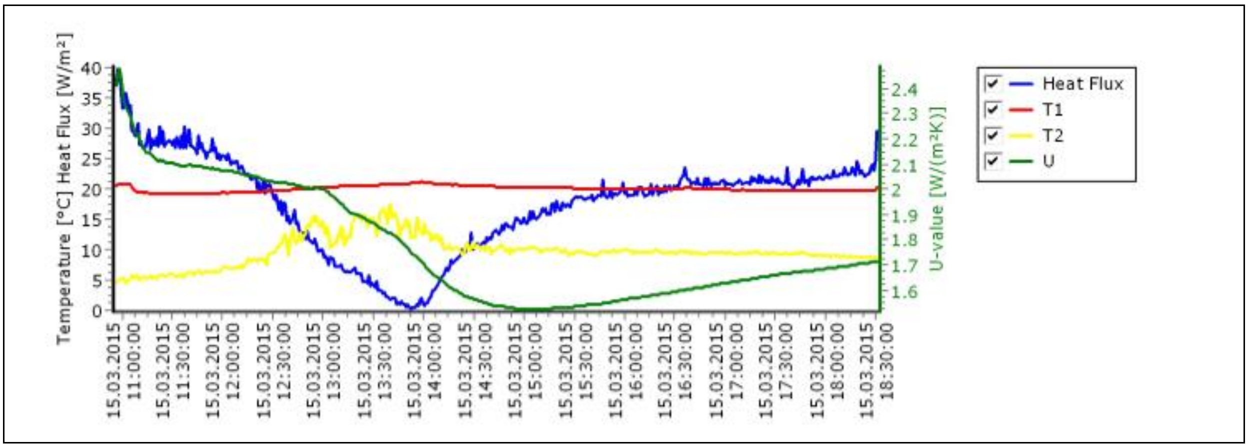


Abbildung 3: Ergebnisse der Tagmessung, inkorrekter U-Wert durch Sonneneinstrahlung (greenTEG Software V1.00.03, 2015)

In der folgenden Tabelle wird der U-Wert und die Standartabweichung der Tagmessung mit dem Durchschnitt der Nachtmessungen verglichen.

	U-Wert (W/m²K)	*Std. Abw.*
Tagmessung	*1.71*	*22.1%*
Durchschnittliche Nachtmessung	2.10	3.1%

Tabelle 2: Resultate der Tag und Nachtmessungen

Die Tagmessung unterscheidet sich signifikant von dem Durchschnitt der Nachtmessungen und hat eine sehr hohe Standardabweichung. Die Ursache dafür ist die Sonnenstrahlung. Der Graph in Abbildung 3 zeigt deutlich, dass der Wärmefluss bei einem bedecktem Himmel 30 W/m^2 beträgt, sobald die Wolken gegen 12 Uhr verschwunden sind und die Sonnenstrahlen direkt auf das Fenster scheinen sinkt der gemessene Wert auf 0 W/m^2.

Der Wärmefluss von innen nach außen wird durch die direkte Strahlung kompensiert. Als sich gegen 14:00 Uhr wieder eine Wolkendecke bildet und die Sonneneinstrahlung blockiert, steigt der gemessene Wärmefluss langsam auf einen Wert von 25 W/m^2 wieder an.

Zusammenfassend ist zu sagen, dass durch eine Messung am Tag nicht nur der Wärmeverlust gemessen werden kann, sondern auch der Wärmegewinn durch Sonneneinstrahlung. Somit sind Messungen am Tag hilfreich wenn das komplette Wärmeverhalten von einem Fenster gemessen werden soll. Eine akkurate und verlässliche U-Wert Messung gemäß ISO 9869 kann jedoch nur, wie beschrieben, Nachts durchgeführt werden.

Berechnung Heizkosten Einsparung

Wenn man die bekannten Merkmale und Eigenschaften der installierten Fenster aus den 90er-Jahren zur Bestimmung des U-Wertes heranzieht kann man einen U-Wert von 1.7 bis 2.8 W/m²K schätzen. Diese Spanne ist relativ groß, sodass sich daraus keine genauen Heizkosten Ersparung für einer Sanierung berechnen lässt. Durch die in-situ U-Wert Berechnung mithilfe des gSKIN® Wärmeflusssensors kann ein genauer Wert bestimmt werden, durch den sich die Heizkosten Ersparung genau berechnen lässt und man eine genaue Amortisationszeit bestimmen kann. Die Messungen am Fensterglas beziehen den Rahmen nicht mit ein und sind daher nicht auf das gesamte Fenster übertragbar. Zusätzliche Messungen am Rahmen können ebenfalls mit dem gSKIN® Wärmeflusssensor gemacht werden.

