

Article

Bridging the Gap to Decarbonization: Evaluating Energy Renovation Performance and Compliance

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Abstract: Achieving a decarbonized built environment by 2050 requires significant advancements in building renovation strategies, with a strong emphasis on energy efficiency and emissions reduction. This study examined the compliance of buildings renovated between 2015 and 2022 with national energy performance regulations. While many buildings have undergone improvements, a substantial portion still fail to meet the stricter, current requirements, particularly in terms of window and floor insulation, highlighting the need for further retrofit measures. Comparing static and dynamic simulation models reveals that static models frequently overestimate energy savings, leading to misaligned investment decisions. Dynamic simulations, by incorporating real-time climate interactions and transient thermal behaviors, provide a more accurate assessment of energy demand and efficiency improvements. A financial analysis indicates that static models often predict unrealistically short payback periods, potentially resulting in suboptimal renovation investments. To meet decarbonization goals, future strategies must integrate advanced simulation methodologies, strengthen regulatory oversight, and enhance financial incentives for comprehensive energy renovations. A data-driven approach is essential to ensure that building retrofits achieve meaningful energy savings and contribute to climate neutrality. Strengthening compliance frameworks and promoting standardized renovation practices will be key to bridging the gap between expected and actual performance, ensuring a sustainable and resilient built environment.



Academic Editors: Alenka Temeljotov Salaj, Eva Zavrl and Mohamed El Mankibi

Received: 16 February 2025

Revised: 20 February 2025

Accepted: 24 February 2025

Published: 26 February 2025

Citation: Stegnar, G. Bridging the Gap to Decarbonization: Evaluating Energy Renovation Performance and Compliance. *Energies* **2025**, *18*, 1146. <https://doi.org/10.3390/en18051146>

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Keywords: energy efficiency; building renovation; decarbonization; dynamic simulation; energy performance; policy compliance; thermal insulation; investment analysis; climate neutrality; regulatory frameworks

1. Introduction

1.1. Background and Importance

The building sector accounts for nearly 40% of global CO₂ emissions, including both operational and embodied carbon, making it a focal point in climate change mitigation [1]. To achieve carbon neutrality by 2050, as outlined in the European Green Deal [2] and Paris Agreement, energy demand reduction, efficiency improvements, and the decarbonization of heating and cooling systems are essential.

The EU Long-Term Climate Strategy [3] identifies energy efficiency as a primary driver of decarbonization, with the building sector consuming 40% of total EU final energy, of which 25% is from residential buildings [4]. Renovating existing buildings is critical, as 75% of the EU building stock is energy-inefficient and will still be in use by 2050. Directive (EU) 2023/1791 reinforces the transition toward nearly zero-energy building (nZEB) compliance as a pathway to reduce GHG emissions by at least 55% by 2030 [5]. Yet, no mandate

currently requires all renovations to meet nZEB levels, posing challenges for widespread implementation [6].

The Energy Efficiency Directive (EED) urges higher renovation rates and requires an inventory of buildings that fail to meet nZEB levels [7]. This is critical as urban populations are expected to reach 68% by 2050, further stressing energy demand [5]. To bridge this gap, Building Energy Modeling (BEM) has emerged as a crucial tool for energy-efficient design, building operations, and retrofitting [8,9]. Increasing reliance on building performance simulation (BPS) enables more accurate whole-life carbon assessments and cost-effective renovation planning [10].

The recast Energy Performance of Buildings Directive (EPBD) introduces zero-emission buildings (ZEBs), which require very high energy efficiency, zero or minimal fossil fuel use, and a reliance on renewable energy sources [11]. However, transitioning from nZEBs to ZEBs presents challenges due to inconsistent renewable energy integration and the lack of standardized greenhouse-gas (GHG) emission thresholds [12]. Addressing these issues through dynamic simulation methods is crucial for aligning building renovation strategies with 2050 decarbonization goals.

1.1.1. The Role of Energy Renovations

Energy renovation plays a crucial role in achieving net-zero emissions by 2050, as much of the existing building stock was constructed under outdated efficiency standards. Without intervention, these buildings will continue to consume excessive amounts of energy, leading to persistent emissions. Renovation strategies typically focus on the following:

- Improving the building envelope performance, such as adding insulation, installing high-performance windows, and enhancing airtightness.
- Upgrading heating, ventilation, and air conditioning (HVAC) systems with more efficient and renewable-based technologies, including heat pumps, district heating, and waste heat recovery.
- Integrating renewable energy systems, including solar photovoltaic (PV) panels and battery storage.
- Enhancing smart energy management systems to optimize building operations and reduce peak loads.

To reduce energy consumption, numerous studies and projects [13–16] emphasized thermal envelope improvements. The most recommended solutions involve adding insulation to external walls and roofs, replacing windows, and improving airtightness [17,18]. Implementing passive measures is considered the first critical step toward energy efficiency [19,20].

Further research highlighted the need to replace outdated energy systems with more efficient alternatives. Depending on the building type and climate, the substitution of traditional boilers (coal, oil, and methane gas) with modern boilers and heat pumps is widely advocated [21,22]. Buildings that aim to achieve nZEB targets often incorporate renewable energy sources, such as solar collectors and photovoltaic panels.

While many studies evaluate building energy demand [23,24], fewer focus on the real performance of energy devices in assessing consumption [25]. The transition of active and renewable energy measures into real-world applications remains a challenge. Historically, energy refurbishments in Europe have primarily focused on winter demand reduction and heating strategies [26]. However, as global warming continues to drive rising temperatures, there is a growing need to incorporate cooling strategies into renovation efforts [27,28].

1.1.2. Energy Performance Regulations and Their Impact

To accelerate building energy efficiency improvements, many countries have implemented stricter regulatory frameworks. The EