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Original Research Article

IMPACT OF FLOOR - GROUND COUPLING AND THERMAL MASS ON SEASONAL HEATING ENERGY USE IN SINGLE - STOREY RESIDENTIAL BUILDINGS IN A TEMPERATE CLIMATE

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Abstract

This study presents an empirical evaluation of winter heating performance in two full-scale single-storey residential buildings located in a temperate transitional climate in western Poland. The buildings, identical in geometry, layout, and insulation levels, differed in wall thermal mass and subfloor configuration. During the 2018/2019 heating season, the building with medium-weight masonry walls consumed 3.6% less heating energy than its lightweight timber-frame counterpart. In the following season, floor insulation was removed in the masonry building to enable direct ground coupling. While this led to a 12.2% increase in total energy use, the difference emerged only in the latter part of the winter. Continuous ground temperature monitoring confirmed that subsoil heat retained from summer acted as a thermal buffer, delaying the onset of increased losses. The actual energy penalty was substantially lower than predicted by standard calculation methods, indicating that steady-state models may overestimate seasonal ground-related losses. These findings highlight the dynamic nature of heat exchange between buildings and the ground and support the use of mass-based and soil-coupled envelope strategies as effective tools for improving seasonal energy efficiency and resilience in temperate climates increasingly affected by climate variability and power supply risks.

Keywords: winter heating demand, energy performance, ground coupling, subsoil heat, thermal mass, residential buildings, experimental monitoring

1. INTRODUCTION

1.1. The winter-centric legacy of building efficiency policies

For the past thirty years, global building policies have mainly aimed at improving energy efficiency by reducing heating-related energy use. This approach, supported by international climate frameworks and

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national legislation, has led to the widespread introduction of insulation and airtightness standards in temperate and cold-climate countries. Buildings are now designed to retain heat more effectively, thereby reducing winter energy use and associated carbon emissions. However, this winter-centered paradigm may no longer be sufficient in the context of a rapidly warming climate.

Growing empirical and modeling-based research indicates that well-insulated and airtight buildings, while successful in minimizing heating demand, may be increasingly vulnerable to summer overheating. Several studies have shown that energy-efficient, passive, and nearly zero-energy buildings may overheat more than older, less insulated stock due to high internal gains and limited passive cooling capacity [1-4]. At the same time, research has highlighted that the effectiveness of thermal performance in such buildings strongly depends on real-life usage [5-7], which often diverges from modeled occupant behavior [8,9]. Together, these findings underscore the need to move beyond traditional winter-centered metrics and to adopt performance frameworks that fully account for both heating and cooling loads under current and future climatic conditions.

1.2. Cilmate-induced shifts in energy demand

Long-term projections show that many regions historically dominated by winter energy demand will experience a gradual shift toward cooling-dominated profiles. For instance, Rahif et al. [10] demonstrated that in Brussels, traditionally a heating-focused climate, the number of cooling degree days is expected to match heating demand by the end of the century, even under optimistic emission scenarios. Likewise, Sarabia-Escriva et al. [24] showed that Spain's current energy certification systems significantly underestimate future cooling needs, by up to 56% in Barcelona and 41% in Almería.

D'Agostino et al. [12], through simulations across 94 European locations and three climate scenarios (2030, 2050, 2070), concluded that current building envelope regulations are increasingly misaligned with emerging thermal loads. While heating demand continues to decline in moderate and cold climates, cooling demand is rapidly rising across the Mediterranean and continental Europe, altering the energy balance of buildings. Consequently, the authors advocate for climate-adaptive insulation standards and greater emphasis on passive cooling and thermal mass integration. They also recommend regular updates to building codes to reflect long-term climate trajectories.

1.3. Overheating risks in cold and temperate climates

The limitations of current thermal design standards are becoming increasingly evident in countries not traditionally associated with summer overheating. Rui et al. [13] documented substantial overheating in newly built residential buildings across four cities in northern China, regions that have historically prioritized winter heat retention. Using empirical data and validated simulations, they showed that bedrooms frequently exceeded 26°C for over 30% of occupied summer hours in Harbin, Shenyang, and Dalian, despite compliance with current insulation standards. Similarly, Yu et al. [14] showed that buildings with low U-values and low thermal mass experienced over 100 more hours of overheating than those with older, less insulated configurations. Their study, covering 24 monitored bedrooms across 13 Chinese cities, confirmed that high insulation levels required by recent building regulations, although effective in reducing winter losses, are exacerbating overheating risks in summer. Simulation results indicated that reductions in U-values could increase overheating duration by 6% to over 22%, depending on local climate and construction.

Findings from other cold-climate countries point in the same direction. In Finland, [15] reported growing summer overheating in energy-efficient apartments. Schade et al. [16] documented unacceptable indoor temperatures during heatwaves in Swedish apartment buildings that comply with current regulations, underscoring the challenges posed by high-latitude solar gains and lack of shading.

Likewise, Wang et al. [17] demonstrated that energy-efficient buildings designed in accordance with updated Chinese standards experienced up to 40% more overheating hours than conventional buildings, despite reduced winter energy use.

Recent research in Ireland further supports these concerns: based on monitored data from 50 nZEB homes, [18] found that 26% of newly built residences failed to meet CIBSE TM59 overheating criteria, and nearly half exceeded WHO comfort thresholds for a significant portion of the year. This growing body of evidence illustrates that even in temperate maritime climates, low-energy design can embed overheating risks unless summer resilience is explicitly addressed.

1.4. Heatwaves and blackouts: a growing risk

Alongside these long-term shifts in seasonal loads, climate change is also increasing the severity and frequency of extreme events such as heatwaves and cold snaps. As Ramallo-González et al. [19] argue, current definitions of heatwaves are typically based on external conditions, while real health impacts are largely driven by internal temperatures. This discrepancy underscores the need for thermal design approaches that ensure safety during rare but high-impact periods, not just compliance with annual averages. Their proposed framework for analytically defining heatwaves based on internal thermal conditions rather than outdoor temperatures offers a pathway for more occupant-centered resilience metrics.

Some winter-focused envelope strategies, such as heavy insulation of floors and walls, may unintentionally hinder heat dissipation in summer. Recent studies have shown that in certain configurations, these measures can increase the risk of overheating during extreme heat events [14,17]. Indeed, as electricity grids face growing pressure from climate-induced peaks and potential outages, buildings must be able to maintain habitable temperatures without relying exclusively on active systems. A series of authors' recent studies has shown that thermal mass and ground coupling may play a critical role in such passive resilience strategies. Gortych and Kuczyński [20] demonstrated that a medium-weight, ground-coupled building maintained indoor temperatures above 15 °C for over 60 hours during a winter blackout, while a lightweight building fell below habitable thresholds in less than 55 hours. In parallel summer experiments, the same medium-weight building avoided overheating entirely during multi-day heatwaves, even without mechanical cooling [21]. Together, these results underscore the year-round importance of envelope-based resilience strategies that can buffer both heat and cold without external energy input.

