

Enhancing Building Energy Efficiency through an Innovative Rapid Diagnostic Method for Thermal Protection of Envelope Structures

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A substantial potential for improving energy efficiency in this sector lies in innovative technologies for detecting and eliminating hidden defects in thermal insulation of building envelope structures, based on the analysis of thermal imaging inspection results. The innovative method for rapid diagnostics of the actual condition of building thermal protection and heat distribution systems, based on thermograms of the building envelope obtained through thermal imaging is proposed. This method allows for the identification of energy-economic and environmental losses resulting from hidden defects in building structural elements that cause excessive heat energy losses, as well as the assessment of the costs associated with their remediation. The results of the study demonstrate the effectiveness of the proposed method for quickly identifying thermal protection defects and making economically justified technical decisions regarding the feasibility of their elimination. The potential for improving the energy efficiency of the investigated buildings by addressing the identified thermal defects is found to range from 2.3 % to 4.4 % of the buildings' annual heat energy requirements.

1. Introduction

The building sector in the European Union is responsible for roughly 43 % of overall energy demand and contributes nearly 40 % of global CO₂ emissions linked to energy use and industrial processes (WBCSD, 2024). Addressing these environmental impacts necessitates prioritising the renovation of existing buildings, guided by circular economy frameworks. Since approximately 80 % of household energy consumption in Europe is attributed to heating (European Parliament, 2024), enhancing the thermal performance of buildings and upgrading heating infrastructure – particularly through the application of renewable energy technologies for both space heating and hot water – plays a vital role in reducing energy use and emissions.

Reducing energy demand in residential heating and cooling can be achieved by implementing both passive and active measures, such as employing intelligent indoor temperature management systems and enhancing building envelopes by application of new materials. Moreover, these innovations can be incorporated into building energy retrofitting projects, enhancing a building's energy systems and decreasing overall energy consumption. Such interventions yield multiple advantages, including reduced greenhouse gas emissions, increased operational efficiency, lower energy costs for both facility managers and occupants, and enhanced indoor comfort and health. Retrofit measures can vary in scope, from minor improvements like sealing gaps around windows and doors to prevent air infiltration, to more comprehensive renovations involving the replacement of roofing systems or significant components of HVAC infrastructure.

To account for the sustainability aspects at building renovation, the multi-objective approach with economic, environment and energy key performance indicators can be applied (Polyvianchuk et al., 2025). The main step of such renovation is the estimation of the building's current state, where an advanced energy audit underpins

renovation efforts for improvement. Inefficiencies in building structures, such as inadequate wall insulation, can contribute to up to 50 % of a building's total heating demand. Moreover, the design of heat demand for transferring to renewable energy sources plays a vital role in the cost and efficiency estimation. As such, detecting and addressing sources of thermal loss represents a highly effective strategy for lowering overall energy consumption in buildings. The comparison of thermometric and the thermographic methods for the analysis of the wall of the office of the building located in southern Europe was done by Rodríguez et al. (2024), where the estimation of thermal transmittance was applied for large building complexes by the aerial thermography. The research revealed that thermometric method needs 60 h, whereas thermography provides reliable results from 24 h monitoring. The stable data were achieved for the coldest winter night comparing with other day intervals and periods of the year.

The Infrared Thermography (IRT) enables to analyse the building envelope for the thermal leaks, air leaks, moisture and estimate the thermal transmittance of enclosures. However, the interpretation of the thermal images for defining the thermal anomalies of the building depends on the device being used for imaging and is affected by environmental conditions, solar radiation and wind speed. The heat loss detection from the building facades at cold climate using the deep learning method was proposed by Waqas and Araji (2024) and can detect the thermal anomalies on the building facades with 0.81 precision. The most limitation of the method is considered to be in the environmental conditions. To improve the reliability of IRT, the integration of the weather forecasting data with thermal imaging was proposed by Golosov and Cervone (2024), for evaluation of the building thermal performance in time. The method is based on deep learning and enables to account for ambient conditions while predicting thermal performance of the building facades over 24 and 48 h, for what it needs long preliminary monitoring of the building state. The quantitative infrared thermography of internal analysis of the building in Shenyang, China was applied for the buildings with different insulations by Li et al. (2024), showing that the highest temperature difference between indoor and outdoor temperature equal to 25 % lead to the smallest relative error of 1 % for the heat flow meter method. The referenced works prove, that the IRT is an effective tool for estimation of the state of the building façade but needs long time for measurements together with the proper weather conditions. The literature review highlights the need for a reliable and rapid diagnostic method that can be conducted on the coldest day of the year to minimize errors in estimating thermal leaks, which can be used for estimation of the thermal leakage of the building.

