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Operational Energy and Lifecycle Assessment of Envelope Retrofit Strategies for District-Heated Residential Buildings: Comparison of Expanded Polystyrene and Bio-Based Insulation

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Abstract

Improving the energy performance of existing multi-apartment residential buildings is critical for reducing energy consumption and greenhouse gas emissions in Central and Eastern Europe, where large stocks of post-war buildings with limited insulation are connected to district heating systems. This study evaluates façade insulation retrofit strategies for two representative typologies in Novi Beograd, Serbia—a high-rise tower and an elongated slab-type ('lamella') building—using calibrated dynamic energy models and cradle-to-use lifecycle assessment (LCA) over a 50-year service life. Models were calibrated against measured 2023–2024 heating consumption data (NMBE < 1%, CVRMSE < 15%) and normalized with Typical Meteorological Year weather for consistent scenario comparison. Retrofit scenarios applied expanded polystyrene (EPS) and cellulose insulation at 10, 12, and 15 cm thicknesses. Results show that external insulation reduces annual heating demand by approximately 19–20% compared to the uninsulated baseline (192 kWh/m^2·a), with the majority of savings achieved at 10 cm and only marginal gains from additional thickness. Insulation thickness has a stronger influence on operational energy reduction than material choice, as differences between EPS and cellulose remain below 0.5%. LCA indicates 23.6–26.0% lower climate change impacts and 23.6–25.8% reduced cumulative energy demand in retrofit scenarios, with cellulose offering modest advantages due to lower embodied emissions and biogenic carbon storage. These findings support targeted envelope retrofits as an effective strategy for decarbonizing district-heated residential buildings in the region.

Keywords: building energy modelling; life cycle assessment; insulation materials; facade retrofit; district heating; residential buildings; bio-based insulation; embodied carbon

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1. Introduction

Buildings represent one of the largest contributors to global energy consumption and greenhouse gas emissions (GHG), accounting for approximately 36% of CO_2 emissions and nearly 40% of final energy demand worldwide [1]. A substantial portion of this energy use is associated with space heating, cooling, and ventilation, making the thermal performance of the building envelope a central focus of energy-efficiency policies and decarbonization

strategies. Within the European Union, initiatives such as the Energy Performance of Buildings Directive (EPBD) and the Renovation Wave strategy emphasize the urgent need to improve the energy performance of existing buildings through large-scale renovation programmes [2–4]. While the primary focus of these policies has been the reduction in operational energy use, increasing attention is now being directed toward the embodied environmental impacts of construction materials and building components throughout their lifecycle [3,5].

In that context, decarbonizing the existing residential building stock represents one of the most significant challenges for achieving long-term climate neutrality in Europe. A large proportion of European buildings were constructed before the introduction of modern energy performance regulations and therefore exhibit relatively poor thermal performance. This challenge is particularly evident in Central and Eastern European (CEE) countries, where a substantial share of multi-unit residential buildings (MURB) was constructed during the post-war period using standardized construction systems with limited thermal insulation [6,7]. These buildings often rely on district heating networks and typically exhibit relatively high specific heating energy demand due to insufficient envelope insulation and outdated construction practices [8–10].

As a result, improving the energy efficiency of existing buildings through envelope retrofits has become a major priority within national renovation programmes, with the addition of external wall insulation recognized as one of the most effective and widely implemented measures for reducing heating energy demand in residential buildings [11,12]. In practice, façade insulation thicknesses between approximately 10 cm and 15 cm are commonly applied using external thermal insulation composite systems (ETICS), particularly in renovation projects aimed at achieving regulatory compliance and moderate improvements in building energy performance [13,14].

Numerous studies have reported substantial reductions in heating energy demand following façade insulation retrofits, often ranging from approximately 20% to 40% depending on climate conditions, baseline envelope performance, and building typology [15–17]. Consequently, insulation upgrades are frequently identified as one of the most cost-effective retrofit measures in residential buildings [18,19].

However, improvements in operational energy performance must also be evaluated in relation to the environmental impacts associated with insulation materials themselves. The production of insulation materials involves resource extraction, energy-intensive manufacturing processes, and waste generation, all of which contribute to environmental burdens. As operational energy demand decreases due to improved building efficiency, the relative importance of embodied environmental impacts within the overall building lifecycle becomes increasingly significant [4,20]. Lifecycle assessment (LCA) therefore plays a key role in evaluating the environmental implications of insulation materials and retrofit strategies across their entire lifecycle [21,22].

A wide range of insulation materials is currently available for building applications. Conventional insulation materials commonly used in the construction industry include expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PUR), glass wool, and stone wool. These materials exhibit low thermal conductivities in the range of approximately 0.030–0.040 W m^{-1} K^{-1}, enabling effective reduction in heat transfer through building envelopes [3,23,24]. However, many of these materials are derived from petrochemical resources or energy-intensive industrial processes. For example, mineral wool insulation is produced by melting raw materials such as basalt or recycled glass at high temperatures, while polymer-based insulations rely on fossil-based feedstocks [20,25]. As a result, these materials may exhibit relatively high embodied energy and associated greenhouse gas emissions despite their favourable operational performance.

In recent years, increasing attention has been directed toward alternative insulation materials derived from renewable or recycled resources. Bio-based insulation materials—including cellulose fibre, hemp fibre, and wood-based products—are attracting growing interest due to their potentially lower embodied environmental impacts and renewable origin [26,27]. These materials are typically produced from agricultural or forestry residues and can exhibit lower non-renewable primary energy use and greenhouse gas emissions compared with conventional mineral or petrochemical insulation materials [3,24]. For example, Tettey et al. [28] demonstrated that replacing mineral wool with cellulose fibre insulation in a multi-storey residential building could reduce total primary energy use by approximately 6–7% and reduce CO_2 emissions by 6–8% over the building lifecycle.

Nevertheless, the adoption of bio-based insulation materials also introduces certain technical considerations. Due to their hygroscopic properties and higher vapour permeability, such materials may be more sensitive to moisture conditions and may require careful design to mitigate risks related to condensation or biological degradation. Consequently, several studies emphasize the importance of integrating thermal, environmental, and hygrothermal performance considerations when evaluating bio-based insulation solutions [29].

Another important factor in insulation design is optimizing insulation thickness. Increasing insulation thickness generally reduces heat losses and heating energy demand; however, the relationship between insulation thickness and energy savings is non-linear. Initial increases in insulation thickness often lead to substantial reductions in heating demand, whereas further increases produce progressively smaller marginal benefits. Climate-dependent optimal insulation thicknesses have therefore been identified in numerous studies, balancing operational energy savings against material-related environmental impacts and costs [12,14,30]. Beyond certain thresholds, additional insulation thickness may result in diminishing environmental benefits due to increased embodied impacts associated with material production [12].

Recent research has increasingly emphasized the importance of evaluating building retrofit strategies within an integrated lifecycle framework that considers both operational and embodied impacts. Several studies have demonstrated that the choice of insulation material can significantly influence the overall environmental performance of retrofit solutions. For instance, wood-based and bio-based insulation materials often exhibit lower embodied energy and GHG emissions compared with conventional petrochemical insulation materials. However, their cost-effectiveness may depend on policy incentives or regional market conditions [10]. Similarly, comparative lifecycle assessments (LCA) have highlighted the importance of material selection, insulation thickness, and service life assumptions when evaluating the environmental benefits of building retrofits [21,22]. LCA provides a comprehensive method to quantify these impacts [25], allowing comparisons across different materials on a functional basis [23]. Reviews show that EPS, stone wool, and glass wool exhibit broadly similar lifecycle profiles, while XPS and PUR generally perform worse [27].