1.5. Scope and novelty of the present study

In light of these findings, it becomes increasingly important to evaluate not only seasonal energy use, but also the long-term energy and environmental performance of buildings under shifting climate conditions. This study addresses that need by building upon our previous research on thermal resilience during summer and winter outages. The empirical dataset is extended by evaluating the year-round heating energy demand in two test buildings with differing thermal mass and subfloor configurations. The analysis uses real measurement data from full heating seasons and integrates it with life cycle carbon assessments to explore how material strategies influence not just immediate energy use but also long-term environmental impact.

Against this background, there is a growing need to assess the energy and environmental performance of buildings not only during extreme events or individual seasons, but across the entire year. While previous research has confirmed the thermal resilience of certain building typologies during heatwaves and winter outages, a comprehensive evaluation of their year-round heating energy demand remains lacking. This is particularly important for buildings employing unconventional envelope configurations, such as masonry construction without ground floor insulation, which challenge conventional efficiency benchmarks.

The present study addresses this gap by quantifying and comparing the winter energy consumption of two full-scale test buildings with differing thermal inertia and subfloor configurations. It extends earlier resilience-focused investigations by incorporating full-season heating data and analyzing the impact of envelope strategies on energy demand. The novelty of the research lies in its integration of empirical performance monitoring, seasonal analysis, and life cycle carbon assessment to evaluate whether unconventional passive strategies, such as thermal coupling with the ground, can enhance winter performance without compromising summer comfort. The findings are intended to inform climate-responsive design and regulatory frameworks by identifying envelope configurations that optimize both passive resilience and year-round energy efficiency under evolving climatic conditions.

2. MATERIALS AND METHODS

Both test buildings (B1 and B2) were single-storey, detached residential houses, each with a floor area of approximately 120 m² and an identical internal layout consisting of a living room and three bedrooms. Despite having the same geometry and internal zoning, the buildings differed in construction type and subfloor configuration.

Building B1 was constructed with medium-weight masonry walls and featured a ground-bearing floor slab with no insulation beneath. This design allowed for direct thermal coupling with the subsoil. In contrast, Building B2 was built using a lightweight timber-frame system filled with mineral wool insulation. Its floor slab was separated from the ground by a continuous layer of thermal insulation, limiting heat exchange with the underlying soil.

These differences in structural mass and ground connection were deliberately introduced to assess their impact on heating energy demand and seasonal thermal performance. The comparative setup enabled a direct evaluation of how envelope configuration and heat storage capacity affect building–ground thermal interaction under identical boundary conditions.

To highlight the thermal differences between the two tested buildings, a comparative summary of the envelope assemblies is provided below. Rather than presenting a detailed tabulation for each element, the values are grouped by construction component type and described narratively, with an emphasis on their impact on thermal performance and heat storage.

In Building B1, external and internal walls were constructed from masonry, yielding high specific heat capacity. For example, internal partition walls achieved specific heat capacities exceeding 400 kJ/m²K, with U-values ranging between 1.39 and 1.99 W/m²K. The external wall, despite its solid construction, exhibited a relatively low U-value of 0.14 W/m²K and a surface heat capacity of nearly 100 kJ/m²K.

By contrast, Building B2, built using timber-frame systems, showed lower heat storage potential across all envelope elements. Its external walls, filled with mineral wool and sheathed with lightweight boards, provided a similar U-value of 0.13 W/m²K, but the heat capacity was substantially lower - about 37 kJ/m²K. Internal partitions in B2 also demonstrated significantly reduced thermal mass (around 45–75 kJ/m²K) compared to their masonry counterparts in B1.

Ceiling assemblies in both buildings were similar in design, with U-values around 0.09–0.11 W/m²K. However, B2 offered slightly higher ceiling heat capacity due to the use of denser interior sheathing materials.

Detailed information on construction of building assemblies, their thermal properties and thermophysical properties of materials were presented in [22], [23].

Two floor configurations were applied in Building B1: a standard insulated slab in 2018 and an uninsulated ground-coupled slab in 2019. Building B2 retained the insulated slab-on-ground configuration throughout the monitoring period.

In the 2019 configuration of Building B1, the original floor finish was removed, the screed layer was demolished, and the PEHD foil together with the mineral wool insulation previously located beneath the foundation slab was removed. Subsequently, a new horizontal damp-proofing layer in the form of a continuous foil, turned up onto the building walls, was installed. Finally, a new concrete layer was cast, forming a two-layer floor construction in accordance with the as-built documentation.

As a result of the absence of thermal insulation, the surface heat capacity of the floor increased to over 150 kJ/m²K, while the U-value rose to approximately 0.80 W/m²K.To compare the total thermal inertia, the Thermal Mass Parameter (TMP) was estimated for each variant. The TMP reached 192 kJ/m²K in B2, 400 kJ/m²K in the original (insulated) version of B1, and 467 kJ/m²K in its post-intervention configuration. However, it should be noted that this metric, based on [24], accounts only for the innermost 10 cm of building layers and thus underestimates the impact of ground coupling, particularly in the uninsulated B1 slab.

The buildings were mechanically ventilated. In all rooms, the air exchange rate was kept constant at 0.6 per hour. The rooms were supplied with air through inlet diffusers, which made it possible to adjust the amount of supply air to the volume of the rooms so that theair exchange in the rooms was the same. An airtightness test using the Blower Door method was carried out on both buildings and confirmed a similar level.

Photographic documentation of both buildings is presented in Fig. 1, while Fig. 2 shows a schematic cross-section illustrating the construction of the floors, walls, and foundations.

Fig. 1. Façade view of the two test buildings

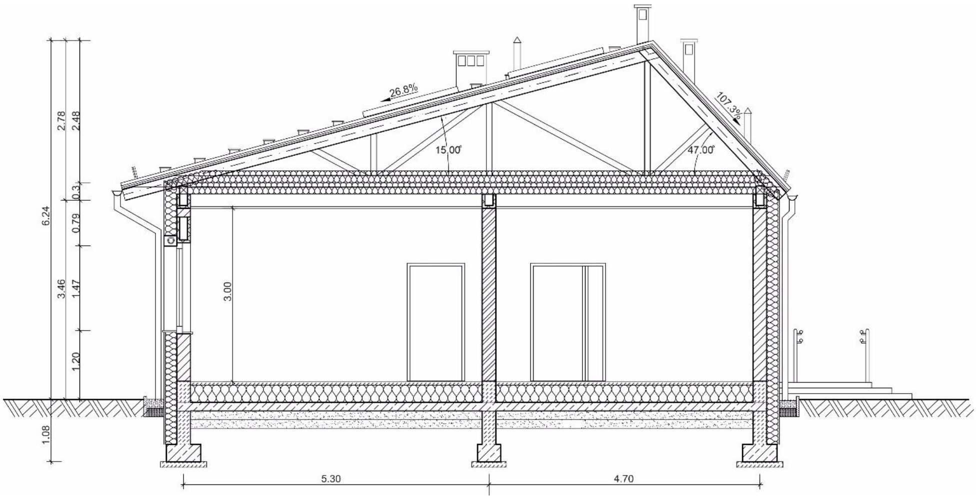

Fig. 2. Cross-section A-A of the experimental buildings

Fig. 3. provides detailed views of the three vertical sensor profiles. Sensors were installed at a depth of 1.5 meters in three vertical profiles: A (in the center of the building), B (0.5 m from the external wall to the inside of the building), and C (0.5 m from external wall to the outside of the building). One located beneath the center of the room, another adjacent to the inner side of the external wall, and a third placed outside the foundation wall.

