Smart Design Policies

2025, Volume 2, Number 1, pages 19–30

Original scientific paper

Implementing an Intelligent Monitoring System to Enhance Energy Efficiency and Support Decarbonization in Sustainable Buildings

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ARTICLE INFO:

Article History:
Received: 4 May 2025
Revised: 13 July 2025
Accepted: 15 July 2025
Available online: 20 July 2025

Keywords:
Decarbonisation,
Energy efficiency,
Intelligent monitoring system,
Internet of Things,
Sustainable Building

ABSTRACT

This paper presents the development and implementation of IoT HEAT, an intelligent, low-cost thermal monitoring system designed to enhance energy efficiency and support decarbonisation strategies in sustainable buildings. Recognizing the critical role of the built environment in global carbon reduction efforts, this study introduces a novel integration of the Temperature-Based Method (TBM) with real-time IoT-based sensing architecture to estimate the thermal transmittance (U-value) of building envelopes. Unlike conventional approaches that rely on expensive heat flux meters, this system leverages compact, affordable sensors to continuously monitor key temperature parameters interior air, surface, and exterior air across building façades with varying orientations. The originality of this work lies in its demonstration of how open-source, scalable technology can be used to perform reliable envelope diagnostics without the need for specialized equipment or complex setups. Academic contributions include validating TBM under real-world, dynamic conditions and providing a replicable framework for deploying intelligent building performance assessment systems. Results confirm the system's potential to detect inefficiencies, inform retrofitting decisions, and significantly reduce operational energy losses. This study contributes to both academic discourse and practical applications by bridging the gap between simplified theoretical methods and cost-effective, real-time implementation for energy-efficient building design and renovation.

SMART DESIGN POLICIES (2025), ***2***(1), 19–30.
https://doi.org/10.38027/smart.v2n1-2

www.smartdpj.com

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How to cite this article: (APA Style)
Mobaraki, A., Nikoofam, M., Mobaraki, Z., Hosseinzadehfar, E., & Mobaraki, B. (2025). Implementing an intelligent monitoring system to enhance energy efficiency and support decarbonization in sustainable buildings. *Smart Design Policies, 2*(1), 19–30. https://doi.org/10.25034/smart-v2n1-2

1. Introduction

Enhancing the energy performance of buildings is critical in achieving global decarbonization targets and reducing greenhouse gas emissions from the built environment. One of the primary challenges in this regard is identifying where and how energy losses occur, particularly through building envelopes. Inefficient insulation and thermal bridging significantly impact indoor comfort and energy demand, especially in older or poorly retrofitted buildings. Therefore, engineers and building scientists continue to search for reliable, accessible, and cost-effective methods to evaluate thermal behavior and guide improvements in energy efficiency (Amen et al., 2023).

Numerous methodologies have been developed to assess heat transfer through walls, roofs, and other structural elements. A widely recognized technique is the heat flux meter (HFM) method, which allows the direct measurement of heat flow across a surface under steady-state thermal conditions. This non-invasive method requires placing heat flux sensors and ambient temperature probes on both sides of the construction element to calculate the transmittance value (U-value), which quantifies the rate of heat loss per unit area and temperature difference (B. Mobaraki, Castilla Pascual, Lozano-Galant, et al., 2023). The method is standardized and offers high accuracy, but it demands precise installation, stable boundary conditions, and expensive instrumentation, limiting its usability for large-scale or long-term monitoring.

To improve upon this, variations of the HFM approach have been proposed. The temperature control box-heat flow meter (TCB-HFM) system integrates a heat flux sensor with a guarded hot box to create a more controlled measurement environment. Although it improves accuracy, the system’s complexity and cost further increase. A simpler alternative is the simple hot box-heat flow meter (SHB-HFM) method, which eliminates the need for a fully guarded hot box by using basic heating equipment, thereby reducing the cost and simplifying deployment. However, this approach may still face challenges in accuracy and repeatability (Zhu/X.F et al., 2012).

Another method gaining traction is infrared thermography (IRT), which uses thermal imaging cameras to visualize surface temperature distributions and identify areas with high heat loss (Albatici et al., 2010). While non-contact and rapid, IRT requires experienced interpretation, controlled environmental conditions, and can be affected by external factors such as wind or solar radiation. Similarly, the natural convection and radiation (NCaR) method combines thermographic data with measurements of air and surface temperatures and emissivity values to calculate heat flow. This approach can provide insight into building performance without invasive instrumentation, but the precision of results heavily depends on environmental stability and calibration of equipment (Agboola et al., 2023).