Numerous studies have focused on improving building envelopes and façade features to enhance energy efficiency, lower costs, and reduce environmental impacts in residential buildings [17]. Tettey et al. analyzed the implications of various insulation materials on primary energy use and CO_2 emissions from material production for a multi-storey residential building designed to meet the Swedish Building Code 2012 and the Swedish Passivhus 2012 criteria. By varying insulation materials (rock wool, glass wool, cellulose fibre, EPS, foam glass) and comparing reference and optimized designs, they found that replacing rock wool with cellulose fibre reduced total primary energy use by about 6–7% and CO_2 emissions by 6–8%, while fossil fuel use for insulation material production

alone decreased by about 39% [28]. Recent research on building retrofits highlights that as operational energy use is reduced, the embodied impacts of envelope materials and components become increasingly relevant throughout the building lifecycle. Several studies have shown that material choice, insulation thickness, and service life can substantially affect primary energy use and GHG emissions, in addition to energy cost savings [22]. Within a sustainability framework, several authors stress that investments in thermal insulation should be evaluated across economic, environmental, and social dimensions. Besides selecting a suitable material, optimizing insulation thickness can yield substantial benefits in terms of both environmental impacts and overall lifecycle costs [10].

Since evaluating energy retrofit strategies has become complex, it increasingly relies on advanced building energy modelling (BEM) approaches capable of simulating building thermal behaviour under dynamic climatic conditions. Dynamic simulation models enable a detailed assessment of heating energy demand across various retrofit scenarios and can be further improved through calibration using measured operational data. Calibrated building physics-based energy modelling approaches using EnergyPlus, TRNSYS, IDA ICE, and IESVE demonstrate substantial capacity to evaluate retrofit strategies [31–34].

Despite the extensive body of research on building insulation retrofits, several important research gaps remain. First, the majority of comparative retrofit studies combining BEM and LCA have been conducted in northern and western European contexts, where building typologies, climate characteristics, and energy supply infrastructure differ substantially from those of the post-war multi-apartment stock in Central and Eastern Europe. CEE buildings connected to district heating systems present distinct modelling requirements: heat delivery is intermittent, temperature-regulated, and sourced primarily from centralized gas-fired plants—factors that directly influence both simulated demand profiles and the primary energy chain underlying LCA. Despite this, comparatively few studies have applied calibrated dynamic energy simulation specifically to district-heated multi-apartment buildings in the CEE region. Second, many existing analyses rely on simplified or uncalibrated simulation models, which may introduce systematic uncertainties into estimated operational energy savings associated with retrofit measures. Third, the relative influence of insulation material choice compared with insulation thickness within the commonly applied retrofit range of 10–15 cm remains insufficiently quantified under realistic district-heated operating conditions.

Furthermore, although LCA studies increasingly evaluate the embodied carbon impacts of insulation materials, the operational energy inputs used in such assessments are not always derived from calibrated dynamic simulation models. This may affect the reliability of whole-life carbon comparisons between different retrofit solutions. In addition, the environmental performance of bio-based insulation materials such as cellulose has received limited attention in the district-heated CEE building context, where the carbon intensity of the heat supply and the dominant building archetype both differ from better-studied Western European markets.

To address these research gaps, the present study investigates the environmental implications of façade insulation retrofits in representative multi-apartment residential buildings located in Novi Beograd, Serbia. Two dominant building typologies characteristic of this housing stock are analyzed: elongated slab-type buildings (regionally termed "lamella", also classified internationally as "bar buildings") and compact high-rise buildings. Both typologies were widely adopted during the late twentieth century and are typically associated with district heating systems, though they exhibit limited thermal insulation [6].

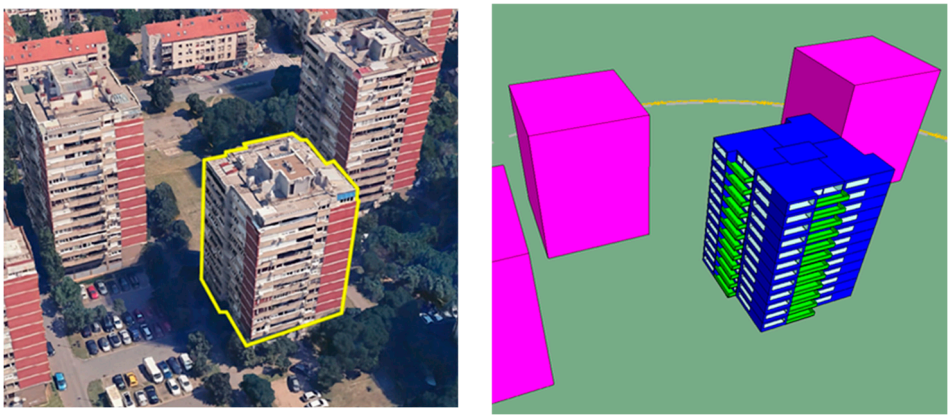
The study compares three scenarios: (1) a baseline case, representing the existing condition, without additional insulation, (2) a conventional retrofit using expanded polystyrene (EPS) insulation, and (3) a bio-based retrofit using cellulose fibre insulation. Operational

heating demand is quantified using calibrated dynamic building energy modelling, while environmental impacts are evaluated through LCA in accordance with EN 15978 [35] methodology. By integrating calibrated energy modelling with lifecycle carbon assessment, the study aims to provide a robust comparison of insulation materials under realistic retrofit conditions representative of residential buildings in Central and Eastern Europe. The principal novelty of this work lies in combining physics-based dynamic BEM—calibrated against utility-measured district heating consumption data for two representative post-war CEE building typologies—with a comparative assessment of conventional and bio-based insulation materials, enabling an evidence-based evaluation of both operational and material-choice effects under district heating conditions that are underrepresented in the existing literature.

2. Materials and Methods

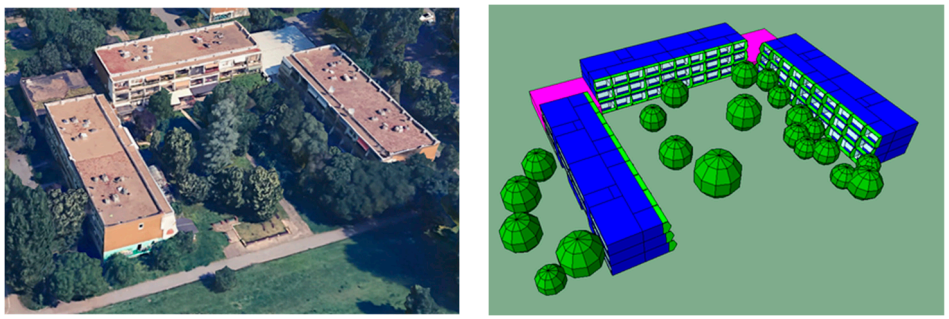
2.1. Case Study

This study investigates two representative multi-unit residential building (MURB) typologies located in Novi Beograd, Serbia, which reflect common forms of multi-apartment housing constructed during the 1960s and 1970s in Central and Eastern Europe. The analyzed typologies comprise compact high-rise residential buildings (Figure 1) and elongated slab-type buildings commonly referred to as "lamella-type" blocks (Figure 2).



(**a**) (**b**)

Figure 1. High-rise residential building (Novi Beograd, Block 70) (**a**) actual, (**b**) 3D model for energy simulation.



(**a**) (**b**)

Figure 2. Lamella-type residential building (Novi Beograd, Block 70) (**a**) actual, (**b**) 3D model for energy simulation.