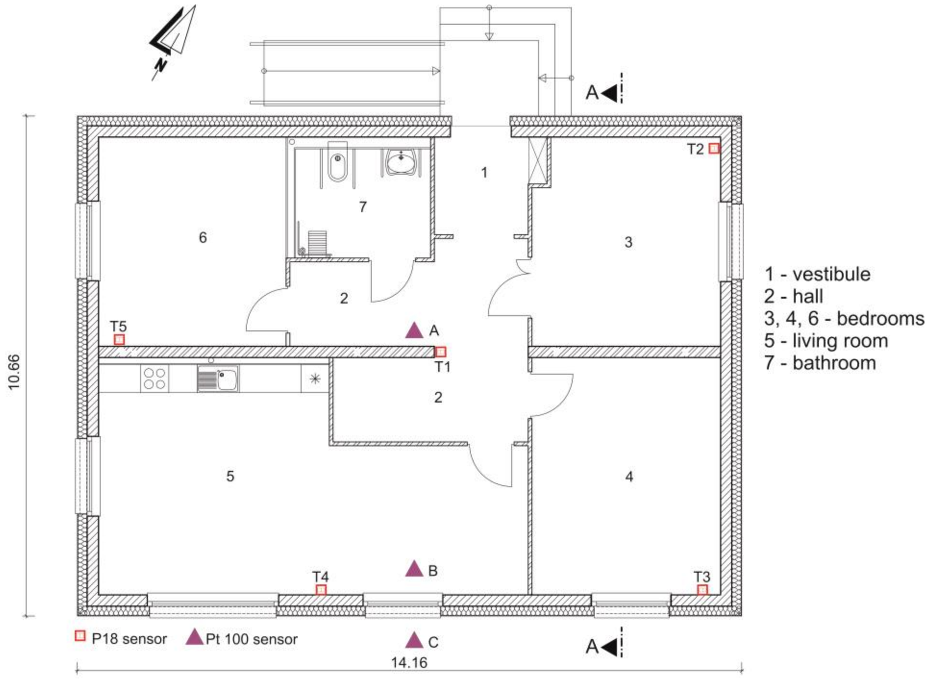

Fig. 3. Ground floor plan of the experimental buildings, showing room layout and positions of indoor air temperature sensors (T1–T5) and ground temperature sensors (A–C)

To minimize lateral heat losses, both buildings were equipped with vertical external polystyrene (EPS) insulation, 20 cm thick and extending 80 cm below ground level, applied along the foundation perimeter. Fig. 4 presents a typical construction detail of this solution, which was identical in both cases.

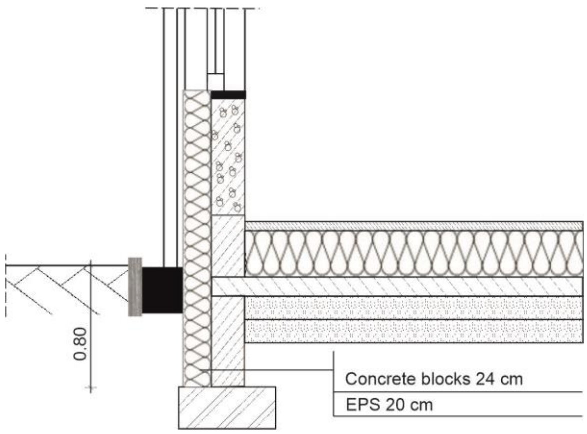

Fig. 4. Diagram of vertical polystyrene insulation applied to the foundation walls of buildings B1 and B2

Heating energy consumption was monitored continuously from 1 November 2020 to 31 March 2021 using calibrated heat meters integrated with the underfloor heating systems. The indoor setpoints and heating schedules were kept identical in both buildings to ensure comparability.

In parallel, long-term soil temperature monitoring was conducted between 1 June 2019 and 31 May 2020. Sensors recorded hourly data using an autonomous logging system, allowing detailed analysis of thermal behaviour within the ground and its interaction with each building.

This dual monitoring approach, combining energy use data with high-resolution soil temperature profiles, enabled a comprehensive assessment of how envelope configuration and ground coupling influence year-round heating performance in residential buildings.

3. RESULTS AND DISCUSSION

3.1. Impact of wall thermal mass on heating energy demand

The first monitoring period, carried out between December 1, 2018, and February 8, 2019, was designed to assess the influence of thermal mass in external and internal walls on heating energy demand under comparable boundary conditions. During this period, both buildings operated with identical internal layouts, heating setpoints, insulation levels in roofs and floors, and exposure to outdoor climate. The only substantial difference between them lay in the construction of their wall systems. Building B1 featured medium-weight masonry walls with relatively high surface and volumetric heat capacities, while Building B2 was constructed using a lightweight timber-frame system filled with mineral wool insulation and finished with lightweight sheathing boards.

Over the course of the 70-day winter season, the total heating energy consumption in Building B1 amounted to 2073.0 kWh, whereas Building B2 used 2151.0 kWh. This resulted in a 3.6 percent reduction in heating demand in the heavier building. Although the difference is modest, it suggests that the higher thermal inertia of the masonry walls in B1 provided some benefit in moderating energy use, even under continuous heating. The cumulative heating energy profiles shown in Fig. 5 confirm this tendency, with B1 consistently exhibiting slightly lower energy demand over time.