A more recent and streamlined alternative is the temperature-based method (TBM) , which estimates the U-value using only three parameters: the temperature of the interior air, the temperature of the exterior air, and the surface temperature of the interior wall. This approach assumes a known value for the convective surface heat transfer coefficient and does not require heat flux measurement, making it potentially simpler and more affordable than traditional methods (B. Mobaraki, Castilla Pascual, García, et al., 2023).

Despite the availability of multiple thermal evaluation techniques, their widespread adoption remains limited due to the high cost of equipment, the technical expertise required, and the logistical challenges of implementing multi-point monitoring systems. For instance, deploying several high-end heat flux sensors and temperature probes across a building can cost thousands of euros, making such systems inaccessible for many homeowners, facility managers, and even researchers. This has led to increasing interest in the use of low-cost sensors and microcontroller-based platforms for thermal and environmental monitoring in sustainable buildings (A. Mobaraki et al., 2022).

Recent literature has explored the feasibility and performance of affordable sensing systems in various domains. (Badura et al., 2018) analyzed the precision and long-term stability of several inexpensive ambient sensors by comparing their outputs under controlled conditions. Their study emphasized the importance of calibration and redundancy when using low-cost hardware. (B. Mobaraki et al., 2019) proposed and evaluated a temperature monitoring system using low-cost components and assessed its usability, communication protocols, and deployment procedures. Their work also included a review of sensor networks for real-time data collection and visualization in structural monitoring (B. Mobaraki et al., 2021), highlighting the growing potential of affordable and scalable systems in building applications.

In parallel with sensor development, the emergence of the Internet of Things (IoT) has transformed how building data is collected, processed, and interpreted. Unlike traditional systems where data are stored locally and analyzed offline, IoT-enabled monitoring platforms facilitate real-time communication between sensors and cloud-based servers. These systems enable users to access data remotely, configure alerts, and perform analysis through user-friendly dashboards. (Ng et al., 2017) explored the conceptual foundations of IoT, describing it as an assemblage of digital-material networks capable of increasing the liquidity of information flows. However, the deployment of IoT in building monitoring raises legitimate concerns regarding data privacy, system security, and the integrity of transmitted information. (Jose et al., 2018) discussed key vulnerabilities in IoT networks and reviewed current best practices for securing data in sensor-based systems.

In the context of building monitoring, the IoT paradigm enables a shift toward intelligent systems those capable of collecting data autonomously, analyzing patterns, and supporting decision-making processes related to energy consumption, maintenance, and retrofitting. (Martín-Garín et al., 2018) presented a comprehensive study on an IoT-based monitoring solution that utilized a selection of low-cost sensors for environmental tracking. Their work demonstrated the feasibility of integrating low-cost and IoT technologies into practical building applications, despite certain limitations in measurement precision.

Despite the growing interest in thermal performance assessment methods, several notable gaps remain in the current literature. Traditional techniques such as the HFM method offer high accuracy but are often cost-prohibitive, technically demanding, and dependent on steady-state conditions, limiting their suitability for widespread or long-term use. Alternative approaches like infrared thermography or radiation-based methods provide valuable insights but are sensitive to environmental variability and require expert interpretation. While the emergence of low-cost sensors and IoT platforms has introduced new possibilities for environmental monitoring, few studies have fully leveraged these technologies in the context of real-time, intelligent thermal assessment tailored to building envelopes. In particular, there is a need for accessible, scalable solutions that apply simplified methods such as TBM to enable reliable U-value estimation without expensive equipment or complex setups. Addressing these gaps, the present study introduces an intelligent thermal monitoring system that integrates low-cost sensors and open-source IoT infrastructure to implement the TBM approach. By collecting interior air, exterior air, and interior surface temperature data, and wirelessly transmitting them to a cloud-based platform for real-time visualization and post-processing, the system enables continuous thermal monitoring, early detection of insulation issues, and practical support for energy audits and retrofitting strategies in pursuit of decarbonization goals.

2. Sensor selection for thermal monitoring system

The implementation of any effective building monitoring system relies on the accurate and consistent capture of temperature data from both the ambient environment and structural surfaces (B. Mobaraki et al., 2024). In recent years, a wide range of low-cost temperature sensors have become commercially available, offering viable alternatives to expensive industrial-grade equipment. These sensors vary in precision, communication protocol, measurement type (contact or non-contact), and application domain (Soriano et al., 2021). Such diversity makes them particularly appealing for scalable, budget-friendly monitoring systems aligned with energy efficiency objectives (Vaghefi et al., 2021).