Der durchschnittliche U-Wert aller drei Nächte beträgt 2.10 W/m²K (zu sehen in Tabelle 1). Dieser Wert kann erheblich verbessert werden, indem man entweder das beste doppeltverglaste Fenster (1.1W/m²K) oder ein dreifachverglastes Fenster (0.7W/m²K) einsetzt.

In der Tabelle 3 wird der gegenwärtige U-Wert und die Heizkosten mit den möglichen Verbesserungen zu doppelverglasten Fenstern und dreifachverglasten Fenstern verglichen. Um genaue Kostenersparnisse zu berechnen, werden die durchschnittlichen Heiztage der letzten zwei Jahre im Norden der Schweiz (Wetterstation Zürich-Kloten) verwendet. Für die Kostenersparnisrechnung wird ein durchschnittlicher Heizpreis von 0,10/kWh verwendet. Die Rechnung in Tabelle 3 basiert auf Annahmen und kann daher nur als ein Indikator für die tatsächlichen Einsparungen verwendet werden. Die exakten Einsparungen hängen von dem verwendetem Rahmen und weiteren Randbedingungen (wie z.B. Nutzverhalten). Die Austauschkosten in Tabelle 3 sind inbegriffen der Arbeitskosten sie können von Fall zu Fall aber in verschiedenen Fälle unterscheiden. Die Amortisationszeit wird berechnet indem die Austauschkosten durch die Heizkostenersparnisse geteilt werden.

Tabelle 3: Energie- und Kostenvergleich verschiedener Fenstertypen

	U-Wert *(W/m²K)*	***Wärmeverlust**[1]* *(kWh/Jahr m²)*	***Kosten erspar-niss**[1]* *(€/Jahr m²)*	***Austauschkosten**[2]* *(€/m²)*	***Amortisations-zeit*** *(Jahre)*
m² Derzeitige Verglasung	2.1	174	-	-	-
m² Vergl. Dop-pel-verglast 3. Generation	1.1	91	~ € 8,-	€ 120,00	~ 14
m² Vergl. Drei-fach-verglasung	0.7	58	~ € 12,-	€ 160,00	~ 14

[1] Ort: Zürich-Kloten; Basistemperatur: 19 °C; www.degreedays.net
[2] Beispielkosten inklusive Arbeitszeit, Quelle: www.dubbelglas-weetjes.nl/hr-glas/driedubbel-glas/
[3] Das beste doppelt verglaste Fenster und dreifach verglaste Fenster; Quelle (VFF, 2014)

Die Amortisationszeit bei einem Wechsel von den jetzigen Fenstern zu den besten doppelt verglasten oder dreifachverglasten Fenstern würde in beiden Fällen ungefähr 14 Jahre betragen. Im Vergleich zu anderen Methoden die möglich sind um Energie und Kosten zu sparen (z.B. LED Lampen) ist dies ein sehr langer Zeitraum. Da ein Fenster aber eine sehr lange Lebensdauer hat, würde sich das Investment rentieren. Eine Sanierung der Fenster hätte außerdem auch andere positive Effekte, wie zum Beispiel Senkung der Geräuschbelastung, Reduzierung von Kondenswassers etc. In diesem untersuchten Gebäude ist die Geräuschbelastung in der Umgebung besonders hoch und würde somit ein wichtiges Entscheidungskriterium darstellen. Durch die neue Messmethode ist es nun möglich die Kostenersparnisse (und die Vorteile der Geräuschreduzierung) mit den Kosten zu vergleichen und eine Entscheidung zu treffen. In diesem Fall nehmen die Fenster eine Fläche von 8 m² ein. Das beste doppeltverglaste Fenster würde eine Investition von €1000,- (8 x €120,-) benötigen und zu Kostenersparnissen von €65,- (8 x €8,29) pro Jahr führen. Anhand dieser Informationen können nun Entscheidungen getroffen werden ob sich eine Sanierung lohnen würde.

Richtlinien zum Aufbau einer Fensterglas-Messung

Eine U-Wertmessung bei einem Fensterglas durchzuführen ist relativ einfach. Die meisten Schritte werden in dem mitgelieferten Handbuch des U-Wert Messgeräts erklärt. Man muss einige wenige zusätzliche Faktoren beachten.