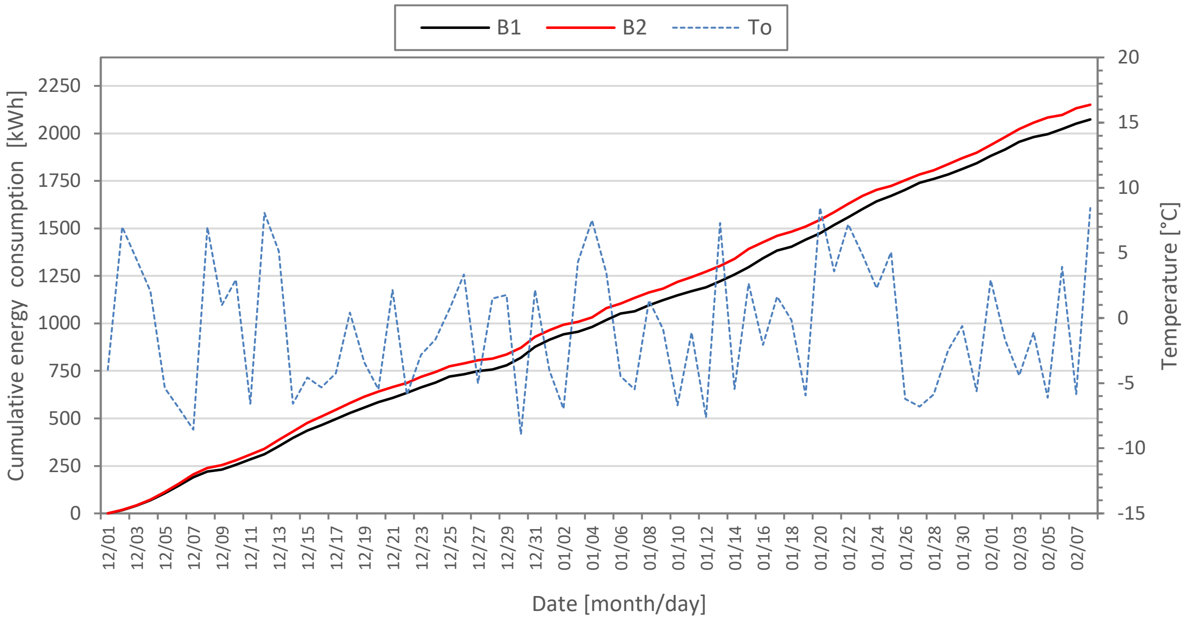

Fig. 5. Cumulative heating energy consumption in Buildings B1 and B2 during the 70-day winter period from December 1, 2018, to February 8, 2019

The temporal patterns of daily energy use further support this interpretation. Both buildings exhibited similar responses to fluctuations in outdoor temperature (To), and their energy demand closely tracked variations in weather conditions.

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In both analysed measurement periods, the primary boundary condition was the outdoor air temperature, which was measured continuously and is presented together with daily heating energy use in Figs. 6 and 9 for Phase I and Phase II, respectively**.**

Fig. 6 illustrates this daily behavior, highlighting the parallel response of both buildings to temperature changes and confirming that control settings and climate exposure were well matched.

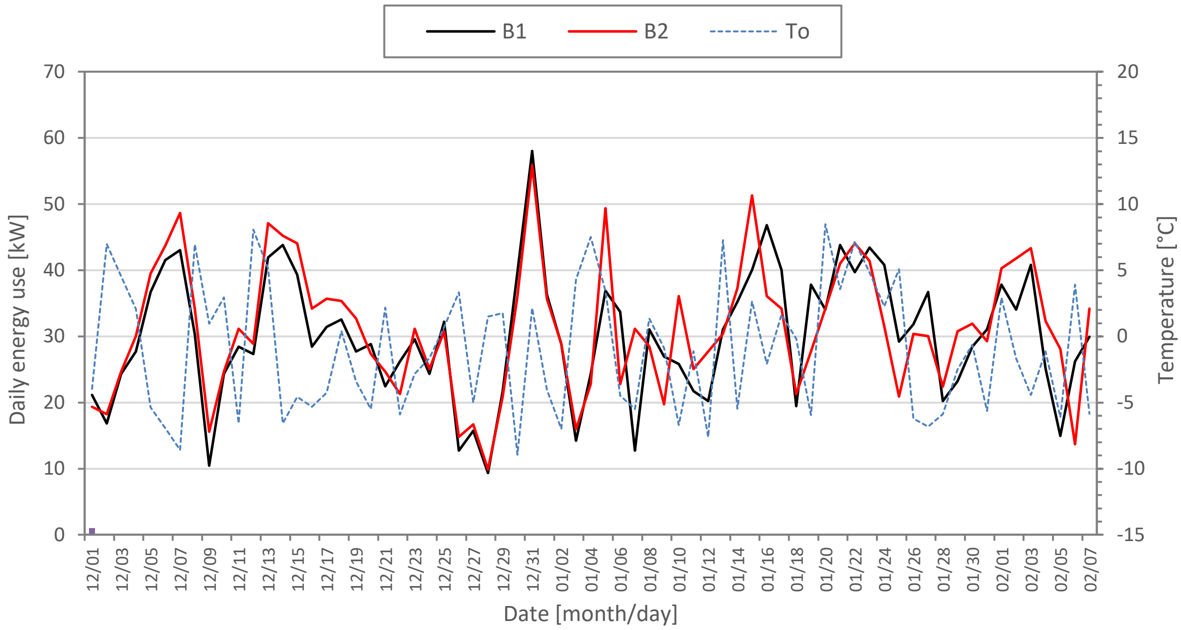

Fig. 6. Daily heating energy use and outdoor temperature during the 2018/2019 winter monitoring period

However, the cumulative energy curve for B1 showed a slightly shallower gradient, indicating a marginally slower accumulation of energy demand over time. This effect can be attributed to the thermal buffering capacity of the heavier envelope, which may have helped to absorb short-term internal and external heat fluctuations, thereby reducing heating system response during mild diurnal transitions.

Nonetheless, the relatively small difference in seasonal energy use highlights the limited role of wall mass under conditions of constant indoor temperature regulation and high insulation standards. In buildings with stable thermostat control and minimal internal gains, the potential of thermal inertia to reduce heating demand may be constrained. The energy performance advantage of higher thermal mass is more likely to become pronounced in buildings with intermittent heating schedules or those exposed to rapid changes in internal or solar heat gains, where stored energy can be effectively utilized to maintain thermal comfort without additional energy input.

In this context, the results from the 2018 to 2019 season indicate that although the mass-related thermal properties of B1 yielded a measurable improvement in energy efficiency, the impact remained moderate. The findings are consistent with other empirical studies that show a more pronounced role of thermal mass in dynamic or passive operating modes, rather than in fully controlled, thermostat-regulated environments.

Overall, this phase of the study confirms that thermal inertia in wall assemblies can contribute to improved heating performance, but its effect under real-world, continuously heated conditions is likely to be limited. Future assessments of wall mass potential may benefit from focusing on dynamic regimes, including passive solar gains, intermittent heating, or night-time setpoint reductions, which can more fully activate the thermal storage and release cycles within heavyweight envelopes.

3.2. Ground temperature dynamics and discrepancy with theoretical models

To better understand the interaction between ground and building, a year-long temperature monitoring campaign was conducted from May 1, 2019 to April 30, 2020. Sensors were installed at a depth of 1.5 meters in three vertical profiles: A (in the center of the building), B (0.5 m from the external wall to the inside of the building), and C (0.5 m from external wall to the outside of the building). Each profile recorded hourly data beneath both buildings, enabling direct observation of the thermal behaviour of the soil and its seasonal evolution.

