

Article

Decarbonizing Residential Stock in Southern Poland: A Technical Roadmap to NZEB Standards Based on a Retrofit Through HVAC Modernisation and Nature-Based Solutions

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Abstract

Decarbonising the existing residential sector is a central priority of European energy policy, yet masonry buildings from the early 2000s remain significantly underrepresented in net-zero energy building (NZEB) research. This study addresses this critical gap by evaluating a holistic deep retrofit of a representative single-family house in Cracow, Poland, providing a scalable model for the Central European housing stock. The methodology integrated structural and systemic interventions: eliminating thermal bridges via balcony removal, enhancing the envelope with 0.25 m of mineral wool ($\lambda = 0.036 \text{ W/m K}$), and installing innovative active triple-glazed windows ($U_w = 0.85 \text{ W/m}^2 \text{ K}$) with integrated electric heating foils. The energy system was transformed by replacing a coal-fired boiler with an 8 kW air-to-water heat pump and a 7 kWp photovoltaic array, complemented by a green roof on the western pitch for passive thermal buffering. Verified results demonstrate a radical reduction in the non-renewable primary energy (EP) index from 224.56 kWh/(m²·a) to 0.00 kWh/(m²·a), achieving full compliance with stringent “WT 2021” standards. Economic analysis reveals that the integrated approach is financially viable, with a simple payback time (SPBT) of 7.1 years when supported by available subsidies. This study concludes that the integration of active glazing, high-performance insulation, and nature-based solutions offers a replicable and economically sound roadmap for transforming legacy housing into zero-emission assets.

Keywords: net-zero energy buildings; deep renovation; heat pumps; photovoltaics; green roofs; thermal bridges; energy performance certificates; residential decarbonisation

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1. Introduction

Economic and civilisational developments are intrinsically linked to industrial transformations, with the construction sector playing a pivotal role [1,2]. Building activities significantly impact the ecological balance, necessitating operations within a rigorous framework of legal and technical constraints. In the current landscape of rising energy costs and evolving performance standards, adapting the existing residential stock represents a formidable technical and economic challenge [3]. Single-family dwellings, often designed under obsolete thermal insulation regimes, now require holistic retrofit

strategies. These must encompass envelope reinforcement, HVAC system upgrades, and the integration of renewable energy sources to satisfy contemporary efficiency benchmarks [4,5].

The European Union's strategic trajectory is defined by the "Renovation Wave" initiative, which aims to double annual energy renovation rates by 2030 to enhance resource efficiency [6]. This effort is bolstered by the "Fit for 55" package, targeting a 55% reduction in greenhouse gas emissions through revised directives on energy efficiency and building performance [7]. Furthermore, the REPower EU plan addresses the geopolitical necessity of reducing reliance on imported fossil fuels by increasing the building sector's energy efficiency target from 9% to 13% by 2030 [8]. Within the Visegrad Group, the scale of this challenge is particularly acute. In Poland, for instance, approximately 70% of single-family homes still rely on hard coal as their primary heating fuel, with over 5 million buildings classified as requiring urgent thermal modernisation [9,10].

In the Polish legislative context, the "Technical Conditions" (WT) serve as the primary instrument governing building design and retrofit. The "WT 2021" amendment introduced stringent limits on non-renewable primary energy (EP) demand and lowered the maximum allowable thermal transmittance coefficients (U-values) for building partitions [11,12]. In national methodology, the EP index acts as a key performance indicator. It represents the annual demand for non-renewable primary energy per square meter [kWh/(m²·a)] required for heating, cooling, ventilation, domestic hot water, and lighting. Future regulatory updates, scheduled for 2025 and 2026, will mandate the implementation of advanced building automation for the monitoring and regulation of HVAC systems. Additionally, glazing standards will be further tightened to a maximum U-value of 0.9 W/(m²·K). Currently, national authorities define energy efficiency as the capacity to maintain occupant comfort at the lowest possible energy expenditure [13]. The evolution of these requirements is substantial; as presented in Table 1, thermal transmittance standards for external walls and roofs have been tightened by over 80% since the 1960s.

Table 1. Historical evolution of thermal transmittance requirements in Poland [14–23].

Period of Validity	Regulatory Document	Maximum Thermal Transmittance U [W/(m ² ·K)]			
		external walls	roofs and flat roofs	windows	doors
1957–1964	PN-57/B-02405	1.16–1.42	0.87	—	—
1964–1974	PN-64/B-03404	1.16–1.42	0.87	—	—
1974–1982	PN-74/B-03404	1.16–1.42	0.70	—	—
1982–1991	PN-82/B-02020	0.75	0.45	2.00–2.60	2.60
1991–2002	PN-91/B-02020	0.55–0.70	0.30	2.00–2.60	2.60
2002–2009	Dz.U. 2002 No. 7, item 690	0.30–0.50	0.30	2.00–2.60	2.60
2009–2014	Dz.U. 2008 No. 201, item 1238	0.30	0.25	1.70–1.80	2.60
2014–2017	Dz.U. 2013, item 926	0.25	0.20	1.30	1.70
2017–2021	Dz.U. 2015, item 1422	0.23	0.18	1.10	1.50
From 2021 (WT 2021)	Dz.U. 2019, item 1065	0.20	0.15	0.90	1.30
1957–1964	PN-57/B-02405	1.16–1.42	0.87	—	—
1964–1974	PN-64/B-03404	1.16–1.42	0.87	—	—
1974–1982	PN-74/B-03404	1.16–1.42	0.70	—	—
1982–1991	PN-82/B-02020	0.75	0.45	2.00–2.60	2.60
1991–2002	PN-91/B-02020	0.55–0.70	0.30	2.00–2.60	2.60

2002–2009	Dz.U. 2002 No. 7, item 690	0.30–0.50	0.30	2.00–2.60	2.60
2009–2014	Dz.U. 2008 No. 201, item 1238	0.30	0.25	1.70–1.80	2.60
2014–2017	Dz.U. 2013, item 926	0.25	0.20	1.30	1.70

For instance, while the U-value for roofs in 1964 was $0.87 \text{ W}/(\text{m}^2\cdot\text{K})$, current WT 2021 regulations mandate a maximum of $0.15 \text{ W}/(\text{m}^2\cdot\text{K})$ [11]. This historical trajectory, combined with the projected rate of thermal modernization (Figures 1 and 2), underscores the necessity of implementing advanced insulation strategies to meet decarbonisation targets.

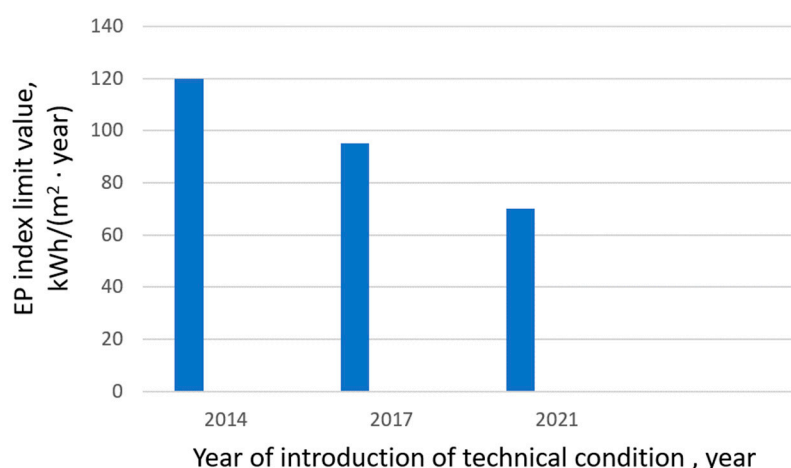


Figure 1. Evolution of the maximum allowable annual non-renewable primary energy demand index (EP) for residential buildings in Poland according to technical standards (WT 2014, WT 2017, and WT 2021).

As illustrated in Figure 1, the maximum allowable primary energy demand was reduced from $120 \text{ kWh}/\text{m}^2\cdot\text{a}$ in 2014 to $70 \text{ kWh}/\text{m}^2\cdot\text{year}$ under the current WT 2021 requirements.

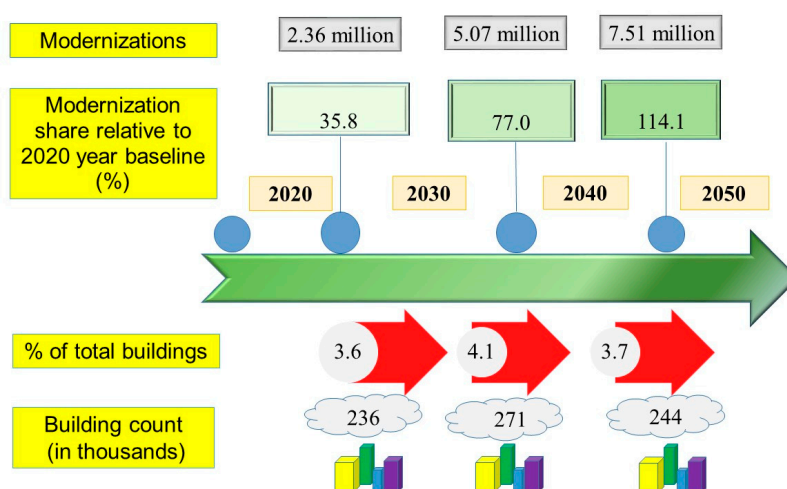


Figure 2. Long-term strategic roadmap for the thermal modernization of the Polish residential building stock (2020–2050). The horizontal arrow illustrates the chronological progression of the modernization process, where the increasing intensity of the green color signifies the gradual achievement of the NZEB standard and the corresponding reduction in primary energy consumption.

The transition towards nearly zero-energy buildings requires the integration of advanced energy-saving technologies alongside nature-based solutions. Globally, green roofs have emerged as a pivotal strategy for enhancing the thermal performance of building envelopes. Research indicates that vegetated surfaces can significantly reduce summer cooling loads while providing additional thermal insulation in winter. Consequently, these systems contribute to the overall energy balance essential for NZEB certification [24]. In Mediterranean and temperate climates, green roofs are recognised for their capacity to mitigate the urban heat island effect and enhance biodiversity [25].

In the specific context of Poland, green roofs are increasingly viewed as both an environmental and economic necessity. Studies conducted in Polish urban centres, such as Warsaw and Lublin, demonstrate that these systems serve as a “forced substitute” for biologically active areas in dense architectural environments. Simultaneously, they provide critical storm-water management. Furthermore, research by Ujma [26] and Wójcik-Madej et al. [27] highlights that green structures in Poland are essential for meeting the decarbonisation goals set by the European Parliament. These nature-based solutions offer a dual benefit: they enhance the energy efficiency of the building envelope while improving inhabitant well-being through superior thermal comfort and psychological health [28].

Achieving NZEB requirements often necessitates moving beyond passive envelope reinforcements toward active thermal management systems. This is particularly relevant for windows, which are traditionally considered the “weakest link” in a building’s thermal structure [29]. While modern triple-glazed units with low-emissivity coatings and argon filling drastically reduce conductive and radiative heat losses [30], they remain static barriers. Recent innovations in active “smart” windows, such as electrically heated glazing, offer a high-performance alternative. By integrating energy sources within the glazing cavity, these systems can eliminate the “cold window” effect and minimise the temperature gradient between indoor air and the glass surface [31]. Although active heating may increase local heat flux, it facilitates a more uniform temperature distribution and enhances occupant radiant comfort. Such interventions can potentially reduce overall heating costs by approximately 10% [32]. In the context of Central European masonry buildings, replacing legacy wooden double-glazing ($U_w = 2.60 \text{ W}/(\text{m}^2\cdot\text{K})$) with active triple-glazed systems ($U_w = 0.85 \text{ W}/(\text{m}^2\cdot\text{K})$) represents a critical step in bridging the performance gap to meet WT 2021 standards.

Retrofitting guarantees adherence to regulatory standards and effectively mitigates the discrepancy between predicted and actual energy performance. Although requiring considerable upfront capital, such interventions provide sustainable long-term cost reductions and contribute to climate change mitigation. Thermal retrofitting in the residential sector is currently propelled by EU requirements targeting a minimum 16% decrease in average primary energy consumption by 2030 relative to 2020 [6]. Recent research further underscores that integrating high-performance glazing with automated thermal management is pivotal for achieving near-zero energy building NZEB objectives [33–35].

The literature on energy retrofitting is expanding rapidly. However, there is still a critical shortage of empirical case studies focusing on early 21st-century masonry buildings. Specifically, few studies document the transition of these structures to NZEB standards within Central European climates. While theoretical models are abundant, practical decarbonisation strategies for this specific building era remain under-represented. These buildings often rely on inefficient legacy systems, making them a significant challenge for modern energy policy. Despite the expanding body of literature on energy retrofitting, empirical case studies documenting the transition of early 21st-century masonry buildings to NZEB standards remain scarce. This is particularly evident within the specific climatic

context of Central Europe. While theoretical models are abundant, there is a lack of empirical evidence regarding the decarbonisation of housing from this era, which remains predominantly reliant on inefficient legacy systems.