The primary objective of this research is to develop a comprehensive approach for identifying and recommending sustainable renovation actions for building envelopes, using IRT as the main diagnostic tool. By analysing thermal anomalies and heat loss patterns captured through IRT, the study aims to assess the current thermal performance of existing buildings and propose targeted retrofit actions that enhance energy efficiency, reduce environmental impact, and support long-term sustainability. For finding the localization of heat losses and to select the best of renovation action based on estimation of energy, environment and economic key performance, the rapid IRT method was developed. The method was validated on two buildings in different climatic regions of Ukraine, using different devices for IRT processing.

2. Method for rapid diagnostic of thermal protection of the envelope structures

The problem of selecting the best renovation measures for improvement of building's energy system, requires the initial renovation on the building envelope to minimize passive energy consumption, and will allow to select the renewable energy source designed for lowered energy consumption of the building. The current research proposes implementing the method for rapid diagnostic of thermal protection of the envelope structures, which allows to define the proper renovation actions (RAs) based on the principles of elimination of envelope's hidden defects, detected by the means of thermal imaging inspection of the building. The proposed methodology for processing the results of thermal imaging inspection of a building is aligned with the method of sequential improvement of building energy system presented by Polyvianchuk et al. (2025), and firstly requires the determination of the initial parameters of the energy, environmental and economic state of the observed building, namely: the annual demand for thermal energy – q (and specific heat consumption q_s taking into account the total heating area $S_{heating}$); fuel consumption (natural gas is considered) V_{fuel} ; pollutant emissions m_{CO_2} , m_{NO_x} ; expenditure of financial resources for heating f_{heat} .

The annual energy demand of the building in its current state is determined with the fixed indoor air temperature level, what meets the country's building standards (in the present work regulatory conditions for Ukraine were used), and is calculated by the following relation:

$$q = q_{en_structures} + q_{inf} + q_{tubes_in} + q_{HWS} - k_{reg} \cdot (q_{indoor_heat} + q_{solar_heat}) \quad (1)$$

where $q_{en_structures}$ is the thermal energy loss by the building envelope through the enclosure structures, Wh; q_{inf} is the thermal energy loss of the building due to infiltration, Wh; q_{tubes_in} is the heat losses from the external

surfaces from pipelines of internal heating system and/or hot water system (HWS), and closed regulation valves installed on the pipelines in unheated rooms, Wh; q_{HWS} is the heat losses from the equipment for HWS preparation, such as boilers and heat exchangers, Wh; k_{reg} is the coefficient, which indicates the presence ($k_{reg} = 1$) or absence ($k_{reg} = 0$) of an automated “smart” control heating system, non-dimensional; q_{indoor_heat} is the amount of thermal energy released by internal heat sources, such as heat from people or electronics, Wh; q_{solar_heat} is the amount of thermal energy entering the building due to the solar radiation through external enclosing structures, Wh. The present work determines the estimation and influence of thermal energy loss by the building envelope through the enclosure structures by IRT method, the estimation of other parameters was described by Polyvianchuk et al. (2025).

Step 1 – estimation of heat leaks by IRT rapid diagnostic method. To estimate the heat losses from the discovered thermal anomalies of the building envelope, the following initial parameters should be defined:

- actual outer temperatures: outside air temperature t_{air}^{out} at the time of thermal imaging and temperatures of the building envelope obtained from the IRT, t_{env}^{out} , °C;
- value of external air temperature taken as a base for calculations according to the regional recommendations for buildings, t_{base}^{out} , °C;
- the comfort air temperature inside the building, which is estimated according to the building regulations for different types as residential or commercial, and the purpose of use of the rooms, t_{base}^{in} , °C;
- the area of each i -th part of the building façade with thermal anomalies detected by IRT, S_i^{defect} , m²;
- average outdoor air temperature for the heating period according to statistical data t_{av}^{out} , °C;
- duration of the heating period for the region $T_{heating}$, h, taken in accordance with building regulations;
- the heat transfer coefficient of the outer surface of the i -th part of the enclosing structure, α_i^{env} , W/(m²·°C);
- coefficient of thermal resistance of the i -th part of the enclosing structure of the building façade, R_i^{env} , (m²·°C)/W.