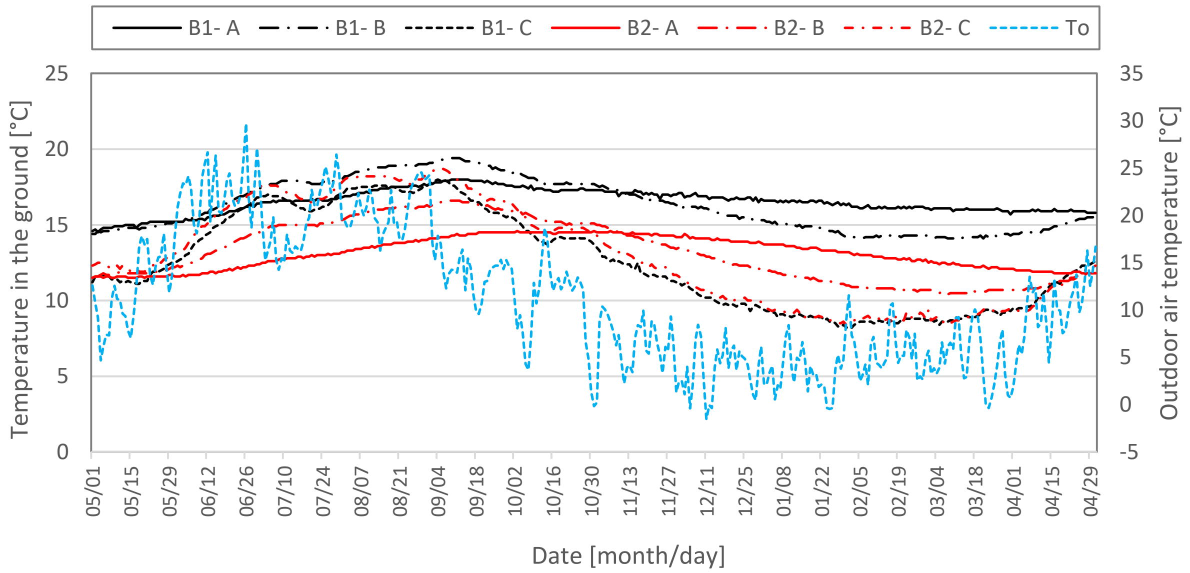

Fig. 7. Ground temperatures recorded at a depth of 1.5 meters beneath the floors of Buildings B1 and B2 between May 1, 2019, and April 30, 2020

The ground temperature profiles, presented in Fig. 7, show a clear and persistent difference between the two buildings. Throughout the winter months, ground temperatures beneath the uninsulated slab in Building B1 remained significantly higher, by approximately 4 to 5 degrees Celsius, than those under the insulated slab of Building B2. The lowest temperatures recorded at Point A, located at the center of B1, hovered around 16 degrees Celsius for over three months, while corresponding temperatures under B2 dropped to approximately 11 to 12 degrees. Even near the foundation edge (Point C), the subsoil beneath B1 remained 2 to 3 degrees warmer than that under B2. These differences persisted despite identical boundary conditions and confirm the thermal influence of direct coupling with the ground in the absence of floor insulation.

This thermal inertia of the subsoil acted as a short-term buffer, reducing conductive losses from the interior in the early part of the heating season. The ground functioned as a seasonal energy reservoir, absorbing heat during the preceding summer and gradually releasing it throughout the winter. This mechanism explains the delayed divergence in cumulative heating demand observed in Section 3.2. Building B1 performed comparably to B2 until mid-February, after which the progressive cooling of the ground led to a steady increase in heat losses through the uninsulated floor.

These findings challenge assumptions embedded in many simplified building energy models, which often treat ground temperatures as static or only shallowly responsive to external conditions. For instance, the [25] method assumes one-dimensional heat flow through homogeneous soil layers and does not adequately reflect time-dependent thermal storage and lateral insulation effects. In this case, standardized calculations predicted a 23.7 percent heating penalty for B1, yet the measured difference was only 12.2 percent. This highlights a fundamental limitation of steady-state simulation tools when applied to buildings with strong thermal coupling to the ground.

This discrepancy between modeled and measured performance also underscores the mitigating role of vertical foundation insulation, which is frequently excluded from simplified assessment methods. Studies by [26, 27, 28] have shown that vertical insulation layers can significantly reduce soil-side conductive losses, especially when horizontal insulation is absent. In Building B1, the 20-centimeter thick and 80 centimetres deep EPS perimeter insulation likely delayed ground cooling and reduced lateral losses during the first part of the heating season.

The empirical data further confirm the temporal asymmetry of ground response. While the soil beneath B1 reached its maximum temperature in early September, it retained heat well into winter. In contrast, the ground beneath B2 followed outdoor temperature variations more closely due to its thermal decoupling from the indoor space. This difference reflects the lag effect of deep soil layers, which respond slowly but significantly to long-term thermal inputs and should be regarded as a dynamic thermal element in building energy performance.

These observations suggest that in climates with mild autumns or delayed heating demand, buildings with uninsulated slabs may temporarily benefit from ground heat storage. However, as winter progresses, the absence of insulation becomes increasingly disadvantageous. The long-term influence of conductive ground losses depends not only on thermal conductivity and capacity but also on the sequence and duration of seasonal load conditions.

From a modeling and regulatory perspective, the results highlight the importance of empirical calibration. Simplified models may misrepresent not only absolute heating demand but also its seasonal distribution, leading to suboptimal design decisions or misclassification of building performance. Incorporating high-resolution ground temperature data, like those recorded in this study, into simulation tools or normative frameworks would significantly improve the accuracy of energy predictions, especially for buildings with unconventional foundations or hybrid insulation systems.

Finally, the measured ground temperature trajectories reinforce the year-round perspective of this investigation. Beyond their role in winter buffering, soil temperatures provide a relevant baseline for evaluating potential summer performance, particularly in buildings relying on passive cooling or thermal mass effects. In this context, the results offer a valuable empirical reference for assessing both seasonal energy balance and climate resilience in ground-connected residential buildings.

3.3. Effect of floor – ground coupling on seasonal performance

In the next phase of the monitoring campaign, conducted between November 1, 2019, and March 31, 2020, the experimental setup was modified to investigate the influence of floor–ground coupling on winter heating demand. Building B1 underwent a deliberate design change through the removal of the thermal insulation layer previously located beneath the ground-bearing slab. As a result, the floor in B1 became directly coupled to the underlying soil, increasing its surface heat capacity and allowing continuous conductive heat exchange with the ground. In contrast, Building B2 retained its insulated slab-on-ground configuration.

This intervention led to a clear change in performance between the two buildings. Over the five-month heating season, the total heating energy demand in B1 reached 6168.7 kWh, compared to 5499.6 kWh in B2. This corresponds to a 12.2 percent increase in energy use in the uninsulated-floor building. The cumulative heating energy profiles for this period are presented in Fig. 7. The data show that until mid-February the total demand in both buildings remained relatively close, with noticeable divergence occurring only in the latter part of the season.