To address this research gap, the primary objective of this study is to evaluate the technical and environmental feasibility of transforming a representative early-2000s single-family masonry dwelling into an NZEB. The investigation focuses on achieving full compliance with the most stringent national energy benchmarks (WT 2021) through a holistic deep-renovation strategy. To achieve this, the following specific research tasks were executed:

- conducting a comprehensive baseline assessment of the existing building envelope and the legacy coal-fired HVAC system, using original energy performance certificates (EPC) from 2000 as a reference;
- mitigating thermal bridging by evaluating the impact of removing architectural elements (balconies) on linear thermal transmittance and the subsequent reduction in transmission heat losses;
- decarbonising the thermal supply by assessing the energy efficiency gains achieved by replacing fossil-fuel heating with an air-source heat pump (ASHP) integrated with an east-facing photovoltaic PV array;
- validating the energy transition by quantifying the reduction in final energy (EK) and non-renewable primary energy (EP) indices, thereby demonstrating a practical pathway toward a zero-emission balance.

2. Material Configurations and Design Strategies for Energy Performance

2.1. Site Analysis and Climatic Context

The research focuses on a residential building located in Cracow, Poland. This region is characterised by a temperate continental climate, with a design outdoor temperature of -20°C and an average annual temperature of approximately 7.6°C . The city experiences significant seasonal variations, with a heating season typically lasting 222 days.

The climatic conditions across Poland exhibit significant regional variations, which are best quantified through the heating degree days (HDD) index. For the investigated location in Cracow (50.06°N , 19.94°E), the HDD value reaches 3748, as illustrated in Figure 3. This metric is approximately 7.5% higher than that of the warmest urban area in the city Opole, signifying a substantial heating load requirement.

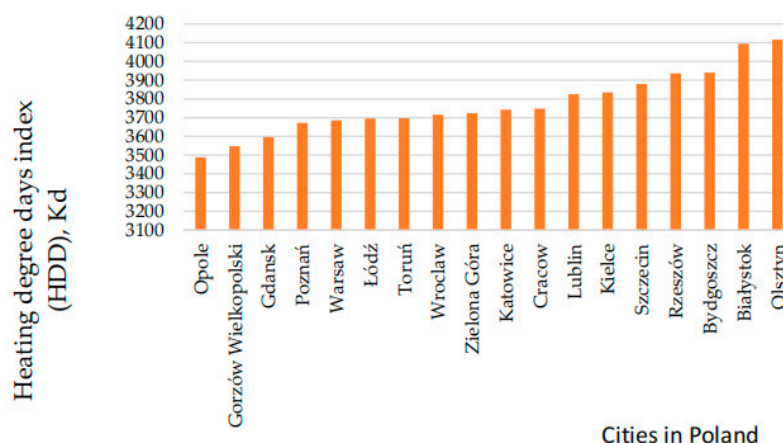


Figure 3. Comparative analysis of annual heating degree days (HDD) for major Polish cities (base temperature 18.3°C).

To ensure compliance with the Polish (NZEB) framework (WT 2021), the thermal characteristics of the building envelope were designed based on the peak environmental loads. According to the national standard PN-EN 12831-1:2017-08 [36], the critical design parameters used for the heating load simulations and HVAC system sizing are consolidated in Table 2.

Table 2. Design outdoor climate parameters for Cracow.

Parameter	Symbol	Value	Unit
design outdoor temperature	T_e	−20	°C
annual average outdoor temperature	$T_{m,e}$	7.6	°C
climatic zone (Poland)	-	III	-
heating degree days	HDD	3748	-

The specific climatic profile of Cracow, which defines the thermal boundary conditions, is illustrated in Figure 4. The monthly temperature analysis (Figure 4a) reveals a cold winter season with average lows reaching −5 °C [37]. Furthermore, the hourly temperature heat map (Figure 4b) demonstrates significant diurnal fluctuations during the summer period. These peaks justify the strategic implementation of a green roof on the western pitch as a nature-based solution for passive cooling. The solar path diagram (Figure 4d) provides the necessary data for optimizing the photovoltaic array's yield and evaluating the shading effect on the building's overall energy balance.

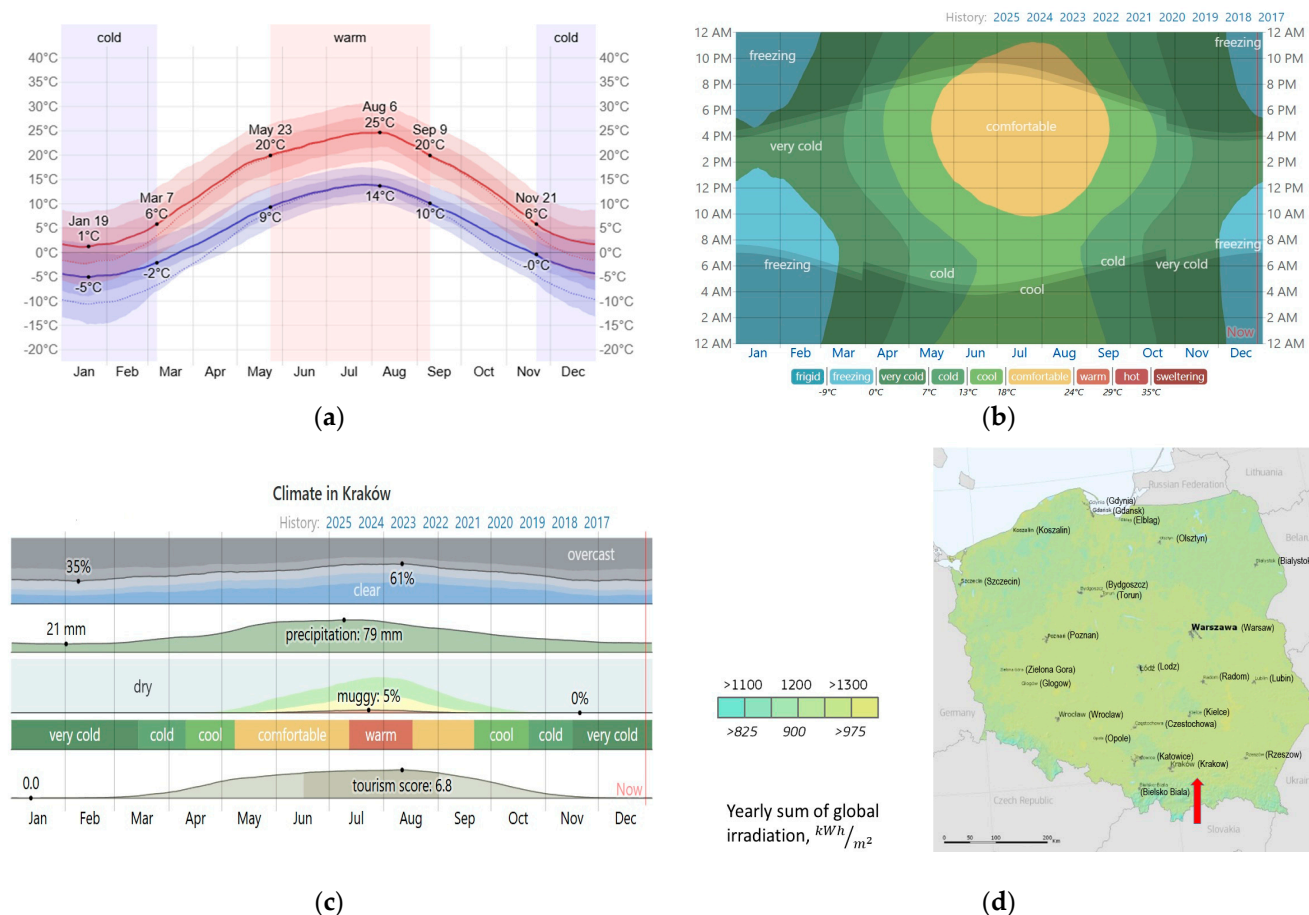


Figure 4. Climatic profile of Cracow city (50.06° N, 19.94° E) relevant for NZEB design: (a) average daily maximum (red) and minimum (blue) temperatures; (b) hourly temperature distribution throughout the year; (c) daily probability of precipitation and cloud cover categories; (d) solar path

diagram. Data adapted from [37]. The red arrow indicates the location of the investigated building in Cracow, Poland, where the experimental data were collected.

The solar energy potential of the location was assessed using the photovoltaic geographical information system (PVGIS) database [38]. As indicated by the solar path diagram (Figure 4d), Cracow is situated in a region with favourable solar conditions for Central Europe. The annual solar irradiance on an optimally inclined plane reaches approximately 1200 kWh/m². To further assess the impact of solar exposure on the building envelope, a detailed solar path analysis was performed using the PvLib Python library 0.13.1 and SunCalc tool [39]. The resulting polar plot visualizes the solar trajectories during the summer solstice, winter solstice, and equinoxes (Figure 5).

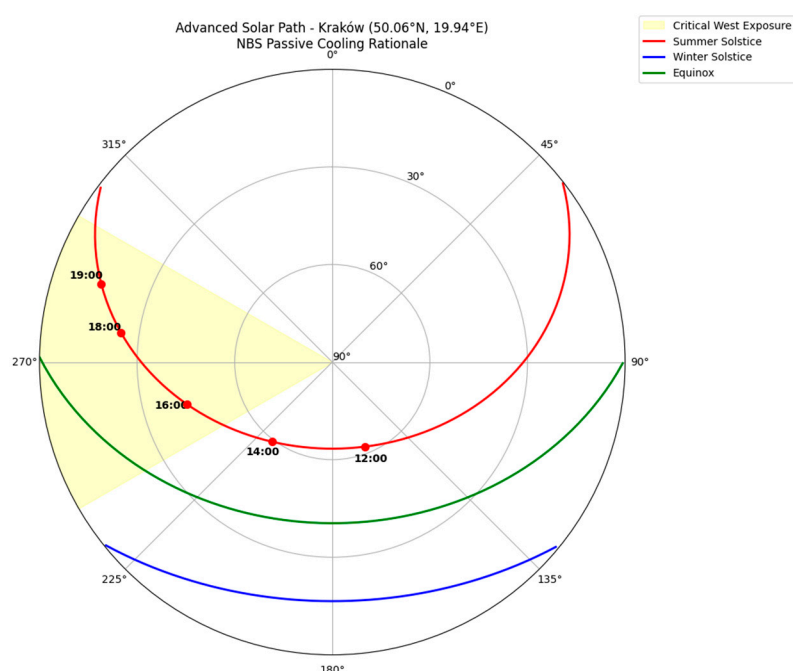


Figure 5. Solar path polar plot for Cracow, Poland.

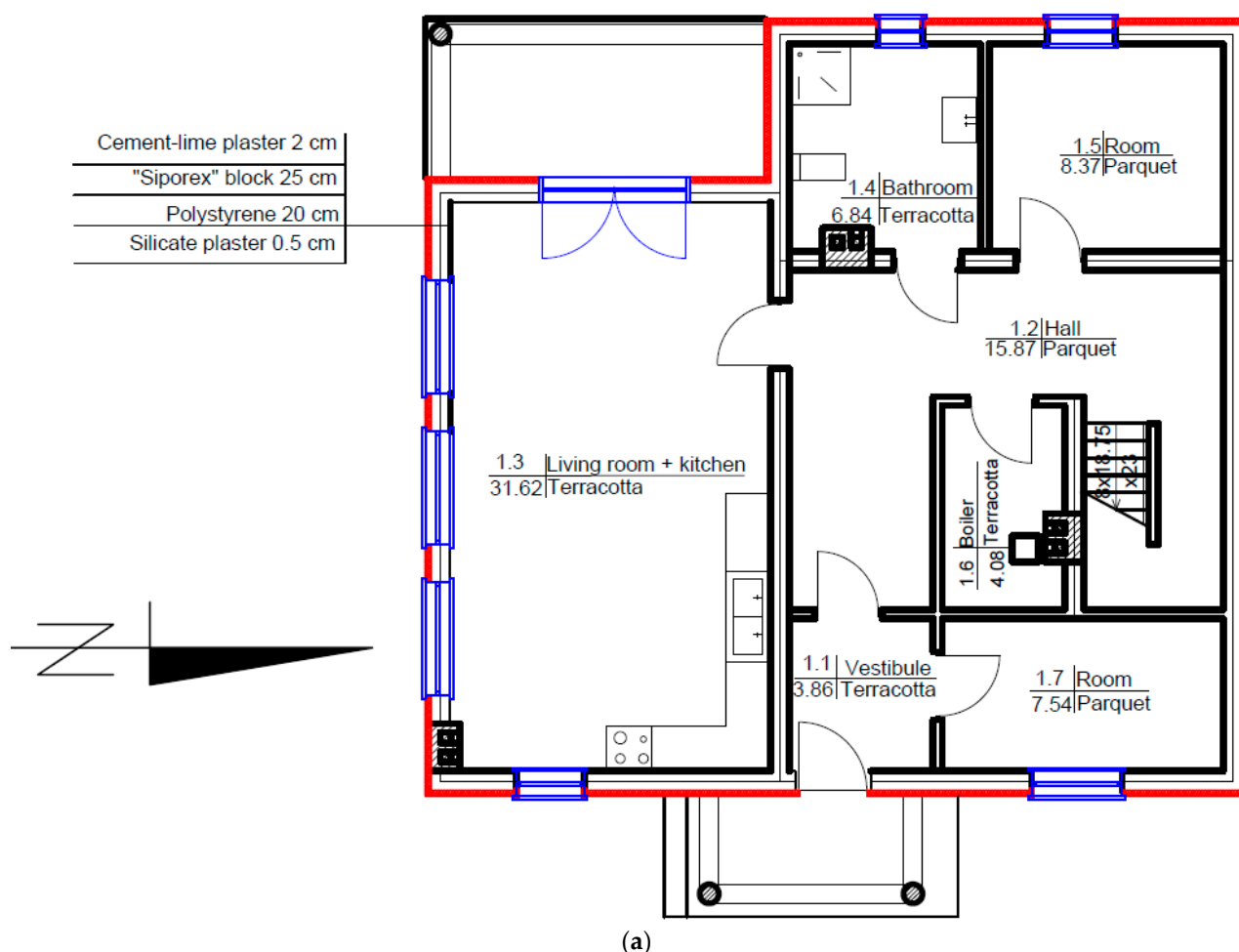
The yellow-shaded area identifies the critical west exposure zone (240–300° azimuth), where low-altitude solar radiation coincides with peak diurnal temperatures. The markers indicate the precise solar position at specific intervals (12:00, 14:00, 16:00, 18:00, and 19:00) during the summer solstice, highlighting the prolonged thermal stress on the western building envelope.