For ambient temperature measurement, several affordable and widely supported sensors have been used in environmental and indoor climate studies. Among these are the SHT10 einzadehfard & Mobaraki, 2025), SHT21 (Suárez et al., 2018), and SHT35 (B. Mobaraki et al., 2022b). These devices are compatible with the NodeMCU ESP8266 and similar open-source development boards, enabling easy integration into customized sensing platforms. Each sensor has distinct performance features, including differing operating voltages, digital or analog output options, and communication protocols such as I2C or SPI. Their detection ranges typically span from -55 °C to 125 °C, with varying accuracy between ±0.2 °C and ±0.5 °C. The pricing of these sensors is highly accessible, generally ranging from €4.95 to €29.60, making them well-suited for large-scale or distributed monitoring networks.

In parallel, measuring the surface temperature of building elements requires sensors designed for contact or infrared detection. Some of the most prominent options in this category include the DS18B20 (Ahmad Nia et al., 2016), MAX30205 (Abu Bakar et al., 2020), MAX30208 (Giordano, 2021), and thermistors such as the NTC type (Salah et al., 2024). Like ambient sensors, these are often compatible with microcontrollers and are designed for a variety of applications, including structural diagnostics, biomedical sensing, and HVAC monitoring. The selection criteria for surface sensors generally center on factors such as measurement resolution, time response, operating temperature range, and method of installation (i.e., probe-type, adhesive-backed, or embedded).

After reviewing and evaluating multiple options for both ambient and surface monitoring, two sensors were selected for the development of the intelligent transmittance meter introduced in this study (Yoon et al., 2017). The SHT35 was chosen for monitoring ambient environmental conditions, while the DS18B20 was selected for capturing surface temperature data of the wall element. These choices were based on a combination of technical performance, cost-efficiency, and ease of integration into the proposed IoT-based system.

The SHT35 sensor stands out as one of the most reliable and frequently cited devices for environmental temperature and humidity monitoring. It offers a dual-function capability, simultaneously measuring relative humidity and temperature, which is advantageous for multi-parameter assessments. It operates across a broad voltage range (2.15 V to 5.5 V), making it compatible with a wide range of microcontroller platforms. The SHT35 communicates via the I2C protocol at speeds up to 1 MHz, enabling fast and stable data transfer. In terms of detection range, the sensor can measure humidity from 0% to 100% RH and temperature from -40 °C to 125 °C. Accuracy levels are notable, with temperature measurements precise to ±0.2 °C and humidity accurate to ±1.5% RH. Additionally, the sensor's response time is approximately 8 seconds, providing relatively real-time data capture for ongoing thermal assessments.

For surface temperature monitoring, the DS18B20 was selected due to its widespread use in thermal diagnostics and its compatibility with both indoor and outdoor applications. It is a digital, contact-based sensor with a waterproof variant available for field deployment. The DS18B20 operates within a temperature range of -55 °C to 125 °C, matching the expected conditions encountered in building envelope testing. It communicates through the 1-Wire protocol, allowing multiple sensors to be connected in parallel using only a single data line, which simplifies wiring in multi-point setups. Its measurement accuracy reaches ±0.5 °C, which is acceptable for energy efficiency diagnostics, particularly in systems focused on trend analysis rather than laboratory-grade precision.

The final selection of these two sensors balances key considerations such as cost, compatibility, accuracy, and operational reliability. Together, they support a robust yet economical platform for thermal data acquisition as part of a broader IoT-enabled monitoring system. These components were integrated into the prototype device used in the experimental validation phase of this study, with performance details and setup parameters described in the following sections (Muhy Al-Din et al., 2023; Nikoofam et al., 2020).

2.1. Internet of Things Hyper Efficient Arduino Transmittance-meter (IoT HEAT)

The proposed intelligent monitoring system, referred to as IoT HEAT (B. Mobaraki et al., 2022a), was designed and implemented to enable real-time thermal monitoring of building envelopes through a network of low-cost, high-accuracy temperature sensors. The system architecture consists of two distinct modules: an indoor module and an outdoor module, each tailored to measure key environmental and surface parameters necessary for U-value estimation based on the TBM.