The determination of the background value in W/m² of the specific heat flux through the i -th part of the enclosing structure of the building façade is performed using the following relation:

$$q_{base}^{env} = \frac{t_{base}^{in} - t_{base}^{out}}{R_i^{env}} \quad (2)$$

Determination of the actual value of the specific heat flux through the i -th part of the enclosing structure of the building façade with thermal anomalies, in W/m²:

$$q_{actual}^{env} = \alpha_i^{env} \cdot (t_{env}^{out} - t_{air}^{out}) \quad (3)$$

Estimation of the excess heat loss through the i -th part of the enclosing structure of the building façade with thermal anomalies, in Wh:

$$\Delta q_{en_st} = \left(q_{actual}^{env} \cdot \frac{t_{base}^{in} - t_{av}^{out}}{t_{base}^{in} - t_{air}^{out}} - q_{base}^{env} \cdot \frac{t_{base}^{in} - t_{av}^{out}}{t_{base}^{in} - t_{base}^{out}} \right) \cdot S_i^{defect} \cdot T_{heating} \quad (4)$$

Step 2 – optimal selection of renovation actions to cover the discovered heat leaks. The proposed renovations should minimize the q_s value, taking the maximal energy demand as the upper boundary determined by the regulations for the specific type of buildings. For the optimal selection of the renovation actions for building heating system the method based on estimation of their economic, environmental, and energy efficiency was applied (Polyvianchuk et al., 2025). The energy efficiency (E_1) is defined as the difference between current energy consumption of the building q and the value after completing the proposed RA or several RAs, $q_{RA(i)}$. The environmental efficiency (E_2) is determined based on the quantity of emissions $m_{pollutant}$ for initial state and after the implementation of the renovation actions $m_{pollutant_RA(i)}$. The economic efficiency (E_3) is derived from the investment funds available to repair the thermal defect, denoted as C_{TD} , and represents the potential cost savings of implementation of proposed RAs ($C_{TD_RA(i)}$). The equations for the efficiency criteria are:

$$E_1 = q - \sum_{i=1}^n q_{RA(i)}; \quad E_2 = m_{pollutant} - \sum_{i=1}^n m_{pollutant_RA(i)}; \quad E_3 = C_{TD} - \sum_{i=1}^n C_{TD_RA(i)} \quad (5)$$

The cost of work to eliminate the identified thermal defects ($C_{TD_RA(i)}$) that do not require additional analysis of the causes of their occurrence is determined based on monitoring and analysis of commercial offers for the last five years. The estimation of the energy saving potential of the building by proposing renovation actions to eliminate the identified thermal defects of the i -th part of the enclosing structure, Δp_i^k , where k is the group number, enables to distribute all the proposed RAs on the following groups:

- Δp^1 representing the quick-payback RAs, which allow to eliminate thermal defects of the building façade with payback periods, $T_{pp} \leq 4$ y,
- Δp^2 , which are medium-payback RAs, where T_{pp} varies from 4 to 8 y,
- Δp^3 for the RAs with long-payback period with $T_{pp} \geq 8$ y,
- $\Delta p^{n/d}$ is introduced for the cases, where the estimation of the cost and payback periods is non defined and requires additional research.

Then the cumulative value for each group is calculated, enabling to estimate the efficiency of implementation of the proposed RAs and to select the optimal renovation actions to be done.