- Verlässliche und ISO konforme Messungen können nur nach Sonnenuntergang und vor dem Sonnenaufgang durchgeführt werden. Die Timerfunktion lässt den Beginn der Messung zeitlich nach hinten verschieben. Alternativ kann man durch das Auslesen der Daten in einem Excel Dokument nur die relevanten Zeiten auswählen.
- Künstliches Licht kann die Messung ebenfalls verfälschen, daher sollten alle Lichtquellen ausgeschaltet bleiben.

Fazit

Das U-Wert KIT kann benutzt werden um sehr genaue in-situ U-Wertmessungen durchzuführen. Messungen die während der Nacht unter stabilen Umständen durchgeführt werden liefern genaue und zuverlässige Daten schon nach wenigen Stunden. Messungen die am Tag durchgeführt werden weisen starke Schwankungen auf die auf die Sonneneinstrahlung zurückzuführen sind. Eine in-situ U-Wertmessung bei Fensterglas kann sehr hilfreich sein, da sich das Wärmeverhalten stark unterscheiden kann und es oftmals bei verbauten alten Fenstern unbekannt ist. Daher ist die Gewinnung von exakten Messdaten unerlässlich um eine richtige Kostenrechnung zu erstellen.

Referenzen

Axel-Lute, M. 2009; Three steps to super-efficient windows; Green America, retrieved at: April 2, 2015 aus http://www.greenamerica.org/livinggreen/windows.cfm

International Standard Organisation. ISO 9869:2014: Thermal insulation – Building elements – In-situ measurement of thermal resistance and thermal transmittance – Part 1: Heat flow meter method. Genève; ISO; 2014

VFF-BF, 2014, Mehr Energie sparen mit neuen Fenstern; retrieved at April 1, 2015, from http://www.bundesverband-flachglas.de/cms/upload/publikationen/VFF-BF-Studie_Mehr_Energie_sparen_mit_neuen_Fenstern.pdf

Appendix C: Publications

Exact date of publication	Name of publication organ	Title	Type
01.02.2015	Bauhandwerk	Gebäudeisolation einfach und präzise messen	Print&Online
27.02.2015	Bauflash	U-Wert Verifikationsmessungen an einem Minergie-zertifizierten Neubau	Print
24.02.2015	Sens2B Newsletter	Heat flux and temperature measurements compared	Online
12.03.2015	http://scitechnews.co.uk/	Quality of building insulation simply and precisely measured	Online
März 2015	Bauen Heute	Wärmeflusssensor im Einsatz zur U-Wert Messung	Print
April 2015	Swiss Engineering	Verbesserte Präzision: Thermische Einflüsse kompensieren	Print&Online
April 2015	Domotech	Une vanne de chauffage innovante et économique	Print
10.05.2015	Industrielle Automation	Thermische Sensoren -geeignet für Messungen mit hoher Präzision	Print&Online
23.06.2015	SchweizerBauJournal	Gebäudeisolation präzise bestimmen	Print
22.07.2015	Energate.ch	Daten zur Isolationsqualität wichtig für Sanierungsentscheidungen	Online
02.07.2015	Baubiologie	Gebäudeisolation präzise durch U-Wert Messung bestimmen	Print
01.08.2015	Wohnen	Sensor checkt ihre Gebäudehülle	Print
25.08.2015	TGA Fachplaner	Gebäudeisolation durch U-Wert Messung bestimmen	Print&Online
20.08.2015	Bauen Heute	Wärmeflusssensor im Einsatz zur U-Wert Messung	Print
20.08.2015	Umweltperspektiven	U-Wert Messung als Alternative zu Schätzverfahren	Print
25.09.2015	HLK	Gebäudeisolation präzise durch U-Wert Messung bestimmen	Print
15.09.2015	IKZ Energy	Messen oder berechnen?	Print&Online

Find these articles in the following paragraphs

Scitechnews – 12.03.2015

Quality of building insulation simply and precisely measured

By Joanna Davis On March 12, 2015 · Add Comment · In Energy Efficiency, Infrastructure, Renewable Energy, Technology

greenTEG (Switzerland) has developed a U-value measurement tool to assess the quality of building insulation. The U-value KIT is now available on the market.

Each day large amounts of energy is spent through the heating and cooling of buildings. A large proportion of buildings were constructed before 1980 which have below standard insulation, leading to high energy waste and as a result substantial financial costs to the building owners and occupants.

In order to optimise insulation, the quality of the insulation has to be assessed. Precise data on insulation quality of building elements contribute to the determination of existing conditions, justification of investments and validation of completed improvements. Several methods can be used to do so but only U-value measurements with heat flux sensors delivers reliable and precise, quantitative data on the quality of building insulation.