The indoor module was equipped with three non-contact infrared temperature sensors (MLX90614) strategically installed across selected interior surfaces. These sensors are capable of measuring surface temperatures without requiring physical contact, allowing for accurate and unobtrusive monitoring of inner wall temperatures over time. The three MLX sensors were distributed to capture spatial variability across different parts of the wall and ceiling surfaces, where thermal bridging or insulation weaknesses might occur (Komarizadehasl et al., 2020).

In addition to surface temperature readings, some MLX sensors were oriented to measure the ambient indoor air temperature, thereby reducing the need for additional sensors and minimizing system complexity. The MLX90614 sensors offer high accuracy (±0.2 °C in the 0–50 °C range), and communicate via the I2C protocol, which simplifies wiring and data acquisition. All sensors were interfaced with a central microcontroller unit, which collected and pre-processed the raw data before transmission.

The outdoor module was designed to record external temperature conditions and ensure continuity in thermal gradient measurements. For this purpose, three SHT35 sensors were deployed on the building's exterior façade. These sensors were positioned to avoid direct exposure to sunlight and precipitation, using radiation shields and waterproof enclosures to ensure accurate ambient readings. The SHT35 sensor is known for its high precision in both temperature and humidity measurements, with a temperature accuracy of ±0.2 °C and operating voltage between 2.15 V and 5.5 V.

Each SHT35 sensor was connected to a second microcontroller unit, dedicated to the outdoor module, which managed data collection and communication. This configuration enabled the parallel measurement of environmental conditions from multiple points, accounting for variations in wind exposure, shading, and microclimatic conditions around the building envelope.

The IoT HEAT system was designed for wireless data transmission using Wi-Fi communication modules integrated with the indoor and outdoor microcontrollers. Sensor data from both modules were transmitted in real time to a cloud-based IoT platform, where data were stored, visualized, and processed. The cloud platform provided a user-friendly interface for monitoring live temperature readings, downloading historical data, and visualizing thermal behavior across selected zones.

The system architecture supports continuous operation, allowing users to track thermal performance dynamically, identify insulation issues, and generate data for energy audits or retrofitting decisions. Moreover, the cloud-based post-processing pipeline facilitated the automatic calculation of U-values using the TBM methodology, enabling engineers to evaluate envelope efficiency without manual data manipulation.

This modular and scalable installation method demonstrates the practicality of deploying low-cost, intelligent monitoring systems in both research and real-world applications, contributing directly to energy optimization and decarbonization in the built environment.

3. Measurement technique

To support global efforts in reducing building-related carbon emissions, it is essential to quantify the thermal performance of building components accurately and cost-effectively. Various international standards provide structured guidelines for determining key thermal parameters, including heat transfer coefficients and U-values. These protocols establish requirements for test durations, sampling frequencies, treatment of anomalies, and verification methodologies, all of which impact the reliability of measurements. Among the most widely referenced are:

(1) ISO 6946:2017, which outlines a theoretical framework for calculating the U-value of building elements based on material thickness and known thermal conductivities. It is primarily used in conjunction with TBM.

(2) ISO 9869:2014, which describes the use of HFM for in-situ measurement of U-values under steady-state conditions. However, achieving a perfect steady state is practically impossible, so the standard allows long-duration measurements (typically 72 hours or more) to generate a time-averaged U-value.

(3) ISO 6781-3:2015, which applies infrared thermography techniques to assess building envelope performance in terms of heat transfer, air leakage, and moisture content.

(4) ISO 10456:2007, which standardizes the thermal properties of construction materials for use in simulation-based or analytical calculations of building thermal behavior.

Although these standards form the backbone of building energy diagnostics, their application in real-world settings can be both time-consuming and expensive. Factors such as long measurement windows, the need for multiple sensors, sensitivity to weather variability (e.g., solar gain, wind, cloud cover), and the required temperature gradients contribute to the overall complexity and cost of implementation (B. Mobaraki et al., 2015). Consequently, many of these traditional methods are less practical for widespread use, especially in large-scale monitoring or rapid diagnostics scenarios.

Given these limitations, the TBM emerges as a promising alternative. TBM offers a simplified yet effective means of estimating U-values without the need for heat flux sensors. Instead, it utilizes easily measurable temperature values indoor air temperature (Ti), outdoor air temperature (Te), and the indoor surface temperature of the wall (Tsi) to infer the thermal transmittance. This approach is rooted in Newton's law of cooling, which states that the rate of heat transfer between an object and its environment is directly proportional to the temperature difference between them.