To assess the impact of solar radiation on the building's thermal performance, a detailed solar path analysis was conducted (Figure 5). The polar plot reveals that during the summer solstice, the sun remains above the horizon for over 16 h, reaching a maximum altitude of 63.4°. However, the most significant thermal challenge for the building's energy balance occurs in the late afternoon. As shown in the critical west exposure zone (Figure 5), between 16:00 and 19:00, the solar azimuth shifts from 255° to 298°. During this period, the solar altitude decreases, which leads to a more direct incidence of solar rays on the western roof pitch and facade. This astronomical configuration, combined with the maximum daily ambient temperatures (as previously shown in the climatic profile in Figure 4b), creates a substantial risk of indoor overheating.

2.2. Case Study Object

The subject of this study is a two-story, detached single-family house designed for a five-person household. The total usable floor area is 158.65 m², with a volume of 424.85

m³. Constructed using traditional masonry technology, the building represents typical early 21st-century Central European residential architecture. The functional and spatial distribution of the analysed dwelling in its reference state is presented in Figure 6, where panel (a) illustrates the ground floor day zone and panel (b) details the first-floor night zone. The ground floor layout is designed to facilitate communal activities and features a large living room integrated with a kitchen (room 1.3), a versatile guest room (room 1.5), and essential service areas including a boiler room (room 1.6) and a bathroom (room 1.4). As shown in the architectural plan, the circulation is centred around a vestibule (room 1.1) and a main hall (room 1.2), which provides a transition between the entrance and the primary living spaces. In contrast, the first-floor arrangement (Figure 6b) is dedicated to the private requirements of a five-person household, being organised around a central hall (room 2.1) that serves as the main distribution point. This level incorporates four bedrooms of varying orientations (rooms 2.2, 2.3, 2.5, and 2.7), a shared bathroom (room 2.4), and auxiliary storage spaces such as a wardrobe (room 2.8) and a utility room (room 2.6). This comprehensive spatial mapping was utilised to define the thermal zones and internal heat gain profiles required for the baseline energy simulations.



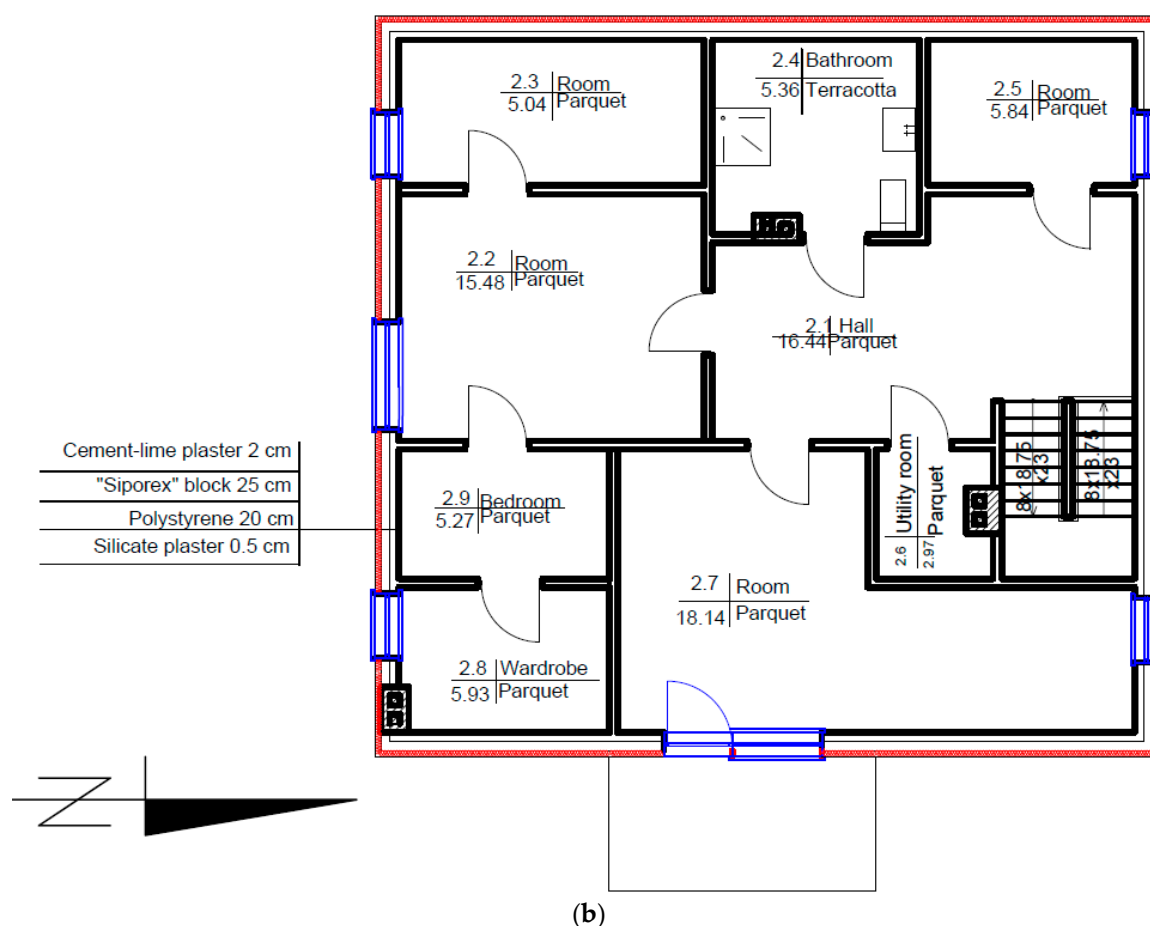


Figure 6. Functional and spatial distribution of the reference building before thermal modernisation: (a) ground floor; (b) first floor.

The structural and material configuration of the building in its baseline state is detailed in Figure 7. The overall vertical assembly and the integration of primary structural elements are visualised in the technical cross-section (Figure 7a). This view illustrates the pitched roof construction, which comprises pine rafters (6/18 cm) with 18 cm of mineral wool insulation, a solution that, while standard at the time of construction, no longer satisfies contemporary energy efficiency requirements (WT 2021). A detailed focus on the external envelope is provided in Figure 7b, which highlights the interface between the 0.25 m aerated concrete masonry “Siporex” and the 0.08 m legacy expanded polystyrene layer. This traditional masonry system, characterised by a relatively thin insulation barrier, results in a thermal transmittance of $U = 0.340 \text{ W}/(\text{m}^2\cdot\text{K})$. The inadequate thickness of these existing layers, as specified in the structural detail, confirms the building’s high energy demand and the necessity for a comprehensive thermal upgrade.

The detailed material composition and the corresponding thermal transmittance coefficients (U-values) for the building’s baseline envelope are summarised in Table 3. These values were calculated based on the technical documentation and the physical properties of the legacy materials, such as the “Siporex” aerated concrete and the original EPS insulation. The U-values for the external walls and the floor on the ground highlight the thermal performance gap compared to current NZEB standards.

The spatial orientation and external form of the analyzed building significantly influence its energy profile, particularly regarding solar gain and transmission losses. The baseline architectural configuration presented in Figure 8 reveals several critical energy-performance factors that determine the current efficiency of the object. While the eastern elevation shown in Figure 8a exhibits a relatively regular distribution of window openings

centered around the entrance axis, the western elevation illustrated in Figure 8b is characterized by a functional asymmetry. This facade includes a combination of small-scale service windows and a large recessed terrace area, which constitutes a major linear thermal bridge at the floor–slab junction due to the traditional masonry technology employed in the original construction. In contrast, the northern facade shown in Figure 8c features a minimal glazing ratio to limit heat discharge in the most shaded zone where solar heat gain remains negligible throughout the year.

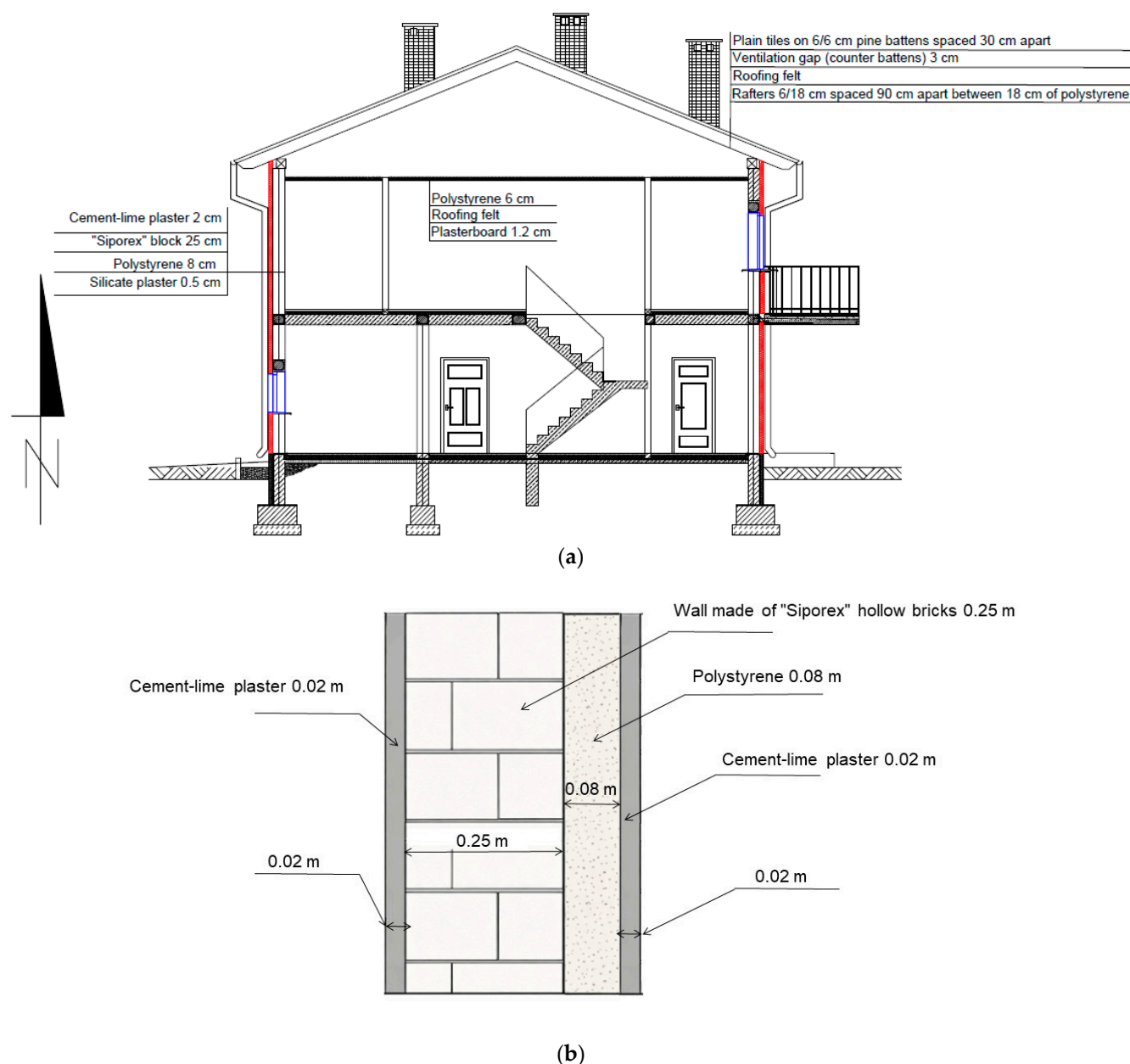


Figure 7. Technical cross-section of the building in the baseline state: (a) The pitched roof configuration; (b) The structural layers of the external walls.

Table 3. Material and thermal properties of the baseline building envelope.