The U-Value KIT consists of a highly sensitive heat flux sensor, two temperature sensors and a data logger. The software developed by greenTEG enables simple read-out and processing of the data.

greenTEG datalogger including temp. sensors

The U-value is the measurement unit for assessing the heat loss of a building element. U-values describe how much heat (measured in watt) passes through 1 square meter of a given material when the temperature difference between the two sides of the element is 1°C.

The lower the U-value, the better the insulation quality of a building element.

There is a large need to measure U-values of building elements empirically in order to obtain reliable and precise data on up-to-date U-values at a specific location. By measuring the heat flux and; the inside and outside temperature the U-value can be precisely calculated. A temperature difference of 5°C is sufficient for a precise U-value measurement. The heat flux method is described in ISO norm 9869. The U-Value KIT is developed taking this norm into account and can therefore precisely describe the thermal behaviour of building elements.

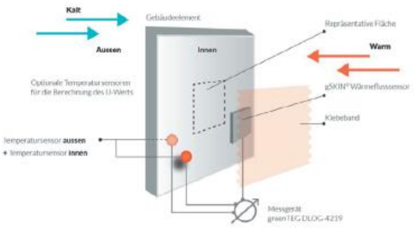
greenTeg U-value Kit

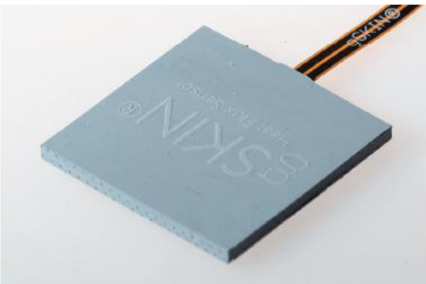
The heat flux sensor can be easily mounted to any building element. With the greenTEG U-Value KIT measurements can either be viewed instantly via your laptop (connected) or further reviewed after the measurement is done with our calculation software. Data points can easily integrated into other calculation models at a later point, e.g. for further use to estimate heat requirements of buildings.

With U-Value KIT; greenTEG offers a tool which allows simple and precise measurement of insulation quality and an optimal insight into the energy performance of a building.

For more information visit: http://www.greenteg.com/heat-flux-sensor/u-value-measurement

Baubiologie – 02.07.2015





Gebäudeisolation präzise durch U-Wert Messung bestimmen

Für eine professionelle energetische Modernisierung von Gebäuden werden Kenntnisse über den aktuellen Zustand der Fassade vorausgesetzt. Die U-Wert Messung mittels Wärmeflusssensor liefert verlässliche quantitative Daten dafür. Das U-Wert KIT besteht aus einem hochsensiblen Wärmeflusssensor, zwei Temperaturfühlern für den Innen- und Außenbereich, und einem Datenlogger. Hinzu kommt eine einfach zu bedienende Software. Zwar existieren verschiedene Methoden, um die Qualität der Dämmung zu beurteilen, aber nur die U-Wert Messung mit Wärmeflusssensor liefert verlässliche quantitative Daten. Die Wärmeflussmethode ist in der ISO Norm 9869 beschrieben. Dieser Norm wurde bei der Entwicklung des U-Wert KITs gefolgt, da sie als die einzige Methode gilt, mit der quantitativ das thermische Verhalten von Gebäudeelementen (Mauerwerk, Dämmungen, Fenstern) beschrieben werden kann. Mit dem U-Wert KIT kann man die Messung live am Laptop mitverfolgen und die gemessenen Werte für weitere Berechnungsprogramme nutzbar machen. Voraussetzung ist eine Temperaturdifferenz von 5 °C.

Anwendungsbeschreibungen und Fallstudien sind auf www.greenTEG.com frei zugänglich. Das Messgerät ist für 1.590,-- SFR zzgl. MwSt direkt bei greenTEG erhältlich.

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www.greenteg.com

U-Wert-Messung als Alternative zu Schätzverfahren

Untersuchungen zeigen, dass der U-Wert von Gebäudeteilen verlässlich über den Wärmefluss berechnet werden kann. Jedoch darf ein möglicher Einfluss von externen Effekten auf die Messungen nicht ohne Beachtung bleiben, insbesondere, da die meisten Messungen in bewohnten Räumen stattfinden.