TBM leverages this principle by formulating the U-value as the ratio of average temperature differences across the envelope. Specifically, Equation (1) calculates U by dividing the sum of the differences between indoor and surface temperatures by the sum of the differences between indoor and outdoor air temperatures, then multiplying the result by the internal convective heat transfer coefficient ($W/m^2.K$), which is ta ken as 7.69 W/m²·K, according to ISO 6946:2017.

$$U = \frac{\sum_{j=1}^{n}(T_{i(j)} - T_{si(j)})}{\sum_{j=1}^{n}(T_{i(j)} - T_{e(j)})} h_{ci} \quad (1)$$

This formulation is adapted from the traditional heat flux-based method (Equation 2), where U is derived from the average heat flux qqq over the average temperature gradient between the interior and exterior:

$$U = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n}(T_{i,j} - T_{e,j})} \quad (2)$$

The essential distinction is that TBM eliminates the need for direct heat flux measurement, significantly reducing the cost and complexity of implementation. This makes it particularly attractive for low-cost, intelligent monitoring systems aimed at enhancing energy efficiency across a wide variety of building types. The TBM framework is ideally suited to integration with IoT technologies, allowing for scalable and real-time thermal monitoring in support of energy audits, retrofitting decisions, and decarbonization strategies.

In this work, we adopt TBM as the computational basis for our intelligent monitoring system. By combining open-source microcontrollers with affordable, high-accuracy temperature sensors, we implement a fully automated, scalable, and low-cost platform to measure the three key parameters required for TBM-based U-value estimation. This not only aligns with international standards but also paves the way for more accessible energy diagnostics in both residential and commercial buildings.

3.1. Test description

The IoT HEAT monitoring system was installed on a targeted residential building located in Barcelona, selected for its representative construction typology and ease of access for sensor deployment. To ensure optimal conditions for thermal monitoring, the system was installed on an exterior wall with direct exposure to outdoor weather and minimal shading, allowing for stable and measurable thermal gradients between the indoor and outdoor environments. The indoor module, equipped with contactless temperature sensors, was mounted on interior wall surfaces using non-invasive supports to ensure fixed positioning throughout the test. In parallel, the outdoor module, containing high-precision environmental sensors, was mounted on the external façade using waterproof enclosures and radiation shields to minimize the effects of direct sunlight and precipitation (A. Mobaraki et al., 2025). The monitoring campaign was carried out over a continuous 7-day period, during which temperature data were recorded at regular intervals to capture daily thermal fluctuations. This duration allowed for the observation of varying ambient conditions, improving the robustness of the U-value estimation using the TBM. All data were transferred in real time to a cloud-based platform, enabling continuous thermal monitoring and post-processing analysis.

4. Result and discussion

Figure 1 presents the variation of indoor air temperature recorded by the indoor module of the IoT HEAT system over the monitoring period. The data were captured using three MLX90614 contactless infrared sensors, with measurements showing a minimum indoor air temperature of 15.53 °C and a maximum of 24.71 °C. These values reflect typical indoor thermal fluctuations influenced by both external environmental conditions and internal factors such as occupancy, heating activity, and ventilation.

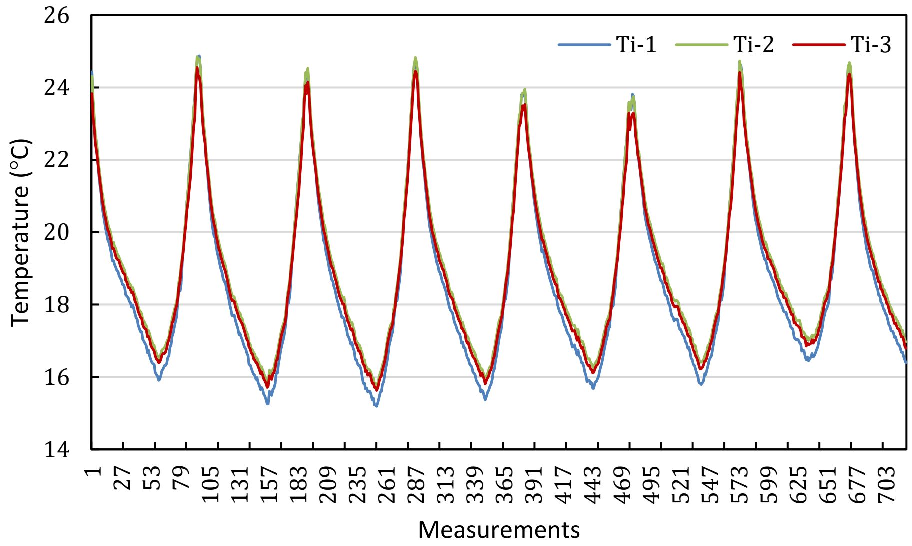

Figure 1. Variation of indoor temperature captured by the indoor module of IoT HEAT.