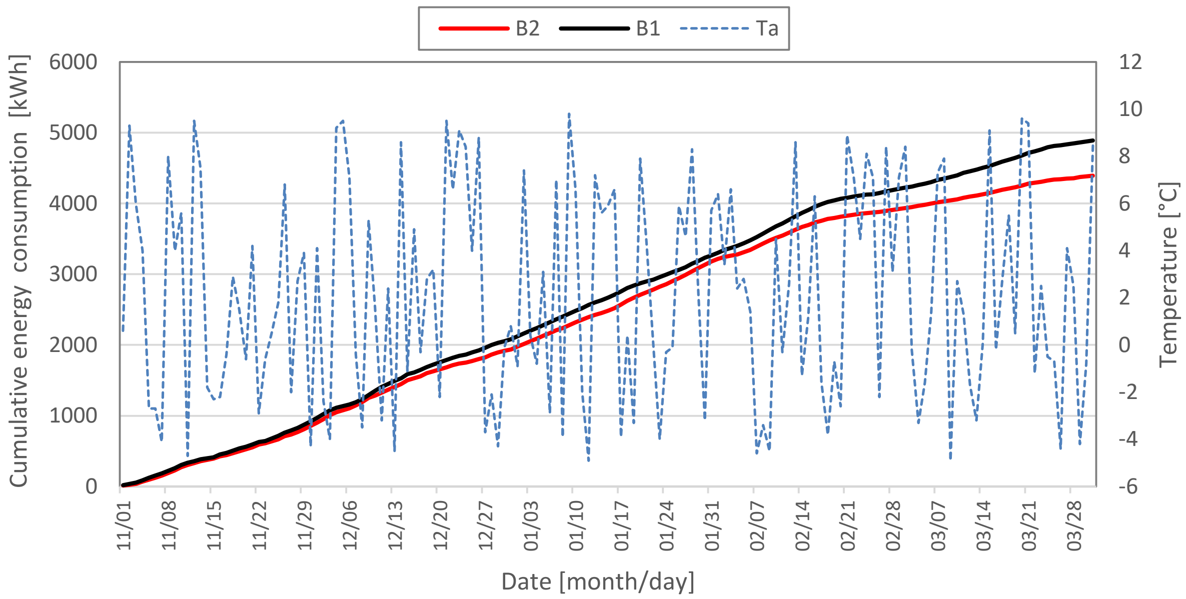

Fig. 8. Cumulative heating energy consumption in Buildings B1 and B2 during the 2020/2021 winter season

The temporal distribution of heating energy demand revealed that this difference did not appear immediately. For much of the heating season, particularly from November through January, the cumulative energy use in both buildings remained similar. It was only in the second half of February that the energy consumption curve of B1 began to diverge more noticeably from that of B2. The day-to-day evolution of this trend is clearly illustrated in Figure 9, which shows that both buildings responded similarly to outdoor temperatures during early winter, but B1 began to consume more energy toward the end of the season.

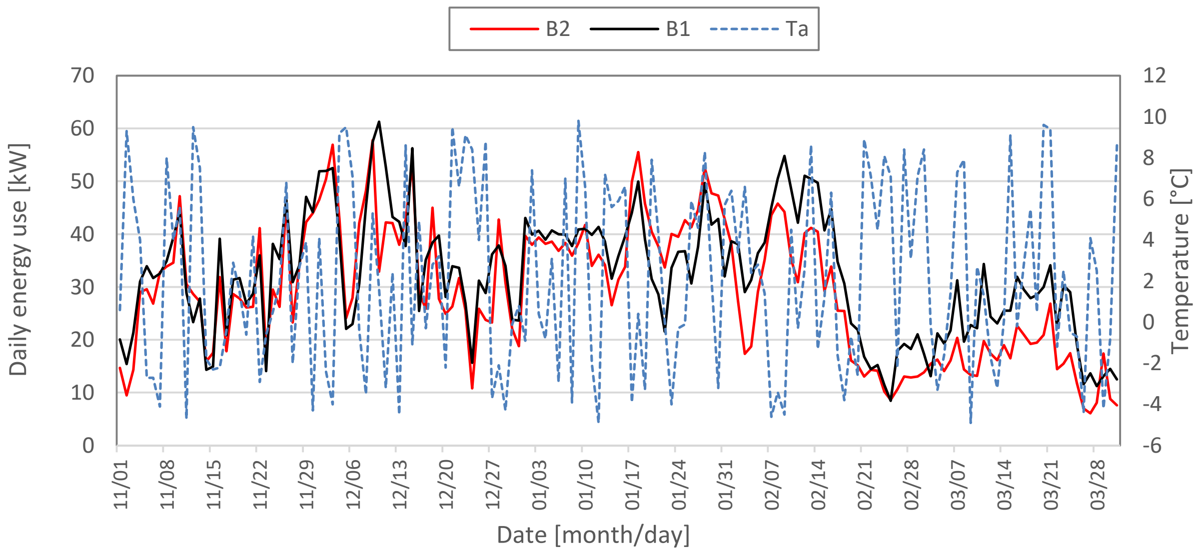

Fig. 9. Daily heating energy consumption and outdoor temperature in Buildings B1 and B2 between November 1, 2020 and March 31, 2021

This delayed effect suggests that the subsoil beneath the uninsulated slab initially served as a thermal buffer, releasing stored heat accumulated during the previous summer and autumn. This buffering effect moderated conductive heat losses and allowed B1 to perform comparably to B2 in the early phase of the season. However, as the heating period progressed and the ground beneath B1 gradually cooled, the absence of horizontal insulation became increasingly consequential. The soil lost its thermal capacity to support indoor comfort, and instead began acting as a thermal sink. The floor of B1, being in direct contact with the colder soil, facilitated continuous downward heat flow, which increased heating demand in the final months of winter. This transition is reflected in the steepening slope of the cumulative energy consumption curve in March.

These observations confirm that floor–ground coupling introduces a time-dependent thermal interaction that cannot be fully described using static performance criteria. The energy penalty associated with uninsulated floors may remain hidden during the initial weeks of the heating season, only to emerge as a dominant factor when the ground beneath the building is no longer thermally supportive. This behavior underscores the importance of assessing not only the absolute amount of energy used, but also the rate and timing of its accumulation over time.

The experimental data therefore highlight the seasonally asymmetric nature of floor–ground heat exchange. While ground coupling may temporarily delay heat losses, it ultimately contributes to cumulative energy demand over prolonged heating periods. These results illustrate that the thermal performance of a building is not defined solely by instantaneous properties such as U-values or thermal mass, but also by the dynamic interactions between envelope layers and adjacent environmental media, such as soil.

Furthermore, the energy penalty measured in this case is significant, but not as severe as might be expected for a floor without insulation. As shown later in Section 3.3, this is partially due to the presence of vertical perimeter insulation applied along the foundation walls. This detailing reduced lateral heat loss and slowed the rate at which the ground beneath the building cooled, effectively extending the buffering period. Nonetheless, the eventual rise in energy use in B1 confirms that vertical insulation alone is insufficient to offset the absence of horizontal subfloor insulation under long-term winter conditions.

In summary, the heating energy demand in Building B1 increased significantly following the removal of floor insulation, particularly in the later stages of the season. The observed delay in performance degradation reflects the short-term benefits and long-term limitations of ground coupling. This case exemplifies the need for seasonal and time-resolved performance assessment in buildings with unconventional subfloor configurations, especially when evaluating their suitability for energy-efficient or climate-resilient construction in temperate climates.

3.4. Implications for building regulations in a changing climate

The empirical results of this study have direct relevance for current building regulations, particularly those that continue to rely on static performance criteria such as maximum allowable thermal transmittance (U-values) for individual envelope components. While such requirements have successfully driven down winter heating loads in temperate climates, they may inadvertently hinder the adoption of climate-responsive design strategies under evolving thermal conditions.

As demonstrated by the tested buildings, real-world thermal behavior cannot be fully captured by U-values alone. For instance, Building B1, despite lacking horizontal insulation beneath the slab, initially exhibited moderate energy demand due to elevated subsoil temperatures and transient thermal buffering from the ground. This effect significantly influenced heating dynamics in the first half of the season. In the latter half, however, cumulative losses in B1 surpassed those in the insulated B2, ultimately resulting in a 12.2% higher seasonal heating demand.

Notably, the measured penalty associated with the missing insulation in B1 was considerably lower than predicted by standard calculations. This discrepancy was largely due to the mitigating role of vertical perimeter insulation, which reduced lateral heat transfer at the foundation edge. Conventional simulation methods such as [25] fail to account for time-dependent ground–building interactions, transient thermal storage, or the thermal effectiveness of edge insulation. As a result, performance estimates based on such methods may overstate expected losses and disqualify viable passive solutions.

More broadly, these findings question the suitability of regulatory frameworks that prioritize prescriptive U-values over holistic performance outcomes. Current codes often fail to incorporate metrics such as annual energy use per square meter, life-cycle CO_2 emissions, or resilience to extreme temperatures [10]. This limitation is especially critical in contexts where innovative passive strategies— such as thermal mass activation or selective ground coupling – do not conform to standardized envelope assumptions but offer demonstrable benefits in year-round performance.

Recent literature has increasingly emphasized this regulatory misalignment. Arriazu-Ramos et al. [29] reported no statistically significant reduction in indoor overheating hours (IOH) in Spanish apartments built after 2006 under the updated CTE code, relative to pre-regulation buildings constructed before 1979. Some Passivhaus-certified dwellings even exhibited among the highest IOH levels, underscoring the limitations of current energy standards in addressing summer resilience. A subsequent urban-scale study by the same authors [30] confirmed that standard roof insulation retrofits were largely ineffective in mitigating thermal stress in over 85,000 dwellings in Pamplona, particularly in top-floor units with single orientation. As the authors note, "current retrofitting strategies focus almost exclusively on winter performance, which may not ensure thermal safety in summer."

Similar concerns have been echoed by Palma et al. [31], who emphasize that retrofit approaches centered solely on insulation can have unintended consequences in a warming climate. Drawing on an extensive review, they argue that insulation-focused strategies, while effective in reducing heating demand, can substantially increase overheating risk in buildings lacking active or passive cooling. This risk is particularly acute in regions undergoing climate reclassification, where building codes continue to reflect historical heating needs. The authors call for a redefinition of high-performance envelopes – beyond insulation – to include passive cooling, roof resilience, and climate-adaptive strategies, especially in vulnerable communities where energy poverty limits access to mechanical cooling.

The passive strategies investigated in the present study, including the use of thermal mass and selective ground coupling, align with this emerging paradigm. In addition to revising energy performance targets, regulatory frameworks should enable the integration of unconventional passive measures, such as seasonal thermal storage, climate-aligned roof assemblies, or systems enabling energy self-sufficiency [32]. This applies not only to new buildings but also to retrofit scenarios, particularly where full insulation compliance is technically or economically impractical.

These insights support a shift from component-level requirements toward outcome-based metrics, such as total annual energy demand, carbon intensity, or thermal resilience under future climate scenarios. As the literature increasingly shows, building performance is governed not just by nominal thermal resistance but by dynamic interactions with site-specific conditions and climatic trends [1,12,13,]. In particular, De Masi et al. [33] have emphasized that insulation strategies should be re-evaluated in light of their variable impact across climates, especially where high solar exposure and limited night cooling reduce their effectiveness in summer conditions.

Finally, this study confirms the value of hybrid solutions such as vertical perimeter insulation, which can reduce edge losses and delay divergence in energy consumption between envelope configurations. Recognizing such strategies in codes, especially in rural or slab-on-ground construction, could provide needed flexibility while maintaining robust performance.

In conclusion, the findings underscore the need for adaptive, performance-oriented regulations that prioritize year-round thermal resilience and carbon reduction. Passive buffering, peak load mitigation, and the ability to maintain comfort without reliance on mechanical systems should be recognized as integral components of energy efficiency. A transition toward dynamic, context-sensitive standards would better align building policy with actual climate risks and foster the development of future-ready, resilient construction practices.

3.5. Regional climate trends and inconsistent standards

While national building codes typically reflect long-standing climatic assumptions, recent weather data reveal a growing mismatch between prescribed design practices and actual environmental conditions. One striking example is the treatment of uninsulated ground-contact floors: although prohibited in new residential buildings in Poland, such constructions remain common and fully compliant in Portugal, despite nearly identical winter conditions between the two countries [34].

Meteorological data illustrate this convergence. During the 2019–2020 heating season, the average outdoor temperature in Zielona Góra (Poland) was 4.9 °C, compared to 5.0 °C in Tabuaço (Portugal), with the latter experiencing substantially hotter summers [35]. This example reflects a broader climatic trend: winters are warming significantly across Central and Northern Europe, while summer extremes are intensifying in Southern regions. Yet regulations continue to enforce static insulation standards based on legacy heating loads, often disregarding evolving risks associated with overheating.

As climates converge, regulatory divergence becomes more difficult to justify, especially when rigid prescriptions prevent the use of passive strategies that could improve overall resilience. In regions where summers are lengthening and power grid reliability is under pressure, standardized solutions that neglect cooling needs or thermal autonomy may prove counterproductive. As highlighted by De Masi et al. [33], even well-insulated envelopes may underperform in hot climates if passive cooling and dynamic adaptation are not integrated into their design.

To remain effective, regulatory frameworks must recognize the shifting thermal profile of Europe's regions and allow for greater contextual flexibility. Harmonized performance metrics, such as seasonal energy balance or summer overheating thresholds, should complement or, where appropriate, replace envelope-level prescriptions. In this way, building policies can remain robust in the face of accelerating climate variability and support the deployment of regionally adapted, future-ready design solutions.

3.6. Passive resilience as a design priority in a warming climate

Beyond formal compliance and heating efficiency, this study reinforces the broader role of passive strategies in promoting resilience, reducing operational dependence, and enhancing year-round thermal stability. Experimental evidence from B1 suggests that mass-intensive, ground-coupled structures not only modulate heating loads but also provide intrinsic protection against summer overheating and winter cold spells, particularly in the absence of mechanical systems.