Building Partition	Material Layers (From Internal to External)	Thickness, d (m)	U-Value (W/(m ² ·K))
external wall (N, W, E, S)	cement–lime plaster	0.02	0.340
	aerated concrete (PGS Siporex 600)	0.25	
	expanded polystyrene (EPS 50-042)	0.08	

external wall E (vestibule)	silicate plaster	0.005	0.340
	cement–lime plaster	0.02	
	aerated concrete (PGS Siporex 600)	0.25	
	expanded polystyrene (EPS 50-042)	0.08	
floor on ground	silicate plaster	0.005	0.249
	concrete (stone aggregate 1900)	0.05	
	expanded polystyrene (EPS 50-042)	0.05	
	polyethylene foil	0.0002	
	concrete (stone aggregate 1900)	0.10	
floor on ground (vestibule)	sand bedding	0.20	0.207
	concrete (stone aggregate 1900)	0.05	
	expanded polystyrene (EPS 50-042)	0.05	
	polyethylene foil	0.0002	
	concrete (stone aggregate 1900)	0.10	
ceiling under attic	sand bedding	0.20	0.174
	gypsum board	0.012	
	asphalt roofing felt	0.004	
	expanded polystyrene (EPS 50-042)	0.06	

The southern elevation, illustrated in Figure 8d, features the largest cumulative area of transparent partitions, strategically designed to maximize passive solar heat gains. In the baseline state, these gains were largely offset by substantial conductive heat losses through legacy wooden joinery with a high thermal transmittance of $U_w = 2.60 \text{ W}/(\text{m}^2\cdot\text{K})$.

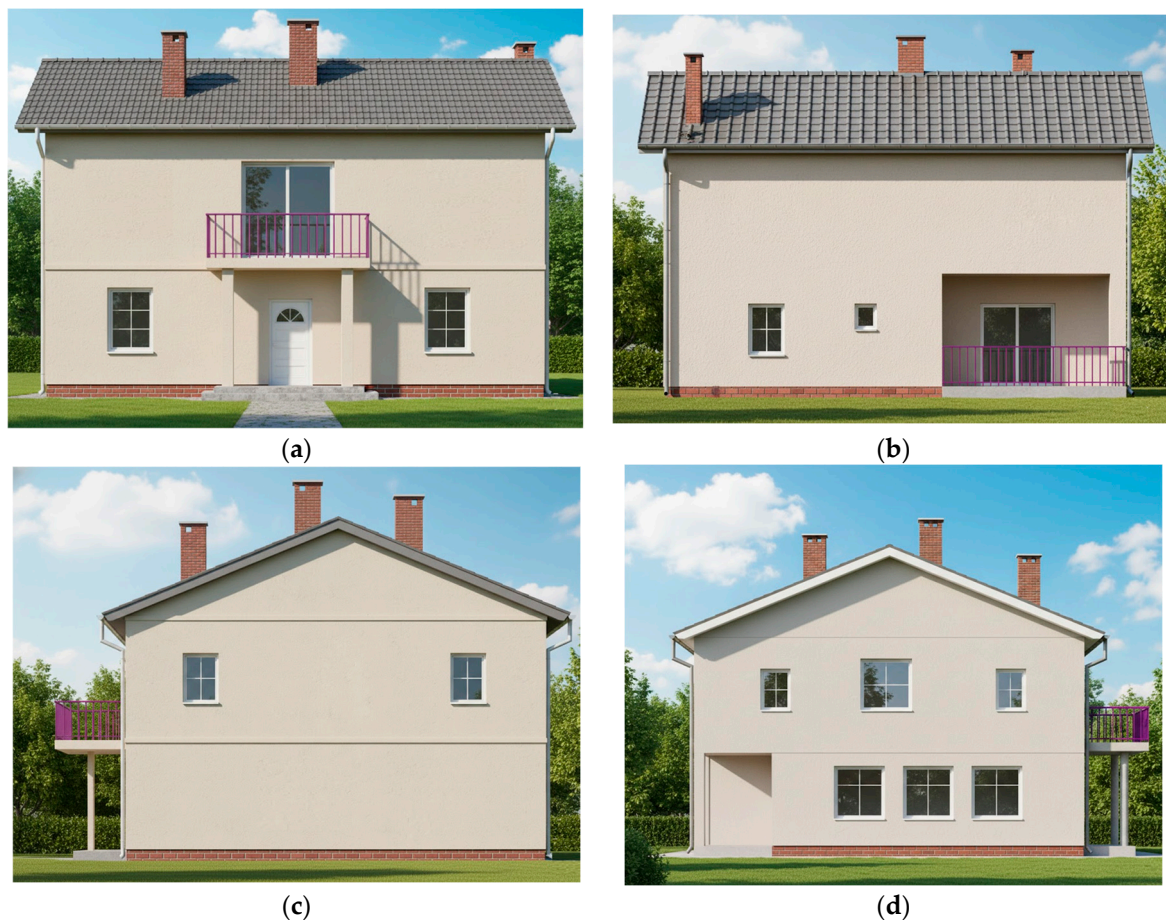


Figure 8. Architectural form and elevation configuration in the baseline state: (a) eastern elevation; (b) western elevation; (c) northern elevation; (d) southern elevation.

2.3. Active Smart Window System

While enhancing opaque partitions is a fundamental step in the retrofitting process, transparent components present the most significant challenge in achieving a near-zero energy balance. In this case study, conventional upgrades to standard triple-glazed units were insufficient to fully eliminate persistent thermal bridges and the radiative discomfort typical of large glazing areas. Consequently, to minimise transmission losses, this research investigates the transition from passive to active glazing systems.

The primary objective of this active system is to modulate the window's thermal state, transforming it from a conventional heat sink into a thermally neutral element. By integrating electrically conductive layers within the glazing assembly, the system provides a controlled heat flux that compensates for transmission losses in real time. This active compensation ensures that the internal surface temperature remains consistent with the indoor air temperature. As a result, the system effectively eliminates draughts and enhances the mean radiant temperature of the living space.

The performance of the active glazing was validated under controlled conditions using a specialised dual-zone climatic chamber at the Laboratory of Energy-Efficient Technologies, Kielce University of Technology (Figure 9).



Figure 9. Experimental setup for active glazing thermal performance evaluation: (a) the dual-zone climatic chamber; (b) active glazing heating system, including thermometer TM-947SD, hukseflux

FHF05 heat flux sensors, pico K-type thermocouples, data logger LI19, and Thermo TECH heating foil integration.

The experimental prototype utilised for validation consisted of a double-glazed unit with a 16 mm argon-filled cavity and a low-emissivity coating ($\varepsilon = 0.17$). The thermal activation was achieved via Thermo TECH self-adhesive PET heating foils (Conrad Electronic, Hirschau, Germany) integrated within the cavity, each providing a nominal power output of 25 W. To ensure high data fidelity and reproducibility, a comprehensive instrumentation suite was deployed (Figure 9b). The heat flux dynamics were quantified using nine FHF05 thin-film flexible heat flux sensors (Hukseflux, Delft, Netherlands.) with a sensitivity of $20 \mu\text{V}/(\text{W}/\text{m}^2)$. Temperature distributions were monitored using calibrated Type K thermocouples connected to a TM-947SD four-channel digital thermometer (logging resolution of 0.1°C). All signals were processed via an LI19 high-precision data logger (Hukseflux), ensuring a measurement uncertainty of less than 0.1%. Thermal regulation was managed by Lumel RE72 PID controllers (Lumel S.A., Zielona Góra, Poland), which modulated the power supply based on real-time surface temperature feedback to maintain the predefined setpoints. The core of the experimental procedure was to identify the thermal neutrality threshold. This is defined as the specific power density q_{active} (W/m^2) required to reach a state where the net heat flux at the internal glazing surface is zero ($q_{\text{net}} \approx 0$):

$$q_{\text{net}} = q_{\text{loss}}(T_{\text{int}}, T_{\text{ext}}) - q_{\text{active}} = 0 \quad (1)$$

The required heating power (P_{heat}) for each glazing unit is determined using the following steady-state thermal equilibrium equation:

$$P_{\text{heat}} = \frac{U_{\text{gl}} \cdot A_{\text{gl}} \cdot (T_{\text{int}} - T_{\text{ext}})}{\eta} \quad (2)$$

where U_{gl} is the thermal transmittance of the glass package $\text{W}/(\text{m}^2\cdot\text{K})$; A_{gl} represents the effective surface area of the glass m^2 ; $(T_{\text{int}} - T_{\text{ext}})$ is the design temperature gradient (K); η is the thermal efficiency coefficient of the heat transfer towards the interior. This coefficient is assumed to be 0.8, accounting for approximately 20% parasitic heat loss to the external environment.

By incrementally adjusting the heating intensity across a range of 10°C to 40°C under varying external temperatures, a correlation was established between the required electrical input and the environmental thermal load. These experimental results provided the basis for scaling the system to the full-scale triple-glazed units ($U_{\text{w}} = 0.85 \text{ W}/(\text{m}^2\cdot\text{K})$) implemented in the case study building. The final dimensioning of the heating elements for each window was calculated to ensure peak demand compensation at the local design outdoor temperature of -20°C . By converting the windows from passive thermal weak points into active heating elements, the southern facade becomes a primary component of the building's integrated energy management strategy, effectively utilising solar radiation while minimising peak demand on the air-source heat pump.

2.4. Building Energy Performance Simulation and Thermal Calculation Methodology

Building energy performance simulations, including steady-state heat transfer calculations for the building envelope, were conducted using the CERTO software package (version 6.1 (Dolnośląska Agencja Energii i Środowiska, Wrocław, Poland)). This computational tool is a standard industry solution in Poland for conducting certified energy audits and verifying compliance with national technical standards. The software operates in strict accordance with the methodology defined by the Ministry of Development and Technology, which aligns with international standards such as ISO 13790.

The thermal analysis was structured around several key parameters and assumptions. The U -values for the external partitions were determined based on steady-state calculations, accounting for the specific material layer sequence and standardised internal and external surface heat transfer resistances. The impact of thermal bridges was integrated into the model using linear heat transfer coefficients, determined via the simplified normative procedures embedded within the CERTO database. Standardised internal air temperatures were applied according to the building's residential function (e.g., 20 °C for living areas). External conditions were based on regional climatic data for Cracow, accounting for design outdoor temperatures and solar irradiation profiles. The simulation assumed standard residential occupancy patterns with a continuous heating schedule throughout the designated heating season. In alignment with national certification methodologies, the model assumed one-dimensional heat flow through planar partitions. To maintain comparability with legal requirements, such as the "WT 2021" technical standards, dynamic thermal mass effects and complex heat accumulation were omitted in favour of a steady-state approach.

The simulation parameters were selected to reflect both the physical characteristics of the building and the standard operating conditions for residential units in the Polish climate. A comprehensive summary of the technical assumptions, including design temperatures, occupancy patterns, and ventilation rates used for the energy balance calculations, is presented in Table 4.

Table 4. Key technical assumptions and boundary conditions for the energy performance simulation.

Parameter	Unit	Value
indoor temperature, T_i	°C	+20
occupancy density	persons	5.0
internal heat gains	W/m ²	2.5
ventilation type	-	natural (baseline)/mechanical with heat recovery (NZEB)
air change rate	h ⁻¹	0.5
heating period duration	days/a	222
domestic hot water demand	dm ³ /day	35.0 per person at 55 °C
thermal bridge methodology	-	linear coefficients ψ according to ISO 14683
heat flow direction	-	one-dimensional, steady-state

The transition from natural ventilation in the baseline state to a mechanical system with heat recovery in the NZEB variant is a key factor in reducing ventilation heat losses while maintaining required indoor air quality. These boundary conditions were maintained consistently across both the baseline and the NZEB-retrofit scenarios to ensure a transparent comparison of the energy-saving interventions.

3. Results

Proposed Modernization Strategies for NZEB Standard

HVAC System and Renewable Energy Integration. To transform the baseline building into a NZEB compliant with WT 2021 and upcoming 2026 reforms, a comprehensive deep-retrofit strategy was implemented. This approach integrates high-performance insulation, nature-based cooling solutions, and active renewable energy systems.

The modernization replaces the legacy coal-fired boiler with a sustainable air-source heat pump system. Based on the calculated energy demand for a low-energy standard building of 40 W/m², the design heat load for the 158.65 m² area is approximately 6.4 kW. A Beretta monoblock hydro unit 008 (8 kW) was selected to provide a power reserve for

domestic hot water production. The system operates with a seasonal coefficient of performance (SCOP) of 4.0, leading to an estimated annual electricity consumption of 2538 kWh for heating and domestic hot water. To offset the total annual electrical demand (including 3500 kWh for household appliances and 2538 kWh for the ASHP), a 7 kWp PV system was designed. The installation comprises 28 polycrystalline modules (250 W each) strategically mounted on the eastern roof pitch to maximize morning harvesting efficiency and minimize thermal degradation. A 10 kW Growatt SPH10KTL3-BH UP hybrid inverter was integrated into the system. This selection ensures compatibility with the 7 kWp array while providing the capacity for future energy storage expansion to increase self-consumption.

Thermal Envelope and Material Specifications.