Von Holger Hendrichs

Für eine professionelle energetische Modernisierung von Gebäuden werden Kenntnisse über den aktuellen Zustand der Gebäudehülle vorausgesetzt. Die U-Wert-Messung mittels Wärmeflusssensor liefert verlässliche quantitative Daten dafür. Denn der U-Wert ist der Ausgangspunkt, um energetische Sanierungsmassnahmen gezielt, kosteneffizient sowie den regulatorischen Anforderungen gemäss zu planen und durchzuführen. Ferner bildet der U-Wert die Basis, um Ansprüche auf Förderung durch öffentliche Gelder (beispielsweise «Das Gebäudeprogramm») geltend machen zu können. Bei neuen Bauteilen wird dieser U-Wert durch die vom Hersteller angegebenen λ-Werte, also die spezifische Wärmeleitfähigkeit einer Gebäudeschicht in W/(m²K), angegeben bzw. berechnet. Diese sind jedoch bei sanierungsbedürftigen Altbauten oft unbekannt und müssten dann geschätzt oder gar durch invasive Proben beurteilt werden.

U-Wert-Messung beurteilt Isolationsqualität

Mithilfe eines U-Wert-Messgeräts kann auf invasive Probebohrungen und Unsicherheiten bei Schätzungen verzichtet werden. Ein U-Wert-Messgerät (siehe Abb. 1), bestehend aus einem hochsensiblen Wärmeflusssensor (B), zwei Temperaturfühlern für den Innen- und Aussenbereich (D), und einem Datenlogger (E), kann schon bei Temperaturunterschieden von 5 °C zu Messwerten führen, die für die weitere seriöse Planung unverzichtbar sind. Die zugrundeliegende Wärmefluss-Messmethode ist in der ISO Norm 9869 («Wärmeschutz – An der Verwendungsstelle durchgeführte Messung des Wärmewiderstandes und der Wärmeübertragung – Teil 1: Heat flow meter method») beschrieben. Das Zürcher ETH-Spin-off-Greenteg ist dieser Norm bei der Entwicklung des U-Wert-Messgeräts gefolgt. Auf Grundlage einer 72-Stunden-Messung kann das thermische Verhalten von Gebäudeelementen mittels der U-Wert Bestimmung quantitativ beschrieben werden. Auch kürzere Messungen liefern brauchbare Ergebnisse, folgen jedoch nicht der ISO-Norm. So können fast ganzjährig U-Wert-Messungen durchgeführt werden.

Fragestellungen vor Sanierungsbeginn: Was kann eine Messung liefern?

Im konkreten Fall ist das zu sanierende bzw. nachzumessende Objekt eine Wohnung in einem Wohnhaus aus dem Jahr 1990, welche noch nicht renoviert wurde. Dem Eigentümer liegen keine Informationen über das verbaute Isolationsmaterial oder dessen Qualität vor. Er möchte jedoch auf Basis der Messungen und gewonnenen Erkenntnisse die anderen Hauseigentümer für eine energetische (Teil-)Sanierung gewinnen. Hierbei ist ihm wichtig, beispielsweise die unterschiedlichen Amortisationszeiten für Sanierungen der Aussenwände vs. Fenster besser zu verstehen.

Die erste Messung wird an einer 32 cm starken Betonwand an der Nordseite des Gebäudes durchgeführt. Da die Wohnung bewohnt ist, schwankt die Innentemperatur durch die Benutzung der Heizung und durch die Öffnung von Fenstern. Diese etwaigen (Temperatur-) Schwankungen werden im Rahmen der ISO-9869-Norm mitberücksichtigt. So ist sichergestellt, dass ein verlässlicher U-Wert gemessen wird.

Ferner wurden doppelverglaste Fenster untersucht, die 50 cm breit sowie 90 cm hoch sind. Die Fenster haben einen PVC-Rahmen und befinden sich auf der Südseite des Gebäudes. An der Aussenseite des Fensters sind in einem Abstand von 10 cm metallische Sonnenblenden angebracht, die nach Belieben geschlossen werden können. Die Sonnenblenden lassen sich nicht hochfahren und wurden deshalb in die Messungen integriert. Auch die Fenster wurden seit der Erbauung weder saniert noch renoviert.

Sachgerechter Messaufbau benötigt Fachkenntnisse

Der Wärmeflusssensor und der Innentemperatursensor wurden beide an der Innenseite der Wand bzw. des Fensters angebracht, der Temperatursensor in einem Abstand von 2–5 cm von der Wand bzw. dem Fenster. Der Aussentemperatursensor wurde an der Aussenseite der Wand bzw. des Fensters gegenüber dem ersten Temperatursensor in einem Abstand von 5 cm angebracht. Die Messdauer für die Wandmessungen beträgt ungefähr 96 Stunden (mindestens drei Tage, gemäss ISO 9869), für die Fenstermessung muss in mindestens drei aufeinanderfolgenden Nächten gemessen werden.