The analyzed high-rise building has 11 above-grade storeys with 4930 m^2 of heated space (Figure 1). The lamella building consists of three storeys arranged in elongated slab

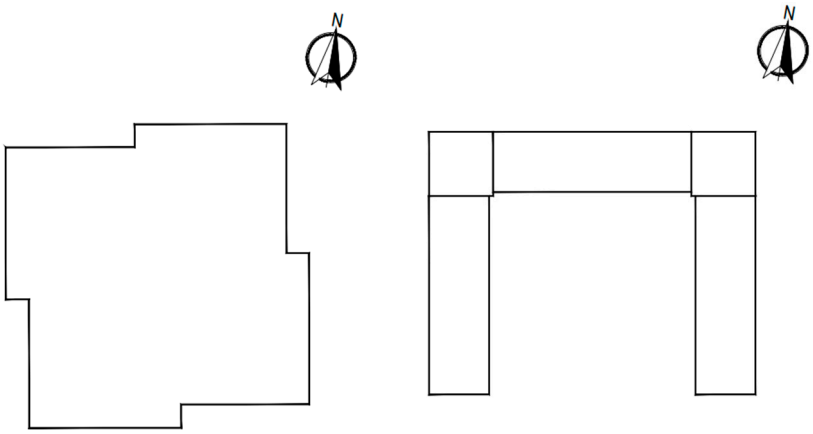
configurations with multiple entrances and 3324 m^2 of heated space (Figure 2). Despite differences in geometry and surface-to-volume ratio, both typologies share construction characteristics typical of residential buildings built during the 1960s, 1970s, and 1980s. These buildings are generally constructed with reinforced concrete structural systems, masonry or concrete external walls, and limited thermal insulation.

The analyzed buildings are located within Block 70 in Novi Beograd, one of the characteristic residential districts developed during the post-war expansion of Belgrade. This urban block, similar to neighbouring blocks such as Block 45, is composed of a combination of high-rise residential towers and elongated lamella-type buildings arranged in an open-block configuration with significant spacing between structures. These typologies were systematically implemented as part of modernist urban planning principles, emphasizing uniform construction, standardized building forms, and integration with district heating infrastructure. The spatial arrangement and coexistence of these two dominant building forms within the same urban block are illustrated in Figure 3, providing context for the selection of representative case study typologies analyzed in this work.

(**a**) (**b**)

Figure 3. Novi Beograd, Block 70 configuration (**a**) high-rise buildings, (**b**) lamella-type buildings.

Building orientation for both analyzed typologies, derived from site observations and implemented in the simulation models, is presented in Figure 4.



(**a**) (**b**)

Figure 4. Building orientation (**a**) high-rise buildings, (**b**) lamella-type buildings.

Key building energy model input parameters for both analyzed building typologies are presented Table 1. They were derived from national residential building typology studies for Serbia [6,7], available building documentation, and site visits. External walls consist of approximately 20 cm of concrete (for lamella-type buildings) or 20 cm of masonry (for high-rise buildings) without thermal insulation. Windows are low-grade double-glazed PVC units with overall *U*-values of approximately 2.3 W/m^{2}K, while flat roofs exhibit thermal transmittance values of approximately 1.07 W/m^{2}K. During the calibration process, the effective thermal transmittance of the external walls and windows was fine-tuned to reproduce measured heating energy consumption. The calibrated overall *U*-values implicitly account for additional heat losses associated with thermal bridging and construction details that are not explicitly represented in the simplified envelope model.

Table 1. Key building energy model input parameters for both analyzed building typologies.

Parameter	High-Rise Tower	Lamella Building	Source
Conditioned floor area (m^2)	4930	3324	Site documentation
Number of heated storeys	11	3	Site documentation
Building orientation (main façade)	Building rotated 5° clockwise from true north	Building rotated 5° clockwise from true north	Site survey
External wall effective U-value, baseline (W/m^{2}K)	1.61	1.66	Calibration [6]
External wall effective U-value, 10 cm retrofit (W/m^{2}K)	0.30	0.30	Simulation
External wall effective U-value, 12 cm retrofit (W/m^{2}K)	0.27	0.27	Simulation
External wall effective U-value, 15 cm retrofit (W/m^{2}K)	0.24	0.24	Simulation
Roof U-value (W/m^{2}K)	1.07	1.07	[6]
Window U-value (W/m^{2}K)	2.35	2.89	Site survey [6]
Air infiltration rate, baseline (l/(s·m^{2}fac))	1.30	3.30	Calibration
Air infiltration rate, post-retrofit (l/(s·m^{2}fac))	1.04	2.64	[36]
Occupancy schedule	Residential	Residential	[37]
Internal heat gains (W/m^2)	People, lighting, plug loads	People, lighting, plug loads	Site survey, typical apartment electricity bill
District heating schedule	06:00–22:00	06:00–22:00	District heating system operation rules

Both buildings are connected to the City of Belgrade's district heating system, operated by the public utility company Beogradske elektrane. A natural-gas-fired heating plant supplies the district heating system serving the Novi Beograd area. According to information provided by the utility operator, the seasonal average efficiency of the district heating system, including generation efficiency and distribution losses, is approximately 75%.

Heat is delivered to buildings through a network of primary distribution pipelines supplying individual building substations. Within each substation, heat is transferred through heat exchangers to the building's secondary heating system, which distributes hot water to radiators in apartments. Control within substations is typically achieved through control valves and electromechanical actuators that regulate heat supply based on outdoor temperature conditions.

The operation of the district heating system follows defined seasonal and daily operating rules established by the utility operator Beogradske elektrane [36]. During the heating season, thermal energy is supplied from 06:00 to 22:00, while heating is interrupted during

night hours. In addition, heating delivery is suspended when the outdoor air temperature exceeds 15 °C. These operational rules were applied directly as model boundary conditions, reflecting the actual heat delivery schedule of the district heating system serving both case study buildings.

Energy use for the analyzed buildings is measured at the building substation level and reported monthly, providing the utility data used to calibrate the building energy models.

2.2. Building Energy Modelling Methodology

2.2.1. Model Development

Building energy models were developed to estimate the operational heating demand of the case study buildings and to evaluate the impact of façade insulation retrofit measures.

The models were created using available architectural documentation, construction drawings, and published building typology data for Serbian residential buildings [6]. Geometric characteristics, envelope constructions, internal loads, and heating system assumptions were defined based on the available documentation and literature describing typical operating conditions for district-heated multi-apartment buildings in the region.

The models include representations of building geometry and orientation, thermal envelope properties, window characteristics, internal heat gains, occupancy schedules, and district heating system operation.

The purpose of the energy modelling was to quantify heating energy demand for both baseline and retrofit scenarios and to generate the operational energy inputs required for the LCA.

Infiltration and natural ventilation represent the most uncertain model inputs and were therefore treated as the primary free parameters during calibration. In this context, infiltration encompasses both uncontrolled air leakage through construction joints and gaps and natural ventilation arising from occupant window-opening behaviour, as neither building is equipped with a mechanical ventilation system. During calibration, the thermal transmittance (U-value) of each envelope component was allowed to vary within ±15% of the nominal value derived from the one-dimensional wall construction model, reflecting the range of uncertainty associated with material property variability, workmanship, and in situ conditions typically reported for calculated envelope parameters [37]. The infiltration rate was subsequently adjusted as the dominant remaining calibration parameter until the agreement criteria described in Section 2.3 were met.

Internal heat gains were modelled as contributions from three sources: building occupants, artificial lighting, and electrical equipment including kitchen appliances, consumer electronics, computers, and other plug loads. The total plug load magnitude was estimated from electricity consumption records for a representative apartment; annual electricity bills were disaggregated into appliance categories and converted to a time-averaged thermal gain density expressed in W/m^2. Metabolic gains from occupants were calculated assuming standard sedentary residential activity at 70 W per person, and maximum lighting power consumption was estimated as 6 W/m^2 based on the site conditions. The aggregate contribution of internal heat gains to total annual heating energy demand was found to be modest relative to the dominant fabric and infiltration losses, which is consistent with the heating-dominated energy profile of the Belgrade climate and the relatively low internal load density of residential buildings compared to commercial typologies.