3. Case studies

To check the applicability of the method for different climatic regions of Ukraine and application of different IRT equipment, two case studies for the commercial buildings were conducted. The presented data are done for the prices actual on 28 Feb 2025. In the case study 1, the investigation was done for state municipality building "Kharkiv Palace of Children's and Youth Creativity of the Kharkiv City Council in Kharkiv Region", presented in Figure 1a. The energy consumption of the building includes heat energy for heating and hot tap water supply, and electricity. The building is connected to the centralized district heating system of the city. The basic data concerning the observed building for case study 1 are listed in Table 1.

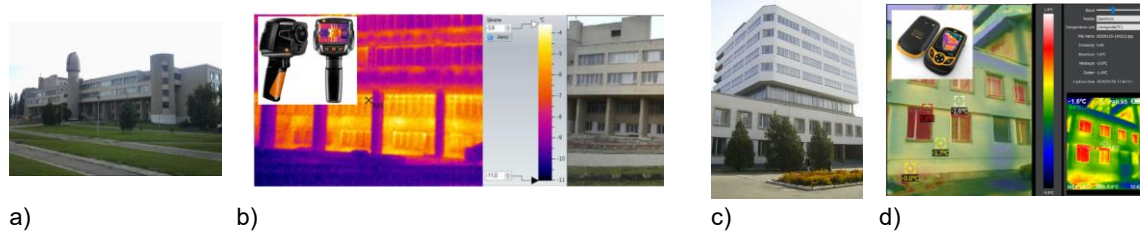


Figure 1: The view of the buildings for case studies and used devices for conducting thermal imaging inspections: a) building for case study 1; b) TESTO 871; c) building for case study 2; d) Walcom HT-A1

Table 1: The data of the inspected buildings

Parameters	Case study 1	Case study 2
Year of commissioning	1993	1985
Number of floors	4 and 2	2 and 9
Total floor area for heating, m ²	15,159.0	8,454.5
Annual heat load for heating, MWh	2,256	1,216

For the modernisation of building enclosing structures in accordance with the developed method for rapid diagnostic, the basic design parameters for commercial building in Kharkiv region were taken, namely t_{base}^{out} equal to -23 °C, t_{base}^{in} equal to 18 °C, t_{av}^{out} is -1.0 °C, the duration of the heating period for Kharkiv region $T_{heating}$ is 4,296 h, the heat transfer coefficient of the outer surface of the building made from clay bricks in all the places α_1^{env} was taken equal to 23 W/(m²·°C). The price for heat energy in the Kharkiv region is equal to 98.95 EUR/Gcal. The estimated parameters for the initial state of the building are presented in Table 2. The IRT was performed using the thermal imaging camera TESTO 871 with resolution 480x360 pixels equipped with software testo IRTSoft (Figure 1b). The precision of both devices is ± 2 °C or ± 2 %. The resulting thermal images with 15 thermal anomalies selected for the current research, are presented in Figure 2a. The defining of the parameters for each found heat loss, including its surface area S_i^{defect} , and estimation of the energy saving potential from undertaking renovation action to eliminate each loss, with corresponding pay-back period and distribution of proposed RAs on the groups, is listed in Table 3, where each thermal image (TI) is listed payback increasing order. Each listed RAs represents the optimal choice selected from several possible alternatives in terms of insulation materials and their thickness for walls, doors, and window glazing.

Table 2: Parameters of the initial energy, environmental and economic state of the investigated buildings

Object	q , MWh	q_s , MWh/m ²	V_{fuel} , $\times 10^3$ m ³	m_{CO_2} , $\times 10^3$ kg	m_{NO_x} , kg	f_{heat} , $\times 10^3$ EUR
Case study 1	2,256	148.8	261.6	138	863	192.3
Case study 2	1,216	143.8	161.2	85.5	532	75.34

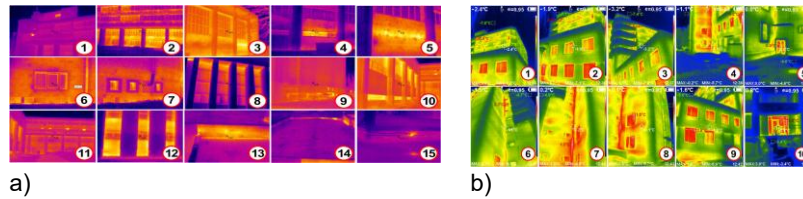


Figure 2: Results of thermal imaging inspection of observed buildings: a) case study 1; b) case study 2