Gute Mess-Ergebnisse trotz Einflüssen seitens der Bewohner

Die hier aufgeführte Untersuchung sollte auch Ergebnisse bei unterschiedlichem Verhalten von Bewohnern analysieren, da-

U-Wert

Der U-Wert, auch Wärmedurchgangskoeffizient genannt, gibt an, wie viel Wärme durch einen Quadratmeter eines Bauteils verlorengeht. Er ist ein spezifischer Kennwert eines Bauteils und unter anderem abhängig von der Wärmeleitfähigkeit und der Dicke des Materials. Es gilt: Je kleiner der U-Wert, desto besser die Wärmedämmung. Der U-Wert wird in W/(m²K), also verlorene Leistung in Watt pro Quadratmeter und Kelvin, angegeben.

DR. HOLGER HENDRICHS
ist Head Building Technologies, greenTEG AG.

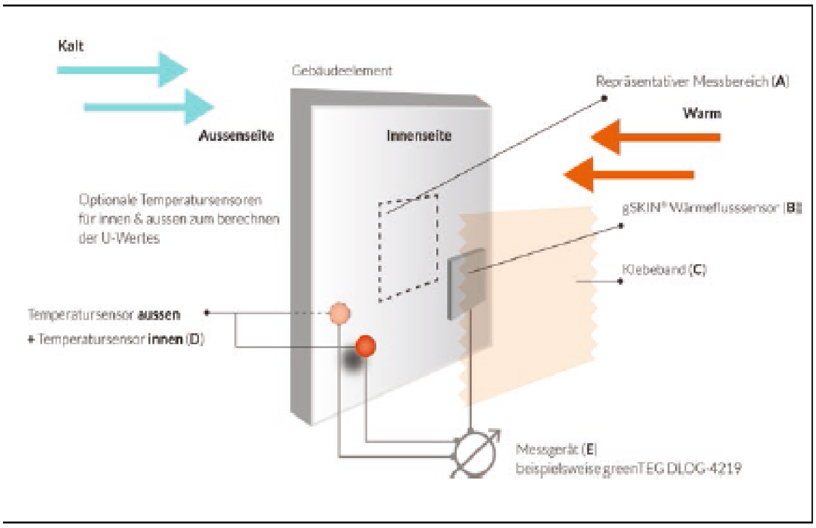

Abb. 1: Aufbau einer wärmeflussbasierten U-Wert-Messung. Grafik: greenTEG AG

her wurden mehrere unterschiedliche Messungen in der bewohnten Wohnung durchgeführt. Die Resultate zeigen den Effekt von wechselnden Temperaturen beim Messen auf und können repräsentativ ausgewertet werden. Die Graphen für die Wandmessung beinhalten den Wärmefluss (blau), die Innentemperatur (rot) sowie die Aussentemperatur (gelb) und den U-Wert (grün) (s. Abb. 3). Wie in der Abbildung der Mess-Ergebnisse der Wand zu sehen ist, schwankt die Innentemperatur recht stark. Diese Schwankungen ergeben sich durch die Beheizung und Lüftung des Raumes durch die Bewohner. Dadurch änderte sich auch jeweils die thermische Aufladung der Gebäudehülle. Der hier dargestellte Wärmefluss wird stark von der Innentemperatur beeinflusst und reagiert auf plötzliche Temperaturänderungen, er liegt zwischen 3 W/m² und 18 W/m². Der Einfluss auf den U-Wert bleibt jedoch gering, eine Standardabweichung über den gesamten Zeitraum von 6,7 % liegt hier zugrunde, die in den letzten 24 Stunden auf 3,6 % absinkt und somit mit der ISO-9869-Norm konform ist. Unsere zweite Vergleichsmessung der Wand (ohne Abbildung) weist eine geringere Anzahl an plötzlichen Temperaturunterschieden auf, da das Fenster geschlossen und die Innentemperatur relativ konstant gehalten wurde. Daher sind auch nur kleine Temperaturschwankungen zu beobachten, die durch die Heizung ausgelöst wurden. Dementsprechend ist der Wärmefluss stabiler, und der U-Wert hat eine Standardabweichung von 0,32 % in den letzten 24 Stunden. Beide Messungen haben nur einen geringen Unterschied im U-Wert aufgewiesen (0,01 W/m²K). Die stark schwankende Innentemperatur hat zwar einen grossen Einfluss auf den Wärmefluss, aber über einen längeren Zeitraum hinweg gleicht sich der U-Wert aus. Trotz grosser Temperaturschwankungen erfüllen beide Messungen nach vier Tagen die Vorgaben gemäss ISO 9869.