The analysis of the baseline parameters reveals that the building envelope is characterized by high thermal transmittance, particularly in the transparent partitions, with a U_w of 2.60 W/(m²·K). According to current Polish technical conditions (WT 2021), these values exceed the maximum allowable limits by approximately 188% for windows and 150% for external walls. Furthermore, the limited thickness of the EPS insulation creates a high susceptibility to transmission heat losses. These structural deficiencies, combined with the legacy coal-fired heating system, result in a high primary energy (EP) demand, making the building an ideal candidate for deep thermal modernization. The following sections detail the strategic interventions aimed at neutralizing these losses through the integration of active glazing and nature-based solutions.

To achieve the NZEB standard, the building envelope was redesigned as a breathable, multi-layered assembly [40,41]. The implementation of a 0.25 m mineral wool layer was strategically chosen to ensure the external walls achieve a thermal transmittance of $U = 0.115$ W/(m²·K). This value is approximately 42% more efficient than the maximum limit required by the WT 2021 standard (0.20 W/(m²·K)). Such over-insulation is a prerequisite for achieving the NZEB target and compensates for thermal bridging, ensuring the building remains thermally stable and energy-neutral throughout the heating season. The detailed technical specifications of the building envelope components following the implemented thermal modernization measures are summarized in Table 5.

Table 5. Technical characteristics of the building envelope after thermal modernization.

Building Partition	Material Layers (From Internal to External)	Thickness, d (m)	U-Value (W/(m ² ·K))
external wall (N, W, E, S)	cement–lime plaster	0.02	0.115
	aerated concrete (PGS Siporex 600)	0.25	
	mineral wool ($\lambda = 0.036$ W/m·K)	0.25	
	wooden frame	0.025	
	vapor-permeable membrane	0.0002	
	pine facade boards	0.015	
external wall E (vestibule)	cement–lime plaster	0.02	0.115
	aerated concrete (PGS Siporex 600)	0.25	
	mineral wool ($\lambda = 0.036$ W/mK))	0.25	
	wooden frame	0.025	
	vapor-permeable membrane	0.0002	
	pine facade boards	0.015	
floor on ground	concrete (stone aggregate 1900)	0.05	0.197
	expanded polystyrene (EPS 50-042)	0.15	
	polyethylene foil	0.0002	
	concrete (stone aggregate 1900)	0.10	
	sand bedding	0.20	
floor on ground (vestibule)	concrete (stone aggregate 1900)	0.05	0.197
	expanded polystyrene (EPS 50-042)	0.15	
	polyethylene foil	0.0002	
	concrete (stone aggregate 1900)	0.10	

	sand bedding	0.20	
	gypsum board	0.012	
ceiling under attic	asphalt roofing felt	0.002	0.125
	expanded polystyrene (EPS 50-042)	0.25	

The eastern pitch remains a traditional metal sheet structure to support the PV array, while the western pitch was converted into an extensive green roof. This nature-based solution provides high thermal mass and utilizes evapotranspiration to mitigate summer overheating. Furthermore, the ceiling under the attic was upgraded with a 0.25 m layer of Rockwool mineral wool to ensure a continuous high-performance thermal envelope. To eliminate major linear thermal bridges, existing balcony slabs were removed at the junction with the main floor slabs, ensuring a continuous thermal break along the facade. The structural transition toward a high-performance NZEB envelope is depicted in Figure 10.

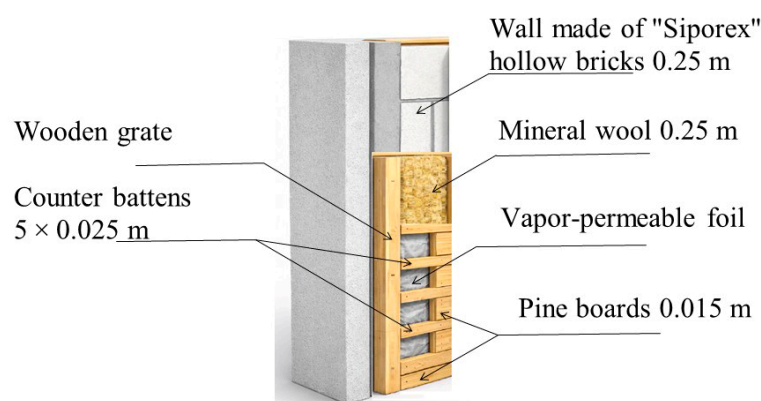


Figure 10. Technical cross-section of the external wall after thermal modernization (post-adaptation). The configuration includes a 0.25 m aerated concrete masonry unit, a 0.025 m wooden frame, 0.25 m of mineral wool insulation, and a 0.015 m pine wood cladding.

The modernized assembly incorporates a 0.025 m timber frame designed to support the new 0.25 m mineral wool insulation layer. This ventilated system is protected by a vapor-permeable membrane and finished with 0.015 m pine wood cladding. The integration of these layers effectively reduced the wall's thermal transmittance to $U = 0.147 \text{ W/(m}^2\cdot\text{K)}$. To achieve the NZEB standard, the building envelope was redesigned as a breathable, multi-layered assembly. The new spatial organization and the distribution of thermal zones, adjusted to the modernized heating system, are presented in Figure 11.

The eastern pitch remains a traditional metal sheet structure to support the PV array, while the western pitch was converted into an extensive green roof. This structural and thermal transition is detailed in the technical cross-section shown in Figure 12.

Joinery and Active Glazing Technology. The legacy wooden windows ($U_w = 2.60 \text{ W/m}^2 \text{ K}$) were replaced with triple-glazed energy-efficient units achieving $U_w = 0.85 \text{ W/m}^2 \text{ K}$. The active window was modified by installing a self-adhesive PE heating foil (Conrad Electronic, Hirschau, Germany) within the glazing cavity. The implementation of the active glazing system in the modernized building was preceded by an extensive experimental phase conducted in a controlled climatic chamber (Figure 9). This preliminary stage was crucial for establishing the empirical power density coefficients required to neutralize transmission heat losses under variable winter conditions. A prototype triple-glazed unit (initial $U_w = 0.85 \text{ W/m}^2\cdot\text{K}$) was subjected to a simulated external temperature of $-10 \text{ }^\circ\text{C}$. The primary objective was to identify the specific power density necessary to achieve a state of thermal neutrality, where the net heat flux at the internal surface equals zero $q_{\text{net}} \approx 0 \text{ W/m}^2$. As illustrated in Figure 13, the glazing unit in its passive state exhibited a constant heat loss of approximately -25.5 W/m^2 . Upon system activation at $t = 10 \text{ min}$, a

rapid reduction in the heat flux was recorded. The system achieved stabilization at the thermal neutrality threshold within 50 min of operation.

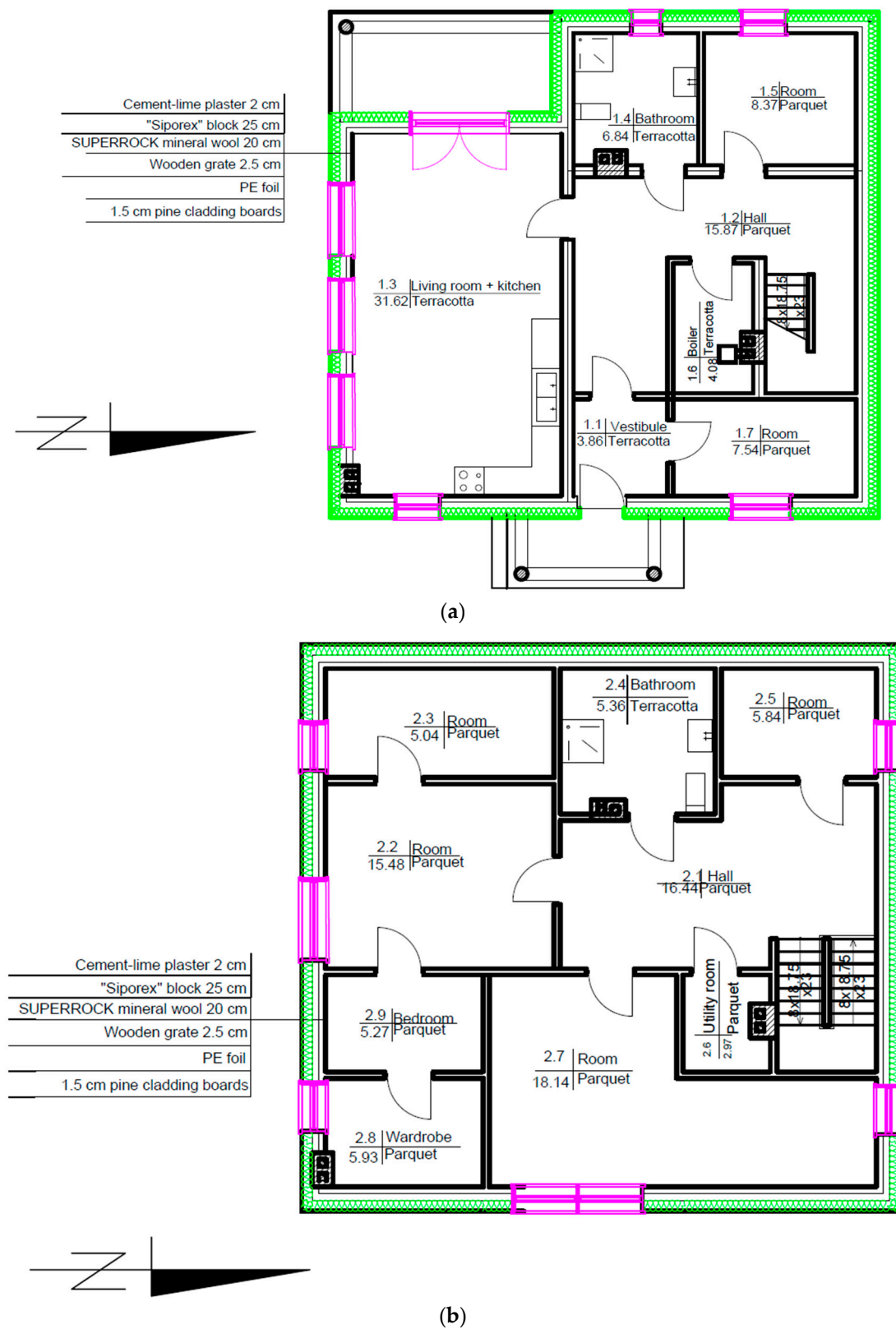


Figure 11. Functional and spatial configuration of the modernized NZEB building: (a) Ground-floor plan; (b) first-floor plan.

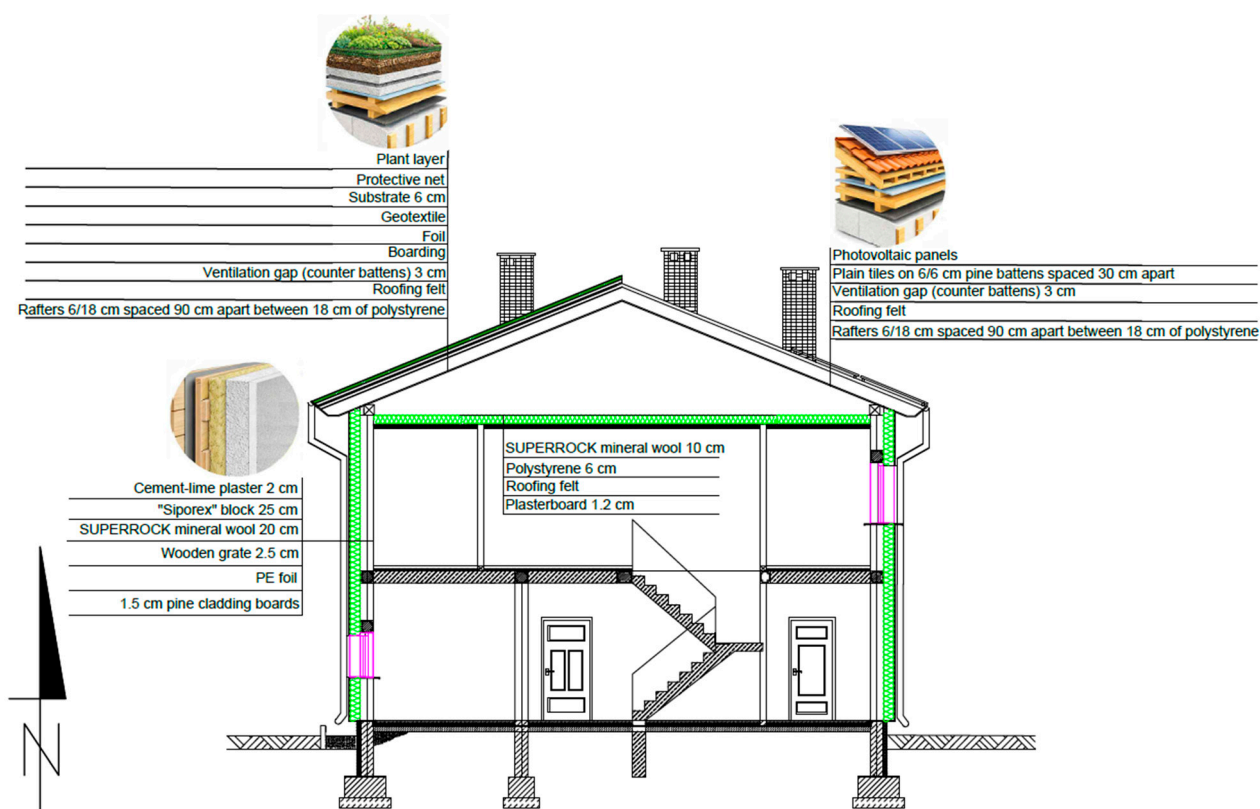


Figure 12. Technical cross-section of the building (post-adaptation).