Table 3: Parameters of the initial energy, environmental and economic state of the case study 1

RA #	TI	Envelope structure	Efficiency parameters of the proposed RAs					$C_{TD_RA(i)}$, $\times 10^3$ EUR	T_{pp} , y	Δp , %	Δp^k , %
			Δq_{en_st} , MWh	E_1 , $\times 10^3$ m ³	$E_{2_CO_2}$, $\times 10^3$ kg	$E_{2_NO_x}$, kg	E_3 , $\times 10^3$ EUR				
1	12	Wall	4.96	0.67	0.36	1.18	0.419	0.5	1.2	0.22	$\Delta p^1 = 1.33$
2	1	Window	0.36	0.05	0.03	0.09	0.03	0.04	1.3	0.02	
3	2	Wall 1	0.33	0.04	0.02	0.08	0.029	0.04	1.4	0.01	
4	2	Wall 2	1.54	0.21	0.11	0.37	0.128	0.19	1.5	0.07	
5	3	Wall 1	0.33	0.04	0.02	0.08	0.027	0.04	1.5	0.01	
6	14	Wall	0.93	0.13	0.07	0.22	0.079	0.13	1.6	0.04	
7	15	Wall	0.15	0.02	0.01	0.04	0.013	0.02	1.8	0.01	
8	3	Wall 2	0.17	0.02	0.01	0.04	0.014	0.03	1.9	0.01	
9	5	Wall	2.30	0.31	0.17	0.55	0.199	0.38	1.9	0.10	
10	13	Wall	2.27	0.31	0.16	0.54	0.196	0.43	2.2	0.10	
11	7	Wall	15.81	2.15	1.14	3.76	1,335	4.94	3.7	0.70	
12	4	Windows	0.82	0.11	0.06	0.20	0.07	0.27	3.8	0.04	
13	6	Wall	8.07	1.10	0.58	1.92	0.691	3.04	4.4	0.36	$\Delta p^2 = 1.11$
14	8	Windows	10.35	1.41	0.75	2.46	0.877	4.03	4.6	0.46	
15	9	Wall	6.52	0.89	0.47	1.55	0.559	3.13	5.6	0.29	
16	11	Wall	13.26	1.80	0.96	3.16	1,133	9.63	8.5	0.59	$\Delta p^3 = 0.10$
17	10	Wall 1	9.35	1.27	0.67	2.23	0.799	6.79	8.5	0.41	
18	10	Wall 2	8.51	1.16	0.61	2.03	0.730	Not defined	0.38	$\Delta p^{n/d} = 0.98$	
19	10	Windows	13.43	1.82	0.97	3.20	1.148	Not defined	0.60		

Table 4: Parameters of the initial energy, environmental and economic state of the case study 2

RA #	TI	Envelope structure	Efficiency parameters of the proposed RAs					$C_{TD_RA(i)}$, $\times 10^3$ EUR	T_{pp} , y	Δp , %	Δp^k , %
			Δq_{en_st} , MWh	E_1 , $\times 10^3$ m ³	$E_{2_CO_2}$, $\times 10^3$ kg	$E_{2_NO_x}$, kg	E_3 , $\times 10^3$ EUR				
1	9	Windows	1.50	0.20	0.11	0.36	0.093	0.09	1.0	0.07	$\Delta p^1 = 0.83$
2	1	Windows	0.85	0.12	0.06	0.20	0.053	0.07	1.3	0.07	
3	10	Door	4.81	0.65	0.35	1.14	0.298	0.56	1.9	0.40	
4	5	Door	1.23	0.17	0.09	0.29	0.076	0.18	2.4	0.10	
5	1	Wall	0.77	0.10	0.06	0.18	0.048	0.16	3.4	0.06	
6	6	Wall	1.54	0.21	0.11	0.37	0.095	0.36	3.8	0.13	
7	7	Wall	0.83	0.11	0.06	0.20	0.051	0.22	4.3	0.07	$\Delta p^2 = 0.50$
8	8	Wall	2.64	0.36	0.19	0.63	0.163	0.72	4.4	0.22	
9	3	Wall	0.87	0.12	0.06	0.21	0.054	0.24	4.5	0.07	
10	2	Wall	1.70	0.23	0.12	0.40	0.105	0.78	7.4	0.14	
11	9	Wall	0.81	0.11	0.06	0.19	0.050	0.49	9.9	0.12	$\Delta p^3 = 0.12$
12	2	Wall	0.94	0.13	0.07	0.22	0.058	Not defined	0.08	$\Delta p^{n/d} = 0.82$	
13	4	Wall	8.95	1.22	0.65	2.13	0.553	Not defined	0.74		