As previously demonstrated in related field studies [20], thermal inertia and subsoil exchange can dramatically reduce overheating duration, even under blackout conditions. These findings align with the conclusions of [29,30], who observed that highly insulated apartments, especially those on upper floors, often fail to maintain acceptable conditions during summer heatwaves. Crucially, insulation alone did not prevent thermal stress, especially where cross-ventilation or external shading was limited.

Palma et al. [31] further caution that excessive reliance on insulation-focused retrofits may be counterproductive in a warming climate. Their review shows that neglecting passive cooling, roof resilience, or diurnal heat rejection strategies exposes occupants to increased discomfort and vulnerability. This is particularly relevant in contexts of energy poverty, where access to mechanical cooling is constrained.

The integration of passive resilience into regulatory frameworks is therefore not a matter of optimization – it is a necessity. As noted by Norouzi et al. [32] unconventional approaches such as seasonal thermal storage or adaptive envelope configurations can contribute meaningfully to self-sufficiency and occupant safety under increasingly volatile climate regimes.

Ultimately, passive design principles, ground coupling, thermal mass, solar management, should be formalized as core criteria for future-ready buildings. Regulatory models that account for delayed heat transfer, thermal autonomy, and peak demand mitigation will be better suited to the needs of both mitigation and adaptation. As buildings evolve from energy consumers to climate buffers, resilience must be recognized not as an optional benefit, but as a measurable and essential aspect of sustainable performance.

4. CONCLUSIONS

This study offered an empirical evaluation of winter heating performance in two residential buildings differing in wall thermal mass and subfloor insulation strategy.

The conclusions are based exclusively on measurements conducted during the heating seasons and reflect the dynamic interaction between outdoor climate conditions, building thermal mass, and ground coupling under winter operating regimes.

Despite identical geometry, envelope U-values, and heating setpoints, measurable differences in thermal behavior emerged as a result of variations in envelope mass and ground contact configuration.

Masonry walls with higher thermal inertia provided modest but consistent buffering, with Building B1 consuming 3.6% less energy than the lightweight B2 during the 2018/2019 season. While limited, this finding confirms that mass can enhance energy efficiency even in well-insulated, steady-state heating regimes.

While substantial day-to-day differences in heating demand were observed under dynamically changing outdoor conditions, these effects largely compensated over the season, resulting in relatively modest differences in cumulative energy use.

More pronounced effects were observed after the removal of subfloor insulation in B1, enabling direct thermal coupling with the ground. During the subsequent heating seasons (2019/2020 and 2020/2021), B1's energy demand exceeded B2's by 12.2%, though this divergence occurred mainly in the latter half of winter. Early-season performance benefited from elevated subsoil temperatures accumulated during the preceding warm season, delaying the onset of conductive losses.

Importantly, this energy penalty was significantly lower than predicted by steady-state methods such as [25]. The discrepancy highlights the influence of dynamic soil behavior and vertical perimeter insulation, factors often overlooked in simplified modeling frameworks. These findings emphasize the need for empirical validation and more nuanced simulation tools that can capture lag effects, heat storage, and foundation geometry.

Beyond winter energy use, the study reinforces the relevance of passive resilience. Previous analyses have shown that ground-coupled, mass-intensive envelopes offer superior protection during both heatwaves and cold spells, particularly in single-storey buildings without mechanical systems. In contexts of rising blackout risk, such attributes may prove critical for maintaining habitable indoor conditions.

Moreover, the capacity to passively retain heat or coolth enhances the compatibility of buildings with intermittent renewable energy sources. Thermal inertia can buffer the temporal mismatch between generation and demand, improving self-sufficiency and reducing dependence on active systems or short-term storage.

Although this study focused on operational heating performance, a complementary environmental and economic assessment has been conducted separately, including embodied carbon, material impacts, and life cycle emissions. The findings confirm that the tested configurations, particularly those combining ground coupling, vertical foundation insulation, and wall thermal mass, can achieve lower total CO_2 footprint and improved cost-effectiveness over a 75-year horizon. Detailed results of the life cycle analysis will be presented in a companion paper.

In summary, this research supports the integration of passive design strategies, particularly wall mass, vertical insulation, and controlled ground coupling, into energy-efficient and climate-adaptive construction practices. These configurations demonstrated measurable gains in seasonal performance, robustness to external conditions, and potential for integration with low-carbon energy systems. As building standards evolve to reflect resilience and flexibility alongside efficiency, such approaches warrant greater recognition in design guidelines, policy frameworks, and performance simulations.

5. LIMITATIONS AND FUTURE WORK

While this study provides valuable empirical insights into winter energy performance and the role of wall mass and ground coupling, several limitations must be acknowledged.

First, the analysis focused solely on seasonal heating demand. Although previous work by the authors has examined summer thermal resilience, no direct measurement of cooling demand or indoor temperatures during warm periods was included here. Consequently, the passive benefits of thermal mass and ground contact under summer conditions, such as heatwave buffering or reduced peak loads, remain outside the present scope.

Second, the findings are based on two single-storey buildings located in a temperate zone of western Poland. While broadly representative of Central Europe, generalizing these results to other climates, building typologies, or construction systems should be approached with caution. Future studies in warmer, colder, or more urbanized settings would help test the applicability of these strategies under varied conditions.

Third, the experimental period covered only the heating season. Transitional periods (spring and autumn), domestic hot water use, and occupant behavior were not monitored, nor were internal comfort parameters such as humidity or temperature distribution. A full-year dataset would enable more nuanced evaluation of thermal inertia effects and control strategies.

Additionally, the modeling reference (PN-EN ISO 13370) [25] assumes steady-state conditions and lacks the ability to reflect dynamic soil behavior or perimeter insulation effects. Although this study documents notable discrepancies between predicted and observed performance, a full parametric sensitivity analysis was not conducted. Future work should incorporate transient simulation tools such as EnergyPlus or TRNSYS to explore the effects of soil diffusivity, slab geometry, and phase lag on thermal performance.

While this paper focuses exclusively on winter heating performance, complementary environmental and economic impacts have been assessed separately. The integration of these results provides a more complete basis for evaluating the long-term viability of ground-coupled envelope strategies.

Further research should also investigate the synergies between passive buffering strategies and renewable energy systems. Ground-coupled buildings may offer significant potential to store and time-shift thermal loads, helping to bridge the mismatch between solar energy availability and demand peaks, especially in climates with increasing cooling loads.

Finally, future campaigns should consider longer-term monitoring, ideally across multiple years, to capture interannual variability, prolonged cold spells, and equipment aging effects. The inclusion of real-time data on indoor conditions and occupant interaction would enrich interpretation and support the development of adaptive, user-informed simulation protocols.

Despite these limitations, the study provides robust evidence that passive strategies – particularly wall mass and controlled ground coupling, can measurably improve winter performance in low-rise buildings. These findings justify further research and broader regulatory recognition of passive resilience as a key dimension of climate-adaptive design.

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