Figure 2 illustrates the corresponding variation in indoor surface temperature, measured by the same indoor module. The surface temperature of the interior wall ranged from a minimum of 15.47 °C to a maximum of 21.31 °C. As expected, the surface temperature showed a narrower range compared to the air temperature due to the wall's thermal mass, which buffers rapid fluctuations. The close proximity of Ti and Tsi during minimum values suggests minimal heat gain or active heating during night hours or unoccupied periods, whereas the divergence at maximum values indicates a moderate accumulation of heat, likely influenced by daytime occupancy or solar gain. Together, these figures demonstrate the ability of the IoT HEAT system to capture both ambient and surface temperature dynamics with sufficient resolution to support thermal performance assessment. The consistency and accuracy of the recorded temperatures validate the system's application for in-situ monitoring and provide a reliable basis for U-value estimation using the TBM.

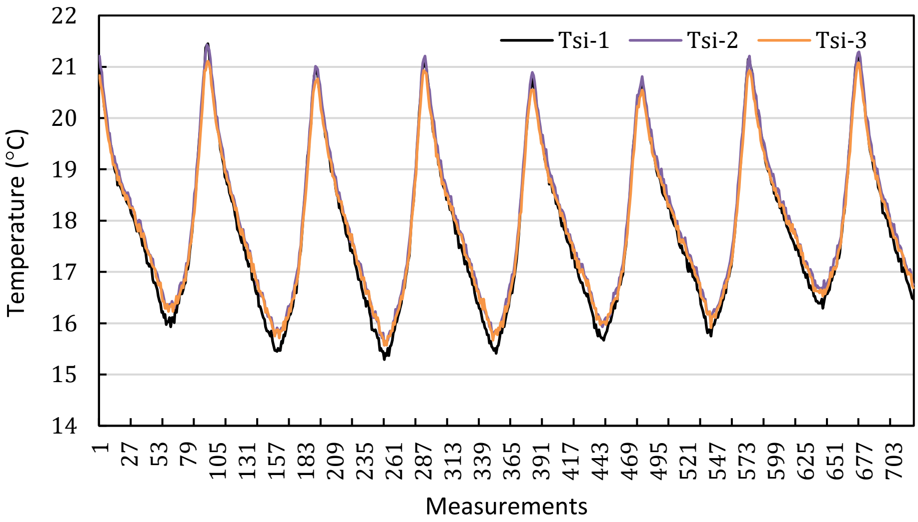

Figure 2. Variation of indoor surface temperature captured by the indoor module of IoT HEAT.

The variations of indoor surface temperature, and outdoor temperature observed during the monitoring period are illustrated in Figure 3. The recorded indoor air temperature ranged from a minimum of 15.53 °C to a maximum of 24.71 °C, reflecting the building's natural thermal dynamics and its interaction with occupancy patterns and internal heat sources. The indoor surface temperature showed a slightly narrower range, varying between 15.47 °C and 21.31 °C, indicating the thermal inertia of the wall materials and their slower response to ambient air temperature fluctuations. Meanwhile, the outdoor temperature ranged from 3.31 °C to 16.73 °C, providing sufficient thermal gradient for accurate transmittance estimation using the TBM. The close alignment between the minimum indoor air and surface temperatures suggests minimal internal heat gain during the night or in unoccupied periods, while the noticeable gap between the maximum indoor air and surface temperatures implies a moderate level of heat accumulation during the day, potentially due to solar radiation, internal heating, or thermal bridging effects. These thermal patterns indicate that the IoT HEAT system successfully captured the dynamic thermal behavior of the building envelope in real conditions. The collected data set is robust and suitable for calculating the U-value of the wall element, offering a clear picture of the envelope's performance over time. Furthermore, the results emphasize the value of continuous, high-resolution thermal monitoring in understanding building behavior, diagnosing insulation performance, and supporting strategies for energy efficiency improvements and decarbonization in the built environment.