Occupancy schedules, lighting use profiles, and plug load operating schedules (Figure 5) were defined with reference to ASHRAE 90.1 [38] and NECB [39], which provide representative daily and weekly schedule fractions widely adopted in building energy modelling practice for cases where building-specific monitored schedules are unavailable.

Schedule fractions were applied uniformly across all conditioned zones, with a weekday/weekend distinction applied to account for typical residential occupancy patterns.

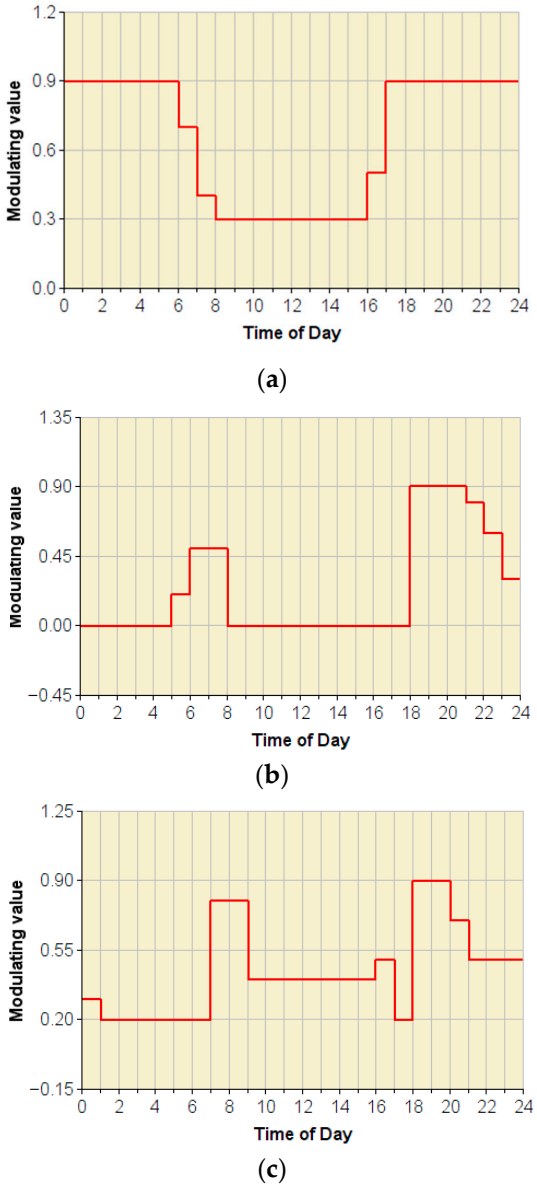


Figure 5. Variation profiles for (**a**) occupancy, (**b**) lighting, (**c**) plug loads.

2.2.2. Model Calibration

To improve the reliability of simulation results, the baseline energy models were calibrated against measured heating energy consumption data obtained from the district heating utility.

Measured energy use data for the 2023–2024 heating season were used for calibration. These data were obtained from the district heating utility operator Beogradske elektrane upon request; building-level consumption data are not publicly available online, as they are collected at individual substation level and provided by the utility on a per-building basis. For the high-rise tower, monthly heating energy consumption data were provided, enabling monthly model calibration. For the lamella building, only annual heating consumption data were available; therefore, calibration was performed at the annual level.

Calibration was performed using actual meteorological data corresponding to the 2023–2024 heating season. Hourly measurements of outdoor air temperature, wind speed,

and relative humidity were obtained from meteorological monitoring associated with the district heating system.

Based on these measurements, a custom weather file was generated and formatted for use within the building energy simulation environment. Using actual weather data during calibration ensured that the simulated heating demand reflected the climatic conditions under which the measured energy consumption occurred.

The calibration process involved iterative adjustment of uncertain parameters such as infiltration rates and overall *U*-values, until the simulated heating energy consumption matched the measured utility data within acceptable tolerance limits.

The lamella-type building exhibits a markedly higher calibrated infiltration rate than the high-rise tower, attributable to two compounding factors. First, as described in Section 2.1, the lamella typology features one entirely glazed longitudinal facade, resulting in a substantially larger proportion of window-to-wall area and correspondingly greater air leakage through frame-to-wall interfaces. Second, the load-bearing structure consists of prefabricated reinforced concrete elements assembled on-site; the construction joints between panels represent a well-documented source of infiltration in buildings of this typology, as the airtightness of large-panel prefabricated systems is generally inferior to that of monolithic or masonry construction. Together, these characteristics result in a considerably higher effective infiltration rate for the lamella building relative to the high-rise.

2.2.3. Adjusted Baseline Model

Once calibration was achieved, the validated building energy models were re-simulated using Typical Meteorological Year (TMY) weather data representative of Belgrade.

This step generated an adjusted baseline model, which represents the expected building energy performance under standardized climatic conditions rather than the specific weather conditions observed during the calibration year.

The adjusted baseline serves as the reference case for evaluating retrofit measures. Using TMY weather data removes the influence of year-to-year climate variability and enables consistent comparison between retrofit scenarios.

Energy savings associated with retrofit measures were therefore calculated as the difference between the adjusted baseline heating demand and retrofit scenario heating demand.

2.3. Retrofit Scenarios

The existing building envelope without additional insulation was used as the baseline case. This scenario reflects the current condition of many residential buildings constructed during the post-war period and represents the highest heating energy demand among the analyzed scenarios.

Parametric simulations were conducted for expanded polystyrene (EPS) and cellulose insulation. For both insulating materials, three thicknesses were evaluated: 10 cm, 12 cm, and 15 cm. These thicknesses reflect typical façade retrofit practice in Serbia and neighbouring CEE countries.

Retrofit scenarios were limited to external wall insulation applied through ETICS. No window replacement or HVAC system modifications were included. However, façade retrofit was assumed to reduce air infiltration due to improved sealing of façade joints. Based on previous studies of envelope retrofits in similar multi-family buildings [40], a conservative 20% reduction in infiltration rate was applied in post-retrofit scenarios.

Expanded polystyrene (EPS) insulation density of approximately 25 kg/m^3 [19]. This thickness reflects typical retrofit practices in Serbia and neighbouring countries. The retrofit reduces the external wall thermal transmittance to approximately 0.30 W/m^{2}K.

EPS insulation is associated with measurable embodied carbon emissions. Reported cradle-to-gate emissions (modules A1–A3) for a typical 10 cm EPS layer range between approximately 4.7 and 8.3 $kgCO_2eq.$ per square metre, depending on manufacturing assumptions and Environmental Product Declaration datasets [41,42].

The alternative bio-based material investigated is a cellulose fibre insulation derived from recycled paper products. Cellulose insulation typically has a density of approximately 45 kg/m^3 and reported embodied energy values ranging from 0.94 to 3.3 MJ/kg depending on manufacturing processes [43–45]. Modelled thermal conductivity and density values are shown in Table 2.

Table 2. Modelled thermal conductivity and density values for retrofit material analyzed.

Material	Thermal Conductivity [W/(m·K)]	Density [kg/m^3]
Cellulose	0.041	45
EPS	0.035	25

Due to its recycled content and renewable origin, cellulose insulation is often associated with lower embodied environmental impacts compared with petrochemical-based insulation materials. In addition, cellulose fibres may be recycled or reused to produce secondary products such as particleboards, thereby supporting circular material flows within the construction sector [46,47].

Apart from infiltration and external wall thermal properties, all other building operational assumptions remained unchanged relative to the adjusted baseline.

2.4. Lifecycle Assessment Methodology

2.4.1. Goal and Scope

The environmental performance of the analyzed retrofit scenarios was evaluated using LCA in accordance with EN 15978 [35] and EN 15804 [48] standards for buildings and construction products.

The system boundary adopted in this study corresponds to a "cradle-to-use" approach focusing on the most influential lifecycle stages: Modules A1–A3—raw material extraction, processing, and manufacturing of insulation materials and Module B6—operational energy use for space heating during building operation.