In the case study 2 the buildings of Vinnytsia National Technical University, which serve both educational and academic purposes, illustrated in Figure 1c, was investigated. The heating system of the building is connected to the district heating system of Vinnytsia, which uses natural gas for the preparation of heat carrier. The information about the building for case study 2 is listed in Table 1. The basic design parameters for commercial

building in Vinnytsia region are the following: t_{base}^{out} equal to $-21\text{ }^{\circ}\text{C}$, t_{base}^{in} equal to $18\text{ }^{\circ}\text{C}$, t_{av}^{out} is $-0.2\text{ }^{\circ}\text{C}$, $T_{heating}$ is $4,368\text{ h}$, α_{env}^{env} was taken for the clay bricks and equal to $23\text{ W}/(\text{m}^2\cdot^{\circ}\text{C})$. The price for heat energy in Vinnytsia region equals to $72.04\text{ EUR}/\text{Gcal}$. The estimated parameters for the initial state of the building are presented in Table 2. The IRT was performed using the thermal imaging camera Walcom HT-A1 with resolution 220×160 pixels with software IRTImage Tools (Figure 1d). The precision of both devices is $\pm 2\%$. The resulting thermal images with 10 thermal anomalies selected for the current research are presented in Figure 2b. The energy saving potential from proposed renovation actions is listed in Table 4.

The cumulative results of the assessment of the energy saving potential of two case studies from elimination of the identified thermal defects of the building façade are presented in Table 5. The total potential for increasing the energy efficiency of the two case studies due to improvement of the building envelope is 4.42% and 2.27% . The total cost of work to eliminate the identified thermal defects, that do not require additional analysis, comes to $33,900\text{ EUR}$ for the 1st and $3,900\text{ EUR}$ for the 2nd case study, while their payback periods vary in the range: from 1.2 to 8.5 y for the 1st and from 1.0 to 9.9 y for the 2nd case study.

Table 5: Cumulative results of energy saving potential due to implementation of the selected RAs

Object	$\Delta q_{en_{st}}$, MWh	E_1 , $\times 10^3\text{ m}^3$	$E_{2_{CO_2}}$, $\times 10^3\text{ kg}$	$E_{2_{NO_x}}$, kg	E_3 , $\times 10^3\text{ EUR}$	Δp^1 , %	Δp^2 , %	Δp^3 , %	$\Delta p^{n/d}$, %	$\sum \Delta p^k$, %
Case study 1	99.46	13.51	7.17	23.7	8.48	1.33	1.11	1.00	0.98	4.42
Case study 2	27.42	3.72	1.98	6.53	1.70	0.83	0.50	0.12	0.82	2.27

4. Conclusions

An innovative method of rapid diagnostic of thermal protection of the envelope structures using thermal imaging for defining the actions for building façade renovation, has been developed. The method allows to apply the energy, environmental and economic efficiency for selection of optimal RAs. The proposed method can be applied for estimation of economically justified procedure for the sequential implementation of RAs for building retrofit. The developed method was verified on two case studies observing the educational institutions located in different regions of Ukraine. The potential for increasing the energy efficiency of buildings was established, owing to the reduction of the annual heat consumption due to the implementation of RAs to eliminate the thermal anomalies of the building façade. The energy efficiency equals to 2.27% and 4.42% for two cases. A significant share of this amount, which comes to 0.83% and 1.33% can be realized by implementing quick payback measures with payback periods of up to 4 y. The proposed method can be used to support decision-making in actual building retrofit projects. The future work will incorporate stakeholder input and policy considerations, what will allow the method to be further adapted for various building types, climates, and regulatory contexts.

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