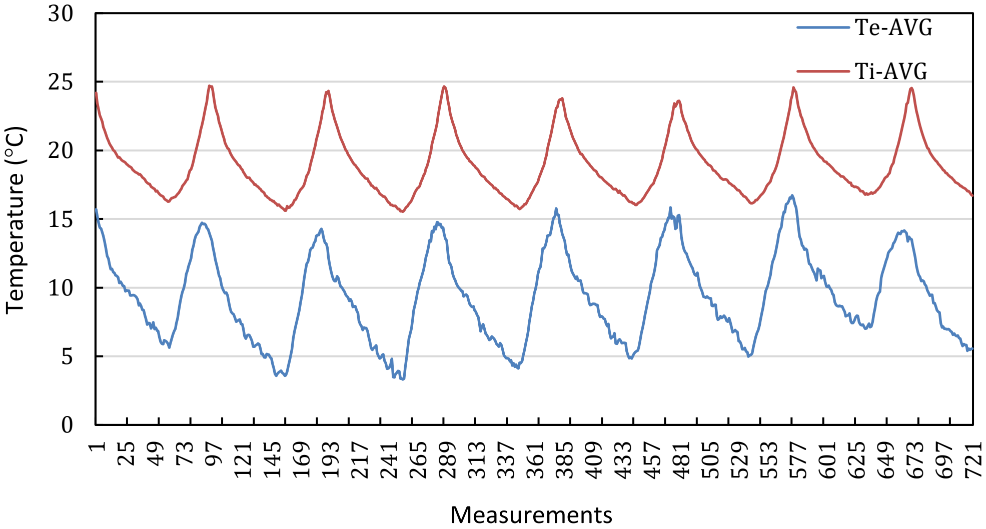

Figure 3. Variation of indoor surface temperature and outdoor temperature captured by the indoor module of IoT HEAT.

Figure 4 illustrates the evolution of the calculated U-value over time, derived using the TBM from the measured indoor air temperature, outdoor air temperature, and indoor surface temperature. The graph reflects the U-value distribution across a range of temperature differences between Ti and Te, specifically from 5 °C to 13 °C, a range that aligns with the minimum recommended gradient for in-situ transmittance evaluations. As seen in the figure, the calculated U-values exhibit a notable sensitivity to the thermal gradient between the interior and exterior environments. In particular, when the difference between Ti and Te is relatively small (e.g., close to 5 °C), the resulting U-values display greater variability, often fluctuating sharply due to increased sensitivity to small temperature measurement deviations. This is a known limitation of TBM and similar indirect methods, where low thermal gradients tend to amplify numerical instabilities in the denominator of the U-value equation, resulting in broader dispersion.

In contrast, as the temperature difference increases (approaching 13 °C), the calculated U-values become more stable and concentrated around a central tendency, indicating improved reliability of the estimation. This behavior highlights the importance of selecting appropriate monitoring periods with sufficient indoor-outdoor contrast to ensure accurate thermal performance assessment. In the present study, the computed U-values ranged from a minimum of 0.004 W/(m²·K) to a maximum of 3.86 W/(m²·K), with an average value of 0.97 W/(m²·K) over the monitoring period. While some extreme values likely stem from transient fluctuations or sensor noise during low-gradient intervals, the average U-value falls within a plausible range for non-insulated or poorly insulated exterior walls, as referenced in thermal performance standards. These results underscore the capability of the IoT HEAT system to generate high-frequency, time-resolved U-value data in real-time, which can be used not only for insulation assessment but also for continuous building diagnostics and retrofit planning.