The LCA was performed using SimaPro version 10.01.06 and the Ecoinvent v3.11 database [49].

The functional unit was defined as 1 m^2 of heated residential floor area over a 50-year building service life. A 50-year reference service life was selected because it represents a commonly adopted lifetime assumption for multi-storey residential buildings in lifecycle studies [50–52].

Operational heating energy demand obtained from the building energy simulation was used as input for the B6 lifecycle stage. The impacts resulting from the energy used in the heating system are modelled during the 50-year lifetime.

2.4.2. Lifecycle Inventory

Operational heating demand values from the building energy models were used to estimate lifecycle operational emissions.

No electricity is used for heating the case study buildings; all thermal energy is supplied via the district heating network (DHS). In Serbia, DHS predominantly rely on natural gas. In 2022, 43.04% of households in urban areas were supplied with heat from

DHS [39]. Lifecycle inventory data for insulation materials were obtained from the Ecoinvent database [49].

2.4.3. Lifecycle Impact Assessment

Environmental impacts were quantified using midpoint indicators with emphasis on climate change and primary energy use.

The Environmental Footprint (EF) impact assessment method, aligned with EN 15804 [48] and implemented in SimaPro v. 10.4, was used. The analysis focused on global warming potential (GWP), ozone depletion, acidification, eutrophication, and resource use impact categories. For GWP, results were reported separately for fossil, biogenic, and land-use related emissions.

Biogenic carbon storage associated with cellulose insulation was accounted for using the static −1/+1 accounting convention, consistent with EN 15804 [48] + A2 methodology. Under this approach, carbon uptake during biomass growth is treated as a negative emission, while an equivalent release is assumed at the end of the material lifecycle.

The treatment of biogenic carbon remains a topic of methodological discussion in lifecycle assessment. Dynamic LCA approaches have been proposed to better account for the timing of carbon uptake and release. However, static −1/+1 accounting remains the most widely adopted convention in building LCAs and Environmental Product Declarations and was therefore applied in this study [53,54].

Additionally, total primary energy demand was evaluated using the Cumulative Energy Demand (CED) method, enabling quantification of both renewable and non-renewable energy flows associated with insulation production and operational heating.

3. Results

3.1. Calibration Performance

The calibrated baseline models demonstrated satisfactory agreement with measured heating energy consumption for the 2023/2024 heating season. For the high-rise building, monthly simulated heating energy consumption closely matched the utility data obtained from the district heating substation (Table 3). The total annual difference between simulated and measured heating demand remained within approximately 1%, indicating very good agreement between the model and observed building performance.

Table 3. High-rise building utility data vs. calibrated model results.

Month	Utility	Model	Differential	
	[kWh]	[kWh]	[kWh]	[%]
January	100,725	109,317	−8592	−9
February	59,483	56,700	2783	5
Marc	56,512	53,807	2705	5
April	21,822	23,021	−1199	−5
May	0	0	0	0
June	0	0	0	0
July	0	0	0	0
August	0	0	0	0
September	0	0	0	0
October	18,250	14,353	3897	21
November	56,257	57,967	−1710	−3
December	87,677	82,345	5332	6
Total	400,726	397,510	3216	1

Calibration accuracy was further evaluated using the statistical indicators recommended by ASHRAE Guideline 14 for energy model validation. As shown in Table 4, the Normalised Mean Bias Error (NMBE) for the high-rise building was 0.9%, while the Coefficient of Variation of the Root Mean Square Error (CVRMSE) was 10.6%. Both indicators fall well within the recommended limits for monthly calibration (±5% for NMBE and ±15% for CVRMSE), confirming that the model adequately reproduces measured heating energy consumption.

Table 4. Calibration metrics for the high-rise building.

Month	ASHRAE 14-2023	
	NMBE [%]	CVRMSE [%]
Heating Energy	0.9	10.6
Acceptable Range	±5	±15

For the lamella-type building, calibration was performed using annual heating consumption data due to the limited temporal resolution of available utility records. Table 5 compares measured and simulated monthly heating demand values, showing close agreement between the calibrated model and utility data, with an annual difference of less than 1%. The corresponding statistical indicators are presented in Table 5, where the calculated NMBE of 0.3% and CVRMSE of 14.3% remain within the acceptable limits recommended by ASHRAE Guideline 14.

Table 5. Lamella building utility data vs. calibrated model results.

Month	Utility	Model	Differential	
	[kWh]	[kWh]	[kWh]	[%]
January	192,760	202,637	−9878	−5
February	113,834	98,957	14,877	13
Marc	108,148	96,630	11,518	11
April	41,761	43,423	−1662	−4
May	0	0	0	0
June	0	0	0	0
July	0	0	0	0
August	0	0	0	0
September	0	0	0	0
October	34,925	24,974	9952	28
November	107,660	126,288	−18,628	−17
December	167,789	171,547	−3757	−2
Total	766,878	764,456	2422	0

Following calibration using measured weather data for the 2023/2024 heating season, the validated models were re-simulated using Typical Meteorological Year (TMY) weather data representative of Belgrade. This step produced the adjusted baseline models used for subsequent retrofit scenario analysis. The adjusted baseline ensures that the comparison of retrofit measures is not influenced by year-specific weather variability.

Overall, the calibration results presented in Tables 3–6 indicate that the developed building energy models reproduce measured heating energy consumption with satisfactory accuracy and therefore provide a reliable basis for evaluating the operational impact of façade insulation retrofit measures.

Table 6. Calibration metrics for the five-storey lamella building.

Month	ASHRAE 14-2023	
	NMBE [%]	CVRMSE [%]
Heating Energy	0.3	14.3
Acceptable Range	±5	±15

To illustrate the climatic differences that explain the variation between the calibrated model results (actual 2023–2024 weather) and the adjusted baseline (TMY weather), the dry-bulb temperature profiles were compared for the heating season only. The 2023–2024 heating season was milder than the typical year, with 1066 heating degree days, compared to 1531 for typical meteorological (base 15 °C). This milder weather condition results in lower heating energy demand in the calibrated models compared to the weather-normalized adjusted baseline used for retrofit scenario evaluation.

3.2. Operational Heating Energy Demand

The calibrated and weather-normalized models were used to evaluate the impact of façade insulation retrofits on operational heating energy demand for both analyzed building typologies. The adjusted baseline scenario represents the existing building envelope without additional insulation, while retrofit scenarios include the application of external insulation layers of varying thicknesses using EPS and cellulose materials.

Tables 6 and 7 present the simulated heating energy demand for the high-rise building, while Tables 8 and 9 show the corresponding results for the lamella building. For the lamella building, the adjusted baseline heating energy demand was calculated at 638,408 kWh annually, corresponding to approximately 192 kWh/m^2 of heated floor area. Applying 10 cm of EPS insulation reduced heating demand to 514,571 kWh, representing a reduction of approximately 19.4%. Increasing insulation thickness to 12 cm and 15 cm resulted in further reductions to 512,618 kWh and 510,580 kWh, corresponding to energy savings of 19.7% and 20.0%, respectively.

Table 7. High-rise: EPS retrofit scenario with various insulation thickness.

		Adj. Bln.	10 cm	12 cm	15 cm
Annual heating energy (consumed at site)	kWh	700,600	528,248	522,161	515,579
	kWh/m^2	142.11	107.15	105.92	104.58
	savings	-	24.60%	25.47%	26.41%
Annual natural gas (at heating plant)	kWh	934,133	704,331	696,215	687,438
	kWh/m^2	189.48	142.87	141.22	139.44

Table 8. High-rise: Cellulose insulation retrofit scenario with various insulation thickness.