Fenstermessungen können nur in der Nacht durchgeführt werden, weil die Sonneneinstrahlung die Messung sonst verfälscht. Die Messung sollte nach Sonnenuntergang gestartet und kurz vor Sonnenaufgang wieder beendet werden. Gemäss ISO-Norm muss in drei aufeinanderfolgenden Nächten gemessen werden.

Sonderfall Fensterscheiben

Fenster sind für 10 bis 20 % des Wärmeverlustes in Gebäuden in der Winterzeit verantwortlich. Das Wärmeverhalten und die Wärmeleitfähigkeit hängen stark vom verwendeten Glas ab und können von einem U-Wert von 5 W/m²K, für einfach verglaste Fenster, bis zu 0,7 W/m²K, für dreifach verglaste Fenster, variieren. Verlässliche in-situ-Messungen können mit dem gSKIN-Wärmeflusssensor durchgeführt werden, jedoch muss wegen dem unterschiedlichen Wärmeverhalten von Glas ein differenzierter Ansatz genutzt werden. Messungen sind aufgrund der Strahlungseffekte nur während der Nacht möglich.

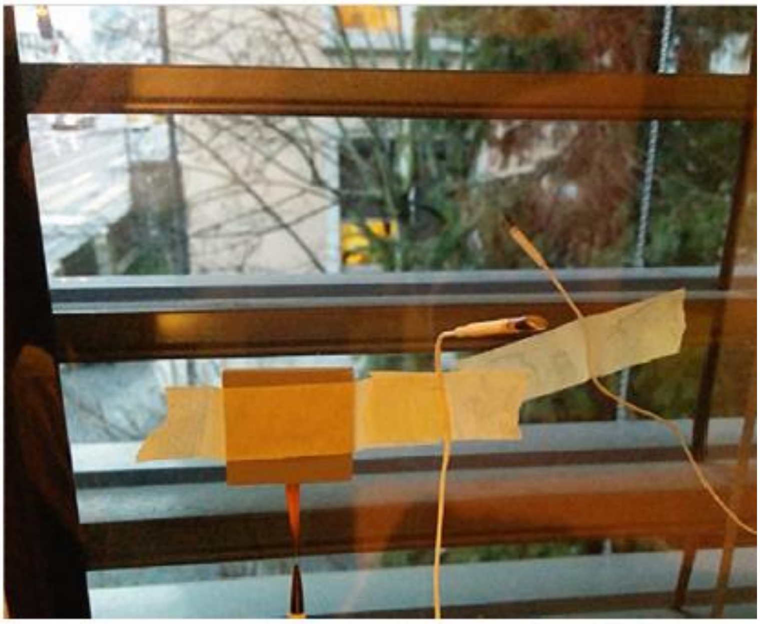

Abb. 2: Messaufbau am Fenster mit metallischer Sonnenblende; Wärmeflusssensor mit zwei Temperatursensoren, einer innen und einer aussen, beide ungefähr mit 2- bis 5 cm Abstand zum Glas. Foto: greenTEG AG