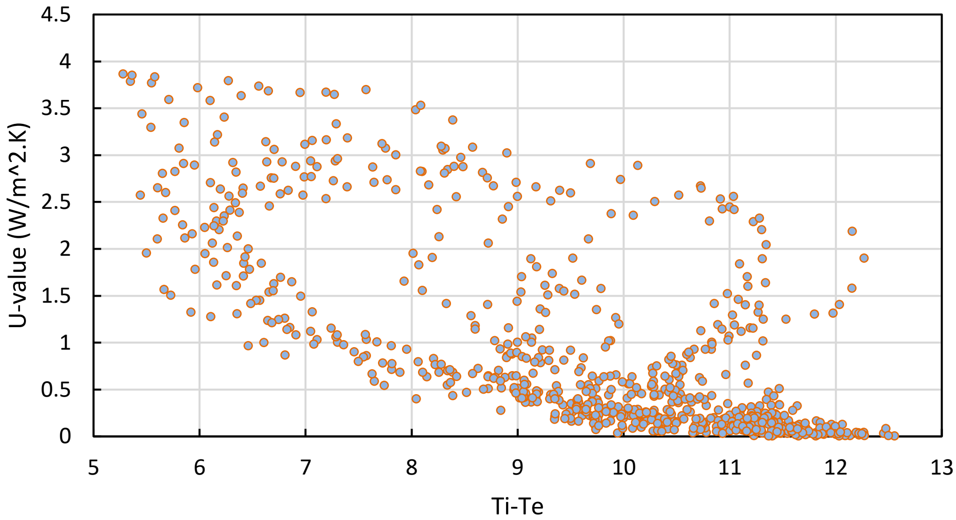

Figure 4. The obtained U-value from the IoT HEAT at different time steps.

4.1. Limitations of study

Despite the promising results demonstrated by the IoT HEAT system, this study has several limitations that should be acknowledged. First, the monitoring period was limited to seven days, which, although sufficient to validate short-term system performance, may not fully capture seasonal variations or long-term thermal behavior of the building envelope. Second, the experimental setup was applied to a single residential building in Barcelona, which may limit the generalizability of the results to other building typologies, climates, or construction systems. Third, while the TBM proved effective, its accuracy is highly sensitive to the indoor-outdoor temperature gradient; therefore, low gradient conditions may introduce uncertainties that were not fully explored in this study. Additionally, external environmental factors such as wind, solar radiation, and sensor placement could impact temperature readings and, consequently, U-value estimations. Finally, although the system was designed to be modular and scalable, further validation in diverse real-world scenarios is necessary to assess its robustness, reliability, and integration potential with other building energy management tools.

5. Conclusion

This study presented the development and deployment of IoT HEAT, a low-cost, intelligent monitoring system designed to assess the thermal performance of building envelopes in real time. The system integrates contactless infrared sensors (MLX90614) and high-precision environmental sensors (SHT35) into an indoor and outdoor monitoring setup capable of capturing the key parameters required for U-value estimation using the temperature-based method (TBM). The modular design and IoT-based architecture allowed for continuous, high-resolution temperature data acquisition and wireless transmission to a cloud platform for real-time visualization and post-processing. The system was installed on a residential building in Barcelona, where it operated continuously for seven days under typical environmental conditions. Indoor air temperatures ranged from 15.53 °C to 24.71 °C, while the indoor surface temperature varied between

15.47 °C and 21.31 °C, and the outdoor temperature fluctuated from 3.31 °C to 16.73 °C. These readings confirmed the capability of the system to detect daily thermal dynamics and build a reliable dataset for envelope analysis.

The calculated U-values, derived from the collected temperature data, demonstrated the strong sensitivity of TBM to the indoor-outdoor temperature gradient. As expected, the accuracy and stability of U-value estimations improved as the thermal gradient increased, with calculated values ranging from 0.004 to 3.86 W/(m²·K) and a mean U-value of 0.97 W/(m²·K). These results underscore the importance of selecting suitable monitoring conditions to minimize uncertainty in transmittance estimation. Overall, the results validate that IoT HEAT is an effective and scalable tool for assessing thermal performance of building envelopes in a practical and affordable way. The system aligns with current international standards, avoids the use of expensive heat flux sensors, and offers a viable solution for large-scale deployment in both research and real-world energy audit applications. Its ability to support data-driven decision-making makes it highly relevant in the context of building energy efficiency improvements, retrofitting strategies, and long-term decarbonization goals in the built environment.

Future work will focus on extending the system's capabilities through multi-zonal monitoring, adaptive sampling strategies based on weather predictions, and integration with digital twins and building energy management systems.

Conflicts of Interest

The Authors declare that there is no conflict of interest.

Data availability statement

The data that support the findings of this study are available from the corresponding author, M.B., upon reasonable request.

Institutional Review Board Statement

Not applicable.

CRediT author statement:

Conceptualization: M.A, M.B; Data curation: M.A, M.B; Formal analysis: H.E, M.B; Investigation: D.S; Methodology: N.M, M.B, M.Z; Supervision: N.M, M.B, M.Z; Validation: M.Z, M.B; Visualization: M.B; Writing - original draft: M.A, M.B; Writing - review & editing: M.Z, M.B, H.E. All authors have read and agreed to the published version of the manuscript.

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