		Adj. Bln.	10 cm	12 cm	15 cm
Annual heating energy (consumed at site)	kWh	700,600	534,926	528,263	520,899
	kWh/m^2	142.11	108.50	107.15	105.66
	savings	-	23.65%	24.60%	25.65%
Annual natural gas (at heating plant)	kWh	934,133	713,234	704,350	694,531
	kWh/m^2	189.48	144.67	142.87	140.88

Table 9. Lamella: EPS retrofit scenario with various insulation thickness.

		Adj. Bln.	10 cm	12 cm	15 cm
Annual heating energy (consumed at site)	kWh	638,408	514,571	512,618	510,580
	kWh/m^2	192.06	154.80	154.22	153.60
	savings	-	19.40%	19.70%	20.02%
Annual natural gas (at heating plant)	kWh	851,211	686,094	683,491	680,774
	kWh/m^2	256.08	206.41	205.62	204.81

Table 10 presents the corresponding results for cellulose insulation in the lamella building. Heating demand was reduced from the baseline 638,408 kWh to 516,349 kWh for the 10 cm cellulose scenario, representing a reduction of approximately 19.1%. Increasing insulation thickness to 12 cm and 15 cm further reduced heating demand to 514,274 kWh and 512,017 kWh, corresponding to total reductions of approximately 19.4% and 19.8%, respectively.

Table 10. Lamella: Cellulose insulation retrofit scenario with various insulation thickness.

		Adj. Bln.	10 cm	12 cm	15 cm
Annual heating energy (consumed at site)	kWh	638,408	516,349	514,274	512,017
	kWh/m^2	192.06	155.34	154.72	154.04
	savings	-	19.12%	19.44%	19.80%
Annual natural gas (at heating plant)	kWh	851,211	688,465	685,698	682,689
	kWh/m^2	256.08	207.12	206.29	205.38

The high-rise building exhibits similar trends, as shown in Tables 6 and 7, with façade insulation producing comparable relative reductions in heating demand across the analyzed insulation thicknesses and materials.

Across both building typologies, the majority of heating energy savings were achieved with the initial addition of insulation. Increasing insulation thickness from 10 cm to 12 cm and from 12 cm to 15 cm resulted in progressively smaller incremental reductions in heating demand. This pattern illustrates the well-known non-linear relationship between insulation thickness and energy savings, where the marginal benefit of additional insulation decreases as thermal resistance increases.

When insulation thickness was held constant, differences in heating energy demand between EPS and cellulose insulation were relatively small across both building types. These results indicate that differences in thermal conductivity between the two insulation materials have only a minor influence on operational heating demand within the investigated thickness range.

Tables 6–9 also report the equivalent primary energy input at the district heating plant, assuming an average seasonal system efficiency of approximately 75%. Under this assumption, the baseline heating demand of 638,408 kWh at the building level corresponds to approximately 851,211 kWh of natural gas consumption at the heating plant. Retrofit scenarios therefore reduce both building-level heating demand and upstream fuel consumption within the district heating system.

3.2.1. Effect of Insulation Material

When insulation thickness was held constant, differences in annual heating energy demand between EPS and cellulose insulation were relatively small for both building typologies (Tables 6–9). For the lamella building, at a 10 cm insulation thickness, the heating demand was 514,571 kWh for EPS and 516,349 kWh for cellulose, corresponding

to a difference of approximately 0.3%. Similar differences were observed at greater insulation thicknesses: in the 12 cm scenario, heating demand was 512,618 kWh for EPS and 514,274 kWh for cellulose, while in the 15 cm scenario, heating demand was 510,580 kWh for EPS and 512,017 kWh for cellulose.

Comparable trends are observed for the high-rise building, where differences between EPS and cellulose scenarios remain within a similarly narrow range across all insulation thicknesses.

These small differences reflect the relatively similar thermal conductivities of the two insulation materials. As a result, the influence of insulation material choice on operational heating energy demand is limited within the investigated retrofit thickness range.

Overall, the results indicate that insulation thickness has a more significant effect on heating energy reduction than the specific insulation material used within the thickness range investigated. This finding reflects the relatively similar thermal conductivities of EPS ($\lambda \approx 0.036$ W/mK) and cellulose ($\lambda \approx 0.040$ W/mK): when integrated into the full wall assembly—including structural layers and surface resistances—the difference in system-level U-value at a given thickness is small, producing the minor differences in heating demand observed. This behaviour is expected to generalize to other widely used ETICS insulation materials with similar thermal conductivities (e.g., mineral wool, stone wool, glass wool), which typically fall in the range of 0.033–0.042 W/mK. For materials with substantially lower thermal conductivities, such as polyurethane foam ($\lambda \approx 0.022$–0.028 W/mK) or aerogel composites ($\lambda \approx 0.013$–0.015 W/mK), material choice could exert a stronger influence on heating demand at equal physical thickness.

These results are consistent with findings by Gustavsson and Piccardo [10], who found that operational energy savings at the cost-optimal insulation thickness were relatively insensitive to whether conventional (rock wool, glass wool) or bio-based (wood fibre) insulation materials were used. Pescari et al. [9], comparing 14 insulation materials for multi-storey residential buildings in Romania, similarly observed that material type had limited influence on operational energy demand at equivalent thickness, with thickness remaining the primary determinant of thermal improvement. Bai et al. [15] likewise demonstrated that, beyond a cost-optimal thickness of 50 mm, further increases in XPS insulation yielded rapidly diminishing energy reductions, consistent with the pattern observed in the present study. Collectively, these findings suggest that the dominance of insulation thickness over material choice, within the conductivity range of standard ETICS products, is a generalizable characteristic rather than a result specific to EPS and cellulose alone.

3.2.2. Diminishing Marginal Returns

The simulation results presented in Tables 6–9 demonstrate the diminishing marginal benefits associated with increasing insulation thickness for both building typologies. The largest reduction in heating energy demand occurs when insulation is first added to the previously uninsulated façade. For example, applying 10 cm of insulation reduces heating demand by approximately 19–20% relative to the baseline scenario.

Further increases in insulation thickness result in progressively smaller additional savings. Increasing insulation thickness from 10 cm to 12 cm reduces heating demand by less than 0.4%, while the additional increase from 12 cm to 15 cm produces a further reduction in only approximately 0.3–0.4%, depending on the insulation material and building typology.

This behaviour reflects the well-established non-linear relationship between thermal resistance and heat transfer through building envelopes. As insulation thickness increases, the incremental reduction in heat losses decreases, resulting in diminishing marginal

energy savings. Within the investigated thickness range of 10–15 cm, additional increases in insulation thickness therefore produce relatively limited operational energy benefits.

From a lifecycle perspective, this effect is particularly relevant because increasing insulation thickness increases the amount of material used and, in turn, the associated embodied environmental impacts. Consequently, the optimal insulation thickness may not correspond to the maximum technically achievable thermal resistance but rather to a balance between operational energy savings and embodied impacts.

To further illustrate the expected behaviour of energy savings beyond the simulated range, the diminishing marginal returns can be quantified from the present results. For the lamella building, the addition of the first 10 cm of EPS insulation reduced annual heating demand by approximately 123,800 kWh (19.4%). Subsequent increases yielded progressively smaller benefits: the additional 2 cm from 10 cm to 12 cm reduced heating demand by only approximately 1950 kWh (0.31%), while the further increase from 12 cm to 15 cm produced an additional reduction of approximately 2040 kWh (0.32%). Expressed per centimetre of insulation added, the marginal energy savings decrease from approximately 12,400 kWh/cm at the initial application, to approximately 980 kWh/cm between 10 cm and 12 cm, and to approximately 680 kWh/cm between 12 cm and 15 cm. Projecting this trend, an increase from 15 cm to 20 cm would be estimated to yield a total incremental heating demand reduction of approximately 3000–3500 kWh, corresponding to less than 0.6% of the baseline annual demand. Insulation thicknesses beyond 20 cm would provide even smaller marginal operational benefits while substantially increasing material mass and associated embodied impacts. This analysis supports the conclusion that, for the studied building typology under Belgrade climatic and district heating conditions, the energy-optimal insulation thickness lies near the lower end of the commonly applied 10–15 cm retrofit range, and that additional thickness beyond 15 cm is unlikely to meaningfully improve operational energy performance relative to the increase in material use.