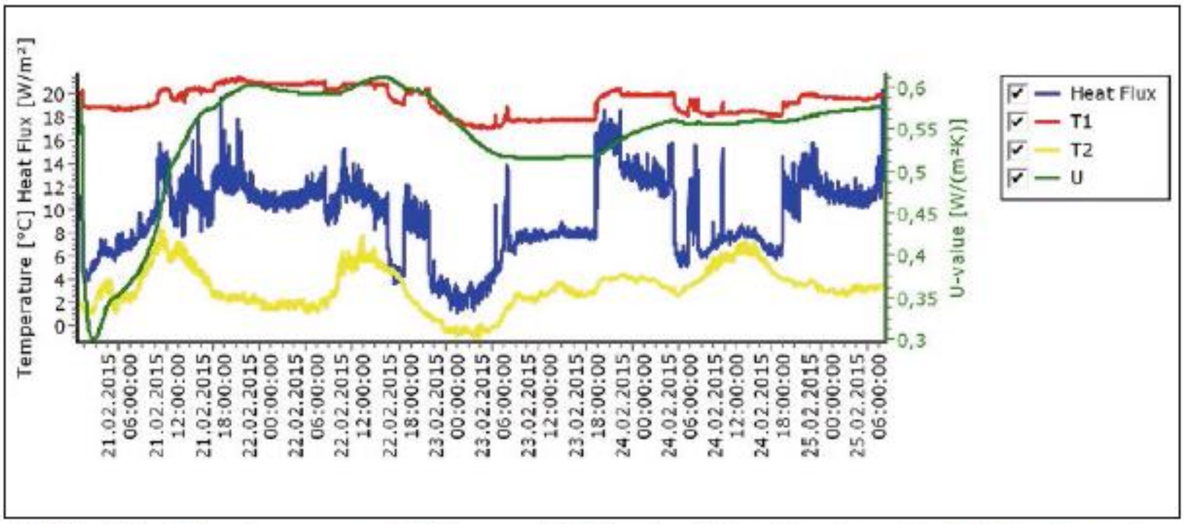

Abb. 3: Resultat der 1. Wärmeflussmessung an der Wohnungswand. Der Wärmefluss ist blau, die Innentemperatur rot, die Aussentemperatur gelb und der U-Wert grün dargestellt.
Grafik: greenTEG AG

Auch diese Messungen haben zu sehr ähnlichen U-Werten geführt, die von 2,09 bis 2,11 W/m²K variieren. Dieser Unterschied beträgt weniger als 1% und erfüllt das ISO-9869-Kriterium von einer Abweichung < 5%. Die Standardabweichung der U-Werte während einer Nacht beträgt im Durchschnitt 3,1% und ist somit niedrig und wenig volatil.

	U-Wert (W/m² K)	Std. Dev.	dU 24 h	Messdauer (h)
Messung 1	0,58	6,7%	3,6%	103
Messung 2	0,57	10,0%	0,32%	95

Vergleich der Ergebnisse der beiden Wand-Messungen.

Sanierungsempfehlungen aus Mess-Ergebnissen

Messungen können in relativ kurzer Zeit durchgeführt werden und werden in der Regel nicht durch die alltägliche Routine der Bewohner verfälscht. Schwankungen bei der Innentemperatur haben bei ISO-konformen Messungen keinen grossen Einfluss auf den U-Wert. Auch der Einfluss der Aussentemperatur ist gering und zeitlich verschoben auf den Wärmefluss und auf den U-Wert. Für verlässliche Ergebnisse sollte die Messung über einen Zeitraum von 72 Stunden oder einen anderen Multiplikator von 24 Stunden stattfinden.

Wenn man die bekannten Merkmale und Eigenschaften der installierten Fenster aus den 90er-Jahren zur Bestimmung des U-Wertes herangezogen hätte, würde man einen U-Wert von 1,7 bis 2,8 W/m²K schätzen. Diese Spanne ist relativ gross, sodass sich daraus keine genaue Heizkosteneinsparung für eine Sanierung berechnen lässt. Der gemessene durchschnittliche U-Wert aller drei Nächte betrug jedoch 2,10 W/m²K. Dieser Fensterglas-U-Wert könnte somit erheblich verbessert werden, wenn im Rahmen einer Teilsanierung entweder das beste doppeltverglaste Fenster (1,1 W/m²K) oder ein dreifachverglastes Fenster (0,7 W/m²K) eingesetzt werden würde.

Um beispielsweise genaue Kostenersparnisse zu berechnen, können die durchschnittlichen Heiztage (Wetterstation Zürich-Kloten) verwendet werden. Für eine Kostenrechnung kann ein durchschnittlicher Heizpreis von 0,10 CHF/kWh verwendet werden. Die Rechnung basiert auf Annahmen und dient daher nur als ein Indikator für die tatsächlichen Einsparungen. Die exakten Einsparungen hängen sowohl vom später eingebauten Rahmen und weiteren Randbedingungen, wie z. B. Nutzverhalten, ab.

In unserer Rechnung erhalten wir eine Amortisationszeit bei einem Wechsel der jetzigen Fenster zu dreifachverglasten Fenstern von ungefähr 14 Jahren. Im Vergleich zu anderen Methoden, die möglich sind, um Energie und Kosten zu sparen (z. B. LED-Lampen), ist dies ein sehr langer Zeitraum. Da ein Fenster aber ebenfalls eine sehr lange Lebensdauer besitzt, würde sich die Investition auf der Basis einer reinen Kostenberechnung rentieren. Eine Sanierung der Fenster hätte ausserdem andere positive Effekte, wie zum Beispiel die Senkung der Geräuschbelastung oder die Reduzierung von Kondenswasser. Im untersuchten Gebäude ist die Geräuschbelastung aus der Umgebung besonders hoch und würde somit ein wichtiges Entscheidungskriterium darstellen. Somit können nun anhand dieser Informationen weitere Investitionsentscheidungen getroffen werden, da nun die einzelnen Sanierungsoptionen (Wanddämmung, Fensterersatz, Leuchtmittelersatz etc.) miteinander besser verglichen werden können.