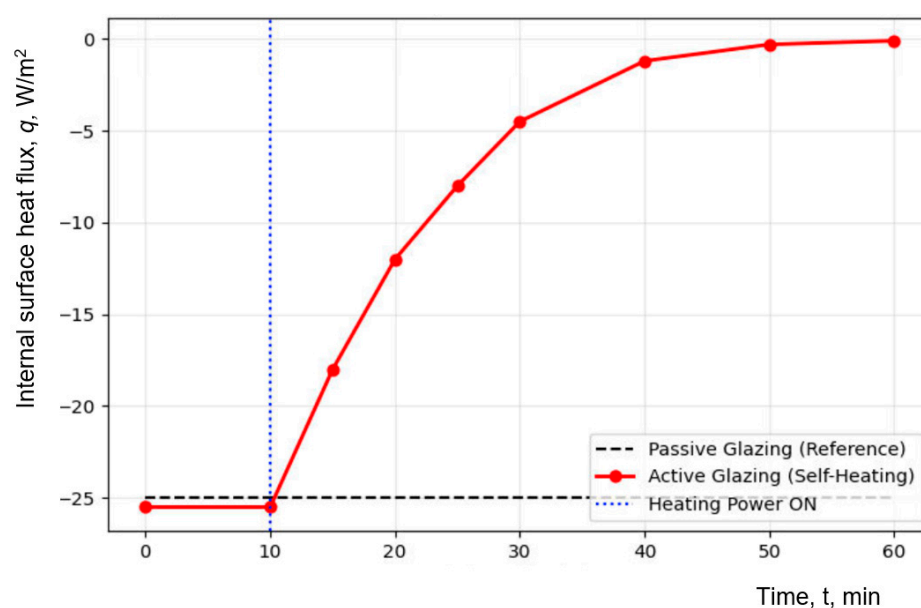


Figure 13. Dynamics of internal surface heat flux stabilization; the blue dotted line indicates power activation at $t = 10$ min (laboratory data).

A comparative analysis of the transversal temperature profiles across the glazing layers for both passive and active states is presented in Figure 14. These experimental results, derived from climatic chamber measurements, demonstrate the significant impact of the active system on the building's internal boundary conditions.

The transition from laboratory validation to the practical scaling of the active glazing system was predicated upon the empirical data acquired during climatic chamber testing. To ensure a robust implementation within the NZEB framework, the system dimensioning was guided by several critical technical considerations. A power density P_d of 38.0

W/m², established at a simulated outdoor temperature of −10 °C, serves as the primary reference point for the heat flux stabilisation observed in Figure 9. This value represents the specific energy input required to achieve a state where $q_{net} \approx 0$ W/m², effectively halting conductive thermal transmission. All power density calculations incorporate a thermal transfer efficiency coefficient of $\eta = 0.8$. This factor accounts for the approximately 20% parasitic heat dissipation directed towards the external environment, thereby ensuring that the active input is sufficient to compensate for internal boundary losses. During the experimental validation, the external surface temperature was maintained at a simulated outdoor design level of −9.2 °C, while the internal air temperature was stabilised at 21.0 °C. In the passive mode, the internal glass surface temperature reached only 15.8 °C. This temperature differential of 5.2 K relative to the indoor air is a primary cause of radiant discomfort and significantly increases the risk of surface condensation. The transversal temperature profiles presented in Figure 14 demonstrate the significant impact of the active system on the building's internal boundary conditions. At an outdoor temperature of −10 °C, the internal glass surface temperature was effectively elevated from 15.8 °C (passive) to a comfort level of 20.2 °C (active). Based on these results and Equation (2), the required electrical power density P_d was determined for various environmental thermal loads, as summarised in Table 6.

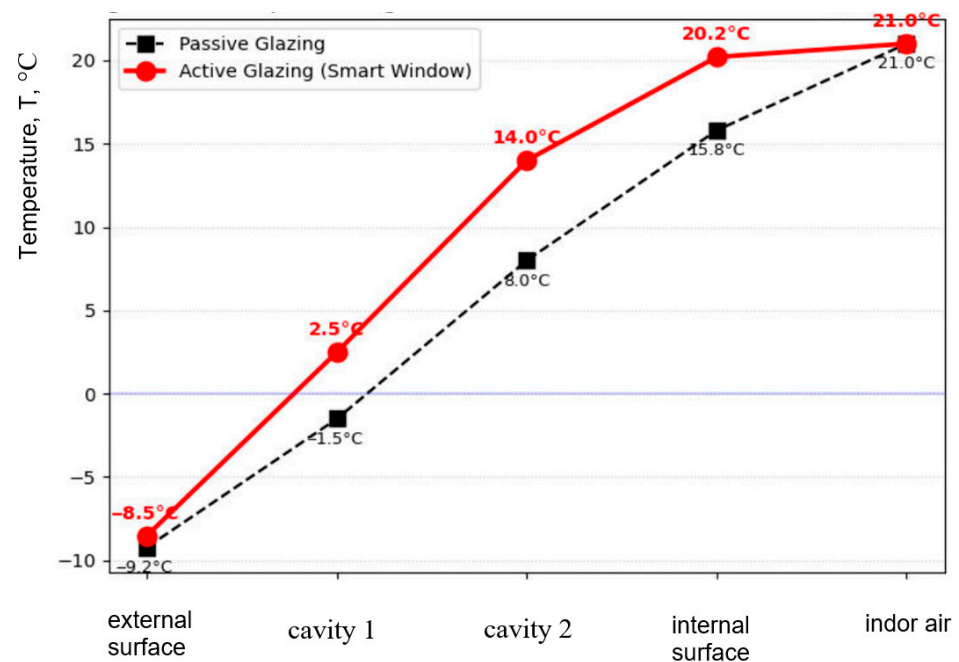


Figure 14. Comparative temperature gradient across the triple-glazed unit at $T_{ext} = -10$ °C for passive and active windows.

Table 6. Operational parameters and power density requirements for achieving thermal neutrality ($T_{int} = 21$ °C).

Outdoor Temperature T_{ext} (°C)	Gradient ΔT (K)	Thermal Load q (W/m ²)	Required P_d (W/m ²)	Total Power for 1.5 m ² Window (W)
0	21	12.5	18.0	27.0
−5	26	18.2	26.5	39.8
−10	31	25.5	38.0	57.0
−20 (design)	41	34.8	52.0	78.0

For a standard window unit $A = 1.5 \text{ m}^2$ at the design temperature of $-10 \text{ }^\circ\text{C}$, the total required power is $P = A_w \cdot P_d \approx 57 \text{ W}$. In practical application, this demand is met by installing heating foils, providing a total of 75 W . This configuration ensures full coverage and uniform heat distribution via glass conductivity while maintaining a sufficient power reserve for extreme climatic events where temperatures reach the local design minimum of $-20 \text{ }^\circ\text{C}$.

The identification of the critical solar exposure zone ($240\text{--}300^\circ$ azimuth), as illustrated in Figure 4, establishes a physical basis for the building's asymmetrical envelope strategy. To mitigate peak solar gains, an extensive green roof was strategically implemented on the western pitch. Unlike conventional roofing systems, this nature-based solution leverages high thermal inertia and evapotranspiration processes to induce a significant thermal lag effect. This mechanism effectively shifts peak heat loads to cooler evening hours, thereby reducing active cooling demand and enhancing indoor thermal stability. Conversely, the eastern pitch is dedicated to active energy harvesting, hosting a 7 kWp photovoltaic array. This orientation was selected to capitalise on morning solar exposure when lower ambient temperatures reduce the risk of thermal degradation, thereby enhancing the conversion efficiency of the polycrystalline modules. The comprehensive architectural transformation resulting from these technical interventions, including the new asymmetrical roof configuration and cladding, are documented in the post-adaptation elevations presented in Figure 15.



Figure 15. Architectural transformation and technical integration of the building envelope following the NZEB adaptation: (a) Eastern elevation showcasing the integrated 7 kWp polycrystalline photovoltaic array and modernized pine wood cladding; (b) Western elevation demonstrating the nature based cooling strategy via the extensive green roof system and the elimination of thermal bridges through the removal of legacy balcony structures.

To quantitatively evaluate the impact of the deep retrofit on summer thermal performance and mitigate the risk of the ‘thermos effect’ which is a common challenge in NZEB buildings where high insulation levels may impede heat dissipation, a dynamic thermal analysis was conducted. This study utilised hourly meteorological datasets for the Cracow region, sourced from the PVGIS-SARAH2 and WeatherSpark databases, with a specific focus on the peak cooling season from June to August. Given that the building's thermal envelope was substantially upgraded with 0.25 m of mineral wool and achieved high airtightness, the analysis prioritised the dynamic response of the roof assembly. The key performance indicators, specifically the decrement factor f and the thermal phase shift ϕ , were calculated analytically in accordance with the ISO 13786 methodology. These parameters

are critical for describing the envelope's capacity to dampen and delay external temperature fluctuations. A comparative performance analysis between the baseline and the retrofitted scenario is detailed in Table 7.

Table 7. Dynamic thermal characteristics and surface temperatures for the roof structure.

Parameter	Symbol	Unit	Baseline (Metal Roof)	Retrofit (Green Roof)	Improvement
peak surface temperature	$T_{surf,max}$	°C	70.0	32.0	38.0
decrement factor	f	—	0.45	0.12	73%
thermal phase shift	ϕ	hours	2.5	9.0	6.5
specific heat capacity	c_p	J/kg K	480	1000	high inertia
estimated discomfort hours ($T_{operative} > 26\text{ °C}$)	H_{disc}	h/season	>500	118	significant reduction

As illustrated in Figure 16, the nature-based solution on the western pitch acts as a high-performance thermal regulator. While a conventional metal-tile roof typically reaches surface temperatures of $T_{surf,max} \approx 70\text{ °C}$ during peak solar irradiance, the extensive green roof maintains a surface temperature significantly closer to the ambient air $T_{surf,max} \approx 30\text{--}32\text{ °C}$.

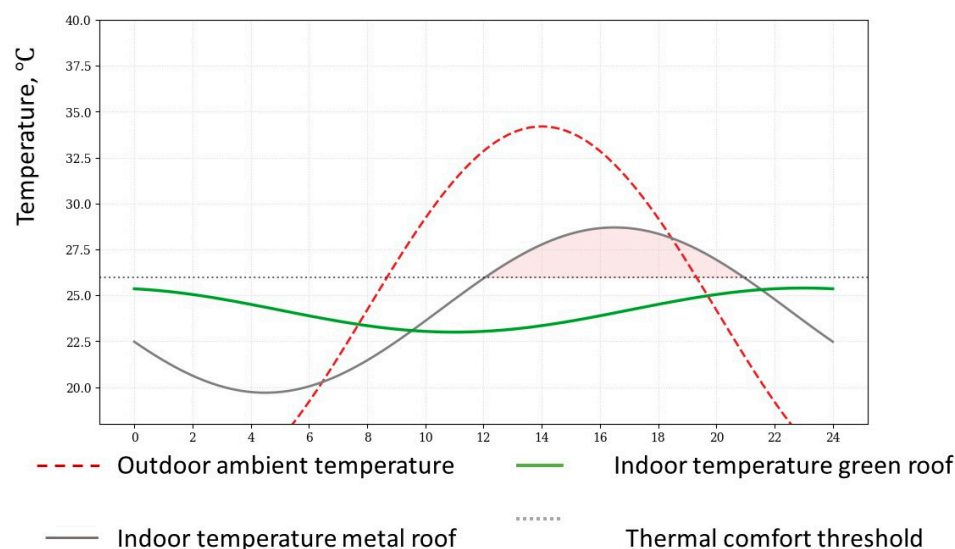


Figure 16. Daily temperature fluctuations and thermal damping effect. The pink shaded area represents the period and magnitude of thermal discomfort, where the indoor temperature under the metal roof exceeds the established thermal comfort threshold (26 °C).

This stability is primarily driven by the high specific heat capacity of the substrate and the cooling effect of evapotranspiration. The retrofit significantly improved the decrement factor from 0.45 to 0.12, resulting in a thermal phase shift of approximately 9 h. This shift ensures that the peak solar heat flux is delayed until the nocturnal period, as shown in the simulated temperature profiles. Consequently, the accumulated heat can be effectively dissipated through passive intensive ventilation when external temperatures are lower. To bridge the gap between material level dynamics and occupant comfort, the number of discomfort hours was estimated by correlating the monthly cooling demand,

calculated using the quasi-steady-state algorithms of CERTO (based on ISO 13790), with the hourly temperature distribution for the Cracow-Balice meteorological station. The analysis confirmed that the integrated strategy restricts the risk of overheating. The total number of discomfort hours $T_{operative} > 26^{\circ}\text{C}$ is projected at 118 for the entire season (approx. 5.3% of the period), as detailed in Table 8 and visualised in Figure 17.