3.3. Lifecycle Impact Assessment Results

Table 11 presents the impact assessment for the midpoint impact categories covered by the EF impact assessment method aligned with EN 15804 [48] (EFxEN15804). The non-insulated scenario has a considerably higher impact across all considered categories, consistent with the higher heating energy required. The reduction in the climate change category from the baseline scenario achieved ranged from 23.6 to 26.0%, depending on the insulation material and thickness, with the highest reduction observed with 15 cm EPS. The difference between materials and thickness was marginal, as a difference in climate change category values for 15 cm EPS and 10 cm cellulose was 3.7%. Similar decreases were observed in other categories, namely acidification, ecotoxicity, and fossil resource use.

Recently, Dalla Valle et al. [21] analyzed the impact of retrofit measures, including the use of pre-shaped modular insulation panels, the installation of high-performance double-glazing windows, and the installation of a new heating system. The LCA results showed that global warming potential decreased by 73% after introducing the retrofit measures. There were also notable reductions in photochemical ozone creation potential and abiotic depletion potential for fossil fuels mainly due to significant reduction in operational energy use [21]. A 23–27% reduction in energy use in the case of retrofit in Spain with mineral wool, polystyrene XPS and polyurethane insulation materials was achieved compared to non-insulated baseline scenario. The majority of the impact was attributed to the operational use, which ranged from 68 to 78% [3]. The results from Almeida et al. also show that the operational use was responsible for 89.8–93.2% of embodied carbon emissions [55].

Table 11. Impact assessment for categories considered for the baseline scenario.

Impact Category	Unit	Non-Insulated	15 cm EPS	15 cm Cellulose	12 cm EPS	12 cm Cellulose	10 cm EPS	10 cm Cellulose
Acidification	mol H + eq.	1.83	1.38	1.37	1.39	1.38	1.40	1.40
Climate change	$kgCO_2$ eq.	2492.69	1844.07	1854.32	1865.55	1880.30	1885.97	1903.85
Climate change—Biogenic	$kgCO_2$ eq.	1.16	0.96	0.97	0.95	0.96	0.94	0.96
Climate change—Fossil	$kgCO_2$ eq.	2491.18	1842.86	1853.09	1864.35	1879.08	1884.76	1902.63
Climate change—Land use and LU change	$kgCO_2$ eq.	0.34	0.25	0.26	0.26	0.26	0.26	0.26
Ecotoxicity, freshwater	CTUe	1824.16	1351.00	1361.47	1366.42	1379.59	1381.16	1396.23
Eutrophication, marine	kgNeq.	0.54	0.41	0.41	0.41	0.41	0.41	0.42
Eutrophication, freshwater	kgPeq.	0.08	0.06	0.06	0.06	0.06	0.06	0.06
Eutrophication, terrestrial	molNeq.	5.84	4.36	4.36	4.40	4.41	4.45	4.47
Resource use, fossils	MJ	35,564.56	26,389.72	26,453.05	26,680.33	26,824.46	26,961.04	27,160.92
Resource use, minerals and metals	kgSbeq.	0.0023	0.0017	0.0019	0.0017	0.0019	0.0017	0.0019

Cumulative Energy Demand

The amount of primary energy needed is shown in Figures 6 and 7. CED calculations indicate that, with retrofit scenarios, the primary energy required decreases considerably, ranging from 23.6% to 25.8%, depending on the material and insulation thickness. Similarly to the results obtained with the EFxEN15804 lifecycle impact assessment method, the differences between the used material and its thickness were marginal and did not exceed 3%. The results support the literature, which states that reducing demand for operating energy is the most important aspect in the design of energy-efficient buildings throughout their lifecycle [56].

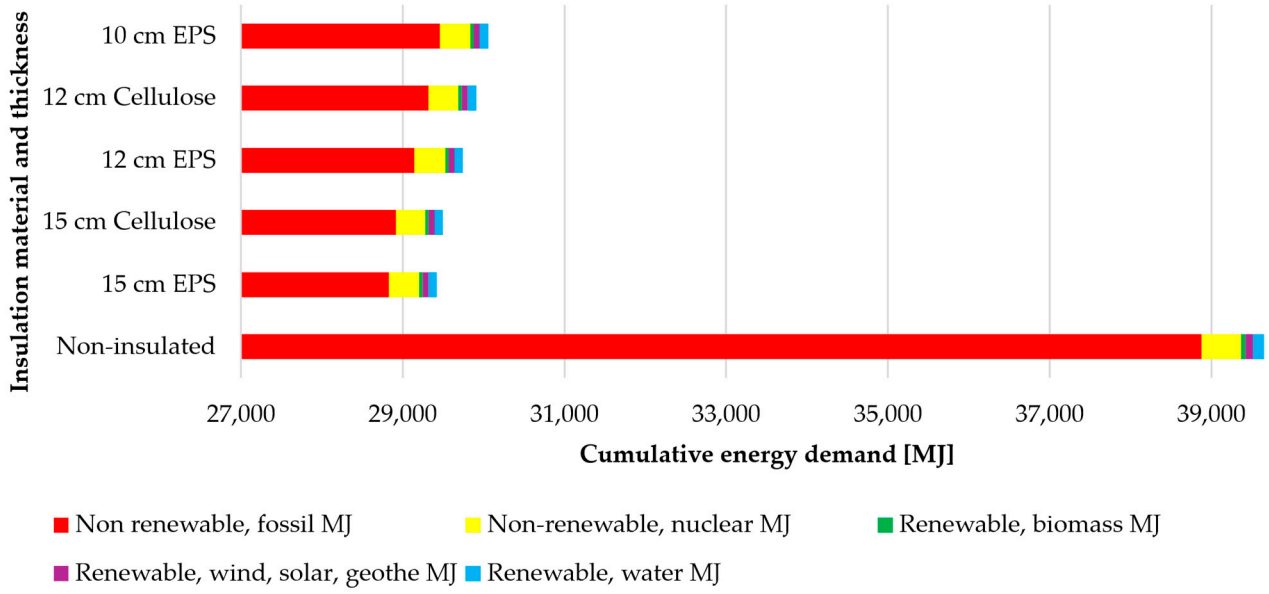


Figure 6. Comparison of cumulative energy demand (CED) for retrofit scenarios.

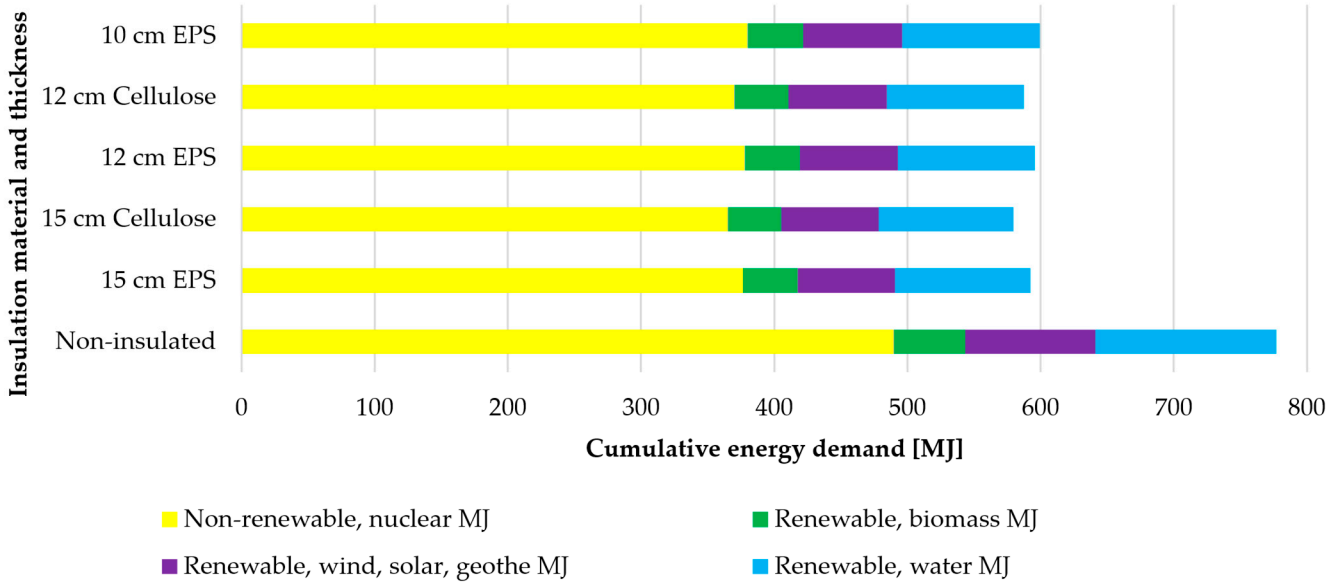


Figure 7. Comparison of cumulative energy demand (CED) for retrofit scenarios for non-fossil components only.

Energy use in building operations accounts for 70–90% of total energy use during a building lifecycle [57,58]. Asdrubali et al. modelled retrofit scenarios for three buildings in Italy. The results showed that implementing energy retrofits, such as improving envelope thermal performance, reduces operational energy demand and decrease lifecycle impacts across all scenarios analyzed. The maximum CED reduction achieved was 48% [59]. Sartori et al. analyzed 60 case studies and concluded that operating energy accounts for by far the largest share of energy demand in a building over its lifecycle retrofit measures for implementing low-energy buildings could achieve greater energy efficiency than conventional measures, even with higher embodied energy [56].

4. Conclusions

This study provides a comprehensive evaluation of façade insulation retrofit strategies for two representative post-war multi-apartment residential building typologies in Novi Beograd, Serbia—lamella-type and high-rise buildings—connected to district heating systems. By integrating calibrated dynamic building energy modelling with cradle-to-use LCA following EN 15978 [35] standards, the analysis quantified both operational heating energy savings and whole-life environmental impacts over a 50-year service life, comparing conventional expanded polystyrene (EPS) with bio-based cellulose insulation at thicknesses of 10 cm, 12 cm, and 15 cm.

The calibrated models achieved adequate agreement with measured heating energy consumption for the 2023–2024 heating season (NMBE < 1% and CVRMSE < 15% for both typologies), confirming their reliability for evaluating retrofit scenarios under standardized TMY conditions. Simulation results indicate that applying external insulation reduces annual site heating demand by approximately 19–20% relative to the non-insulated baseline (192 kWh/m^2·a), with corresponding reductions in upstream fuel consumption at the district heating plant assuming an average seasonal system efficiency of 75%. The majority of energy savings occur with the initial application of insulation, while increasing thickness from 10 cm to 12 cm and 15 cm yields only marginal additional reductions (~0.3–0.4%), illustrating the well-established non-linear relationship between insulation thickness and heat loss reduction.

Within the commonly applied retrofit thickness range of 10–15 cm, insulation thickness exerts a significantly stronger influence on operational heating demand than the choice of insulation material. Differences in heating demand between EPS (λ = 0.035 W/(m·K)) and cellulose (λ = 0.041 W/(m·K)) remained below approximately 0.3–0.4% of total demand, indicating that variations in thermal conductivity play a relatively minor role compared with the overall increase in façade thermal resistance.

From a lifecycle perspective, both insulation materials provide substantial reductions in environmental impacts primarily due to lower operational energy use. Climate change impacts (GWP) decrease by approximately 23.6–26.0% compared with the baseline scenario, with similar reductions observed across other impact categories including acidification, ecotoxicity, eutrophication, and fossil resource use. CED decreases by approximately 23.6–25.8%. Cellulose insulation demonstrates a modest advantage in whole-life carbon performance due to lower embodied emissions during material production (modules A1–A3) and the inclusion of biogenic carbon storage according to the static $-1/+1$ accounting convention defined in EN 15804 [48] + A2.

The results highlight that façade insulation retrofits represent a highly effective strategy for reducing operational energy use and environmental impacts in district-heated residential buildings typical of the Central and Eastern European post-war housing stock. However, beyond approximately 10 cm of insulation thickness, additional material provides diminishing operational energy benefits while increasing embodied impacts, suggesting that environmentally optimal retrofit solutions may often lie within the lower-to-mid range of commonly applied insulation thicknesses.

Cellulose insulation emerges as a favourable option from a lifecycle carbon perspective in scenarios prioritizing whole-life greenhouse gas reduction, particularly where biogenic carbon storage and material circularity are considered. EPS remains a competitive option where factors such as cost, material availability, and installation simplicity are prioritized, given its comparable operational performance and widespread use in façade retrofit systems.

Overall, the findings contribute to addressing important research gaps by combining calibrated dynamic energy simulations with lifecycle environmental assessment under realistic district heating conditions in a Central and Eastern European context. The results support policy initiatives under the EPBD Renovation Wave by demonstrating that targeted façade insulation retrofits—particularly when low-embodied impact materials are considered—can significantly reduce lifecycle emissions of the existing residential building stock without requiring complete system replacement.

Several limitations of this study should be acknowledged. First, the analysis is geographically specific: both case study buildings are located in Novi Beograd, Serbia, and the findings—including calibrated baseline energy demands and the relative performance of retrofit scenarios—are directly applicable to the Belgrade climate zone (Köppen Dfb) and the district heating conditions of that region. Transferability to other CEE cities or different climate zones should be evaluated with caution. Second, the energy models employ simplified operational assumptions, including constant occupancy schedules and fixed internal heat gains that do not account for actual user behaviour variability; the uncertainty introduced by these assumptions was partially mitigated by calibration against measured consumption data but cannot be fully eliminated. Third, cooling demand is excluded from the analysis, as both buildings are not equipped with active cooling systems; the potential effect of improved envelope insulation on summer overheating risk was not assessed. Fourth, the system boundary of the LCA is restricted to the cradle-to-use stages (modules A1–A3 and B6); end-of-life impacts, including insulation disposal or recycling, are not included. Fifth, the biogenic carbon stored in cellulose insulation is treated as a

static credit at the production stage rather than modelled dynamically, which may affect the relative environmental advantage attributed to cellulose over the full service life.

Future work could extend this analysis by evaluating integrated retrofit strategies, including window replacement, ventilation improvements, the hygrothermal performance of bio-based insulation systems, dynamic modelling of biogenic carbon storage, and economic assessments that consider regional energy prices and policy incentives.

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Abbreviations

The following abbreviations are used in this manuscript:

BEM	Building Energy Modelling
CED	Cumulative Energy Demand
CEE	Central and Eastern Europe
CVRMSE	Coefficient of Variation of the Root Mean Square Error
DHS	District Heating System
EPBD	Energy Performance of Buildings Directive
EPS	Expanded Polystyrene
GHG	Greenhouse Gas
GWP	Global Warming Potential
LCA	Lifecycle Assessment
MURB	Multi-Unit Residential Building
NMBE	Normalized Mean Bias Error
TMY	Typical Meteorological Year
U	Thermal Transmittance of Building Elements $W \cdot m^{-2} \cdot K^{-1}$
λ	Thermal Conductivity of Insulation Material $W \cdot m^{-1} \cdot K^{-1}$

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