Table 8. Monthly estimation of indoor thermal discomfort metrics.

Month	Total Hours	Ambient Temperature, $^{\circ}\text{C}$	Discomfort Hours ($T_{op} > 26^{\circ}\text{C}$)	Time in Discomfort, %
June	720	31.5	15	2.1
July	744	34.2	68	9.1
August	744	32.8	35	4.7
total season	2208	—	118	5.3

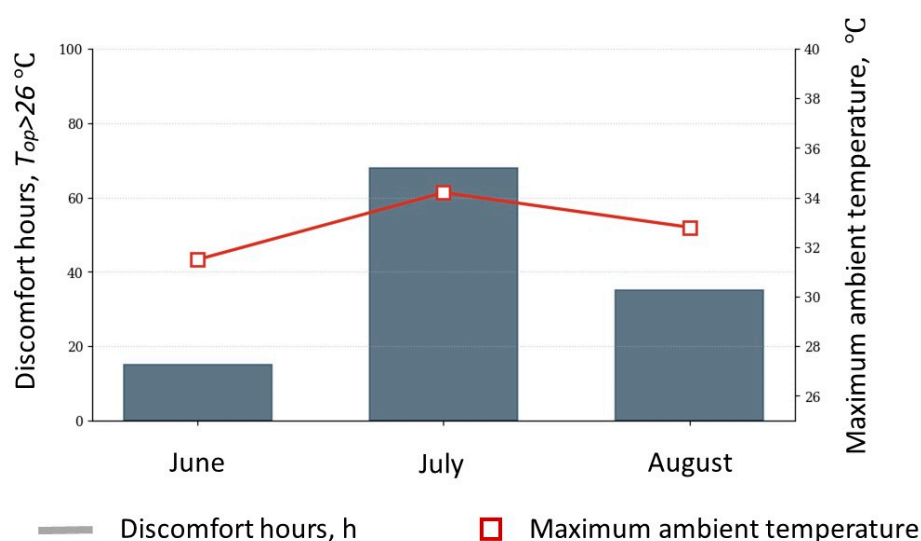


Figure 17. Monthly distribution of estimated indoor thermal discomfort hours in relation to maximum ambient temperatures for the peak summer season.

These findings demonstrate that the proposed retrofit roadmap ensures year-round climate resilience. By mitigating the risk of summer overheating through passive thermal mass activation and nature-based roofing, the strategy prevents the “rebound effect” of increased electricity consumption for active cooling, thereby safeguarding the primary energy savings and emission reductions achieved during the heating season.

4. Discussion

The modernization of the two-story residential building in Cracow demonstrates the technical feasibility of deep energy retrofitting in existing urban housing. By replacing carbon-intensive systems with high-efficiency solutions, the project achieved a significant reduction in energy demand. The initial energy audit, conducted using CERTO software, indicated that the baseline primary energy (EP) and final energy (EK) indicators significantly exceeded the Polish technical requirements (WT 2021) (Figure 18).

The baseline analysis revealed that the building's primary energy (EP) demand exceeded the WT 2021 standards by nearly 188% for windows and 150% for walls. This high energy consumption was primarily caused by the use of an inefficient coal-based heating system and a thermal envelope with high heat transmission losses.

The intervention successfully neutralized this deficit, reducing the EP indicator to net-zero levels (Figure 19).

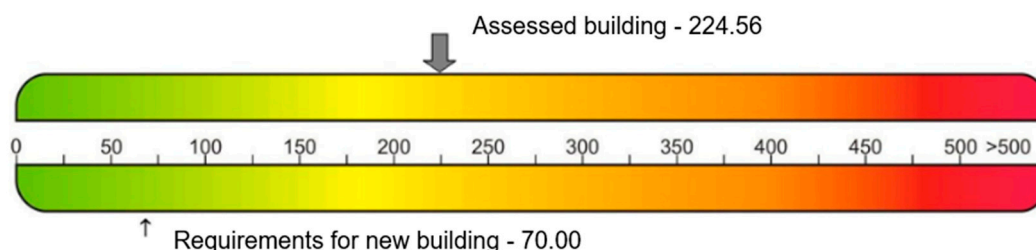


Figure 18. Annual demand indicator for non-renewable primary energy EP, kWh/m²·year.

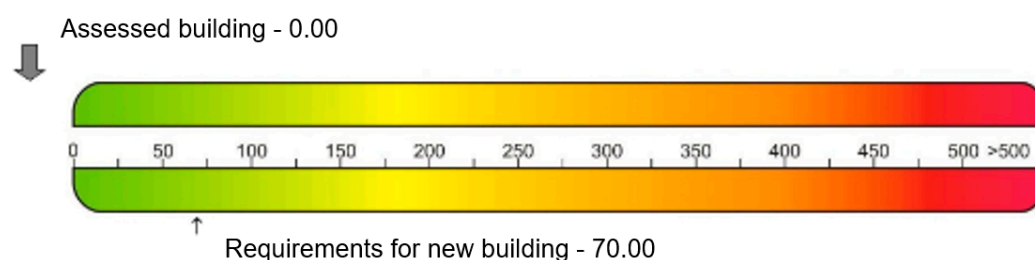


Figure 19. Annual demand indicator for non-renewable primary energy EP, kWh/m²·year, after building modernization.

The comprehensive technical and environmental transformation of the building is summarized in Table 9.

Table 9. Comparison of the building's condition before and after thermal modernization—energy, technical and environmental parameters.

Item/Installation	Before Modernization	After Modernization	Potential Carbon Impact, t CO ₂ /Year
DEFRO coal boiler, power 20 kW	efficiency 65%	-	350–400 kg CO ₂ /MWh of final energy
air to water heat pump monoblock BERETTA 8 kW	-	significant increase in efficiency (COP/SCOP ≈ 4.0)	0–50 kg CO ₂ /MWh (at PV close to 0)
photovoltaic installation	-	production 7000 kWh/year	emission reduction by 5–6 t CO ₂ /year
external walls –8 cm polystyrene, $\lambda = 0.036$ W/(m·K), U = 0.340 W/(m ² ·K)	higher heat losses	-	2.7 t CO ₂ /year
external walls—mineral wool 25 cm, $\lambda = 0.036$ W/(m·K), U = 0.147 W/(m ² ·K)	-	reduction of heat losses by approximately 60%	0.06 t CO ₂ /year
ceiling above the top floor—6 cm polystyrene	low insulation efficiency	-	1.79 t CO ₂ /year
ceiling above the top floor—10 cm mineral wool	-	reduction of heat loss by approximately 50%	0.048 t CO ₂ /year
double-glazed windows, U _w = 2.60 W/(m ² ·K)	annual energy losses 6240 kWh/year	-	3.03 t CO ₂ /year
triple-glazed windows, U _w = 0.85 W/(m ² ·K)	-	reduction of heat loss by approximately 67%	0.05 t CO ₂ /year
steel doors with glass, U _w > 2.0 W/(m ² ·K)	annual energy losses 348 kWh/year	-	0.19 t CO ₂ /year

wooden doors CAL, $U_w = 1.20 \text{ W}/(\text{m}^2 \text{ K})$	-	reduction of heat loss by approximately 40%	0.006 t CO ₂ /year
reinforced concrete balcony	strong thermal bridge	-	0.56 t CO ₂ /year
balcony removed	-	reduction of heat loss by approximately 100%	0.00 t CO ₂ /year
traditional roof made of metal tiles	annual energy losses 4608 kWh/year	-	2.24 t CO ₂ /year
green roof (partially) + PV	-	reduction of heat loss by approximately 40%	0.069 t CO ₂ /year

The values presented in Table 9 illustrate the theoretical carbon emission potential associated with the heat loss of individual building components. However, the overall operational CO₂ reduction of 89% (from 3960 kg to 430 kg/year) was determined using a final energy (EK) balance. In the baseline scenario, the emission was derived from a total energy demand of 25,000 kWh supplied by a coal boiler (65% efficiency). In the post-retrofit scenario, the combination of a 54% reduction in thermal demand, the high seasonal efficiency of the air-source heat pump (SCOP 4.0), and the 7000 kWh/year production from the PV system reduced the net grid energy consumption to approximately 615 kWh/year, resulting in the final residual emission of 430 kg CO₂.

4.1. Thermal Envelope Performance and Passive Strategies

The fundamental reduction in transmission heat losses was achieved by replacing the insufficient 0.08 m EPS layer with a breathable 0.25 m mineral wool system ($\lambda = 0.036 \text{ W}/(\text{m}\cdot\text{K})$). This material substitution, combined with a ventilated timber facade, is critical for hygrothermal safety. Unlike standard external thermal insulation composite systems, the ventilated assembly optimises moisture buffer capacity, significantly mitigating the risk of interstitial condensation typical in humid continental climates.

A novel aspect of this study is the application of active glazing as a comfort regulator. While the triple-glazed units ($U_w = 0.85 \text{ W}/(\text{m}^2\cdot\text{K})$) drastically reduced passive losses, the integration of electric heating foils introduces a dynamic control capability. By elevating the internal glass surface temperature to $T \approx 20.2 \text{ }^\circ\text{C}$, the system effectively stabilizes the mean radiant temperature. This intervention allows for a reduction of the indoor air temperature set point by 2 K without compromising occupant thermal comfort (maintaining a neutral PMV index). These findings align with recent studies by Basok et al. [32,42], confirming that active glazing mitigates the “cold wall” effect and reduces peak loads on the primary HVAC system, justifying its electrical consumption (285 kWh/year) through improved operative temperature stability.

4.2. Asymmetrical Roof Functionality and Nature-Based Solutions

A key feature of the building's adaptation is the functional differentiation of the roof pitches, creating an asymmetrical thermal and energetic strategy without altering the original structural slope. This approach aligns the material characteristics of the roof with the diurnal solar cycle and local microclimatic conditions of Lesser Poland. The eastern pitch is dedicated to active energy harvesting. By installing the 7 kWp polycrystalline PV array on this slope, the system capitalizes on lower ambient temperatures during the morning hours. This is a strategic choice to mitigate the thermal degradation of the photovoltaic cells, as solar radiation captured at lower operating temperatures enhances the conversion efficiency of the modules. In contrast, the western pitch serves as a passive, nature-based cooling shield. The conversion of this slope into an extensive green roof addresses the

critical solar exposure zone (240–300° azimuth), where the building is most susceptible to overheating during the late afternoon. This nature-based solution leverages two primary physical mechanisms. The substrate and vegetation layers increase the thermal mass of the roof, inducing a significant “thermal lag.” This shifts the peak heat transmission from the afternoon to the cooler evening hours.

The correlation between external climatic extremes and internal thermal stability is further elucidated in Figure 17. Despite a notable increase in peak ambient temperatures during July (reaching 34.2 °C), the proposed retrofit strategy effectively limits the duration of indoor overheating. The maximum monthly discomfort duration was recorded in July at 68 h, which corresponds to only 9.1% of the total monthly timeframe. In contrast, the baseline scenario (pre-retrofit) would have faced persistent overheating risks under similar solar irradiance levels. The results confirm that the integration of an extensive green roof with high-inertia insulation layers provides a sufficient thermal buffer, maintaining operative temperatures within acceptable comfort ranges for over 94% of the entire summer season without the need for active air conditioning.

4.3. HVAC System

The replacement of a 20 kW coal-fired boiler with an 8 kW air-source heat pump (ASHP) marks a fundamental shift toward building electrification. The 60% reduction in nominal power was facilitated by the lowered design heat load (6.4 kW), allowing the ASHP to operate at high efficiency with a Seasonal Coefficient of Performance (SCOP) of 4.0. The replacement of high-inertia cast-iron radiators with low-inertia steel panel units was essential to this synergy, allowing for lower supply temperatures and faster system response. The annual energy balance, comprising 2538 kWh for the ASHP and 3500 kWh for household demand, is fully offset by the 7 kWp PV system. The selection of a 10 kW hybrid inverter provides a technical foundation for future energy storage integration, which is increasingly recognized as a necessity for enhancing self-consumption and grid stability in NZEB configurations.

4.4. Energy Self-Consumption and Seasonal Storage Potential

While achieving NZEB status is a primary regulatory milestone, the annual energy balance often masks critical sub-hourly operational challenges. The building's total annual demand of 6038 kWh is offset by a 7 kWp PV array generating 6650 kWh. However, the effectiveness of this configuration is governed by the inherent temporal mismatch between solar energy availability and the thermal load requirements typical of the Lesser Poland climate. To evaluate the operational performance of the system, a monthly energy distribution was simulated, as presented in Table 10.

Table 10. Monthly distribution of simulated PV generation and energy demand.

Month	PV Generation, E_{PV} , kWh	ASHP Demand, E_{PV} , kWh	Household Demand, kWh	Total Demand E_{load} , kWh	Monthly Balance, kWh
January	135	580	310	890	−755
February	240	450	280	730	−490
March	520	280	300	580	−60
April	710	120	280	400	+310
May	890	40	290	330	+560
June	980	10	280	290	+690
July	1020	5	295	300	+720
August	880	5	295	300	+580
September	620	50	290	340	+280
October	380	180	300	480	−100

November	165	368	290	658	−493
December	110	450	310	760	−650
total	6650	2538	3500	6038	+612

The simulation results reveal a self-consumption rate of approximately 28.5%, highlighting a fundamental challenge inherent to ASHP-integrated NZEBs within Central European climatic conditions. This value underscores the significant seasonal divergence where peak solar harvesting in July is inversely correlated with the maximum thermal demand in January, as illustrated in Figure 20.

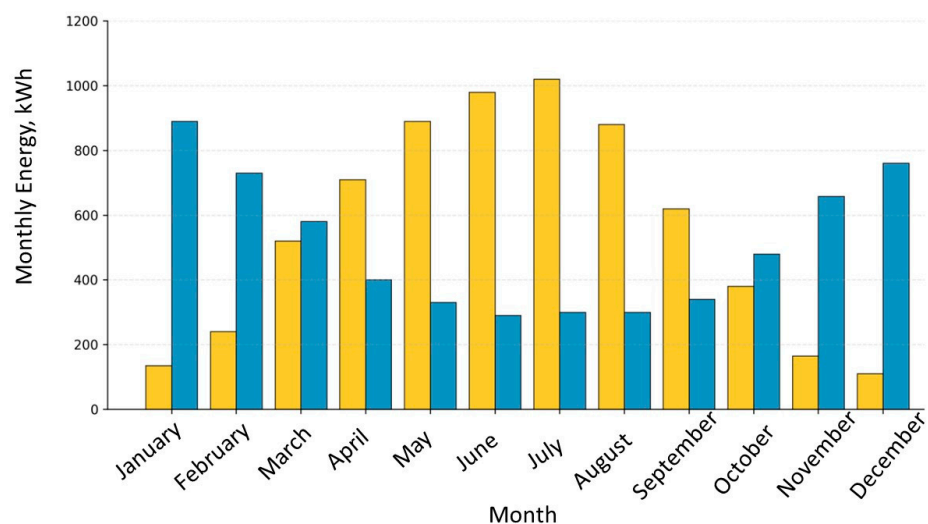


Figure 20. Monthly distribution of photovoltaic energy generation versus total building energy demand for the retrofitted NZEB configuration. The yellow bars represent the monthly energy production from the photovoltaic system, while the blue bars indicate the monthly electrical energy consumption of the building.

To address this discrepancy, the proposed retrofit strategy exploits the building's enhanced thermal inertia, arising from the combined effect of the intensive green roof and high-performance insulation. To mitigate this effect and enhance the practical applicability of the technical roadmap, the study evaluates the role of thermal mass activation. By strategically shifting the ASHP operational cycle to coincide with peak solar irradiance from 10:00 to 15:00, the building fabric effectively serves as a passive thermal buffer. This load-shifting intervention is projected to elevate the direct self-consumption rate to 41% during transitional periods. Consequently, this methodology establishes a technical roadmap for prosumers by maximising the utilisation of on-site renewables through passive structural storage. Such a strategy constitutes a functional precursor to the deployment of a battery energy storage system, as the installed 10 kW hybrid inverter already provides the necessary modular architecture for enhanced energy autonomy. To further optimise this configuration, preliminary calculations suggest that the integration of a 10 kWh battery energy storage system would elevate the self-sufficiency ratio by approximately 25%, effectively bridging the evening energy gap and covering peak loads during the spring and autumn transitional periods.

4.5. Economic Viability and Simple Payback Time Analysis

The economic feasibility of the deep retrofit strategy was evaluated by comparing the lifecycle operational costs against the total capital expenditure. In the context of the Polish

energy market and the transition toward NZEB, the investment in high-performance insulation, an air-source heat pump, and renewable energy systems represents a significant financial commitment that requires rigorous justification through payback analysis.

The total investment cost for the comprehensive modernization package was estimated at 250,000 PLN. As detailed in Table 11, the expenditure is distributed across three primary categories: thermal envelope upgrades (walls, ceiling, green roof), active systems (ASHP, PV), and architectural interventions (joinery, balcony removal).

Table 11. Investment cost estimate for the deep retrofit components.

Element	Cost, PLN	Share of Total
heat pump with accessories (8 kW)	70,000	28%
wall insulation (25 cm wool + wooden facade)	50,000	20%
photovoltaics 7 kWp + hybrid inverter	50,000	20%
window and door joinery (triple-glazed)	45,000	18%
green roof (extensive system)	15,000	6%
ceiling insulation	10,000	4%
dismantling of balconies (thermal bridge removal)	10,000	4%
Total Sum	250,000	100%

It is worth noting that specific low-cost interventions, such as the removal of balconies (10,000 PLN), yield disproportionately high technical benefits by eliminating critical thermal bridges and preventing structural degradation, despite constituting only 4% of the budget.

Prior to the intervention, the building's annual energy consumption was estimated at approximately 25,000 kWh. Following the implementation of the deep retrofit, the final energy demand was reduced to 11,430 kWh/year, representing a 54% reduction. Assuming a unit electricity price of 1.2 PLN/kWh, the annual financial savings are estimated at 16,284 PLN.

The simple payback time (SPBT) was calculated for different modernization scenarios to assess the impact of renewable energy integration and public funding support for the “Clean Air” programme or thermo-modernization tax reliefs (Table 12).

Table 12. Economic performance and SPBT of sustainable retrofit scenarios.

Modernization Scenario	CO ₂ Emission, kg/Year	Final Energy EK, kWh/m ² ·y	Investment, PLN	Annual Savings, PLN	SPBT, Years
full modernization (no PV, no support)	3960	107.50	200,000	16,284	12.3
full modernization + 30% subsidy	3960	107.50	140,000	16,284	8.6
full package + PV (7 kWp) (no support)	430	28.73	250,000	24,684	10.1
full package + PV (7 kWp) + 30% subsidy	430	28.73	175,000	24,684	7.1

The analysis reveals that the inclusion of the photovoltaic system significantly accelerates the return on investment. Although the PV array increases the initial capital expenditure by 50,000 PLN, it reduces the SPBT from 12.3 years to 10.1 years (in the non-subsidized scenario) by offsetting the electrical demand of the heat pump and active glazing. When current financial support mechanisms (30% subsidy) are applied, the SPBT for the most advanced NZEB scenario drops to 7.1 years. This falls within the highly attractive range of 6–12 years, which is cited in the literature as the threshold for economic viability in the Polish residential sector [43,44].

The financial viability of this strategy is underpinned by two primary factors: the strategic leveraging of national subsidy programs and the projected stability of electricity costs. The analysis assumes a cumulative subsidy intensity (integrated in the 30–60% scenarios) reflecting the potential synergy between the “Clean air” (Czyste powietrze) program for the heat pump and insulation, and the “My electricity” (Mój prąd) program for the PV array and active glazing. In addition, the economic model utilizes a conservative energy price escalation rate, assuming that the expansion of domestic renewable energy sources and the implementation of ‘energy shields’ for NZEB-compliant households will maintain electricity price stability over the mid-term investment horizon.

Finally, it is important to note that the environmental efficiency of the investment is striking. Moving from “full modernisation without PV” to the “full package + PV” scenario requires a marginal 25% increase in capital expenditure, yet yields a substantial 89% reduction in residual CO₂ emissions (from 3960 kg to 430 kg/year). This underlines that achieving near-zero emission status is not only technically feasible but also economically competitive when bolstered by targeted energy policies.

To enhance the robustness of the economic findings, a sensitivity analysis was conducted to evaluate how fluctuations in key technical parameters affect the SPBT. Given the climatic variability of the Cracow region, two critical variables were assessed: the annual yield of the 7 kWp PV system and the seasonal coefficient of performance (SCOP) of the air-source heat pump. As shown in Table 13, even under a “pessimistic” scenario (10% lower solar radiation and a decrease in SCOP due to an exceptionally cold winter), the SPBT for the optimized NZEB package remains below 9 years.

Table 13. Sensitivity of the SPBT to variations in PV yield and ASHP efficiency.

Scenario	PV Yield [kWh/Year]	ASHP SCOP	Annual Savings, PLN	SPBT, Years (Assuming 30% Subsidy Scenario)
optimistic (+10%)	7700	4.4	26,800	6.5
baseline	7000	4.0	24,684	7.1
pessimistic (−10%)	6300	3.6	21,500	8.1

Conversely, if energy prices continue to rise beyond the assumed 1.2 PLN/kWh, the payback period could drop to as low as 6.2 years. The sensitivity analysis also implicitly accounts for energy price inflation by demonstrating the SPBT reduction to 6.2 years under rising energy price trends, assuming a conservative discount rate of 3% for future cash flows. This analysis confirms that the proposed technical pathway is resilient to both climatic fluctuations and market volatility.

4.6. Limitations, Operational Challenges, and Future Research Directions

While the proposed NZEB strategy demonstrates high efficiency for the analysed single-family house, several limitations and operational challenges must be acknowledged to ensure the reliability of the findings.

The scalability of this model to multi-family residential buildings presents significant challenges. In high-density urban developments, the available roof area per occupant is substantially lower, which may limit the capacity of the PV array to fully offset the primary energy demand. Furthermore, regional climatic differences significantly influence the performance of nature-based solutions. While the green roof effectively mitigates summer overheating in the temperate climate of the Cracow region, its efficiency in terms of evapotranspiration and thermal buffering would vary in Mediterranean or Nordic climates, requiring localised plant selection and substrate adjustments.

The real-world performance of active systems is highly sensitive to occupant behaviour. For instance, the effectiveness of active glazing depends on user-controlled settings and shading patterns, which, if mismanaged, can lead to unintended cooling loads or reduced solar gains. Additionally, nature-based solutions like extensive green roofs require long-term maintenance, including periodic irrigation during extreme droughts and drainage system inspections to prevent structural moisture issues. Similarly, the longevity of active glazing and the 8 kW ASHP system necessitates specialised technical service, which may increase lifecycle operational costs beyond the initial estimates presented in Tables 11 and 12.

Despite these challenges, this study provides a scalable technical model for the deep retrofitting of Central European housing. While current Polish regulations (WT 2021) set an EP threshold of 70 kWh/(m²·a), this research demonstrates that zero-emission status is attainable even in older structures through the integration of active glazing and nature-based roofing. Future research should focus on the long-term monitoring of “active” window systems to quantify their impact on annual energy savings versus operational costs. Additionally, further investigation is required into the lifecycle assessment (LCA) of the mineral wool and wooden facade materials compared to traditional ETICS to ensure that energy-efficient upgrades align with circular economy principles. Moreover, the current deterministic approach to meteorological data could be enhanced by incorporating distributionally robust optimisation frameworks, such as the Imprecise Dirichlet Model, to improve system resilience against extreme climatic ambiguity [45].

Beyond standalone efficiency, the proposed retrofit enhances the building's potential for grid-interactive resilience. The substantial thermal mass provided by the masonry structure, combined with the 0.25 m mineral wool insulation, significantly increases the building's thermal inertia. This allows the structure to function as a “virtual energy storage” system. By utilising an asynchronous decentralised framework, the modernised HVAC system can shift its electrical load to off-peak hours without compromising indoor thermal comfort. Such a co-response between the building's thermal state and the power grid is essential for supporting energy network stability while ensuring user privacy and data security in a decentralised energy landscape [46].

5. Conclusions

The comprehensive deep retrofit of the residential building in Krakow demonstrates that achieving NZEB status in existing Central European housing stock is technically feasible and economically justified.

1. The transition from a legacy coal-based heating system to an integrated 8 kW air-source heat pump and a 7 kWp photovoltaic array, combined with a high-performance

thermal envelope (0.25 m mineral wool), allowed for a 54% reduction in final energy demand (from 25,000 kWh to 11,430 kWh). The system achieved a net-zero non-renewable primary energy indicator ($EP = 0$).

2. The implementation of active glazing with electric heating foils proved to be a critical factor in optimizing indoor climate. By elevating the internal glass surface temperature to $T \approx 20.2\text{ }^{\circ}\text{C}$, the system effectively eliminated the “cold wall” effect.

3. The asymmetrical roof strategy, featuring an extensive green roof on the western pitch, provided a passive nature-based cooling shield. This solution leverages thermal lag and evapotranspiration to mitigate afternoon overheating, reducing the cooling load and protecting the attic microclimate during peak solar radiation.

4. The modernization package resulted in a radical 89% reduction in operational CO_2 emissions, dropping from 3960 kg to only 430 kg per year. The elimination of the coal boiler and the integration of renewables signify a successful pathway for the decarbonisation of individual residential buildings.

5. The study demonstrates that the integration of nature-based solutions with advanced energy management can effectively compensate for the seasonal solar-demand mismatch, reducing the carbon footprint by 2.24 t CO_2 /year while maintaining high self-consumption standards.

6. The economic analysis confirms that deep retrofitting is a sound investment. Although the inclusion of a PV system increased the initial capital expenditure, it shortened the simple payback time by offsetting operational costs. With current public subsidy mechanisms (30% support), the SPBT reached an attractive level of 7.1 years, which is well within the economic profitability threshold for the Polish residential sector.

7. This project serves as a scalable technical model for the modernization of 20th-century urban housing. Future research should focus on the long-term durability of active window foils and the potential for integrating local energy storage to further increase the self-consumption of the generated solar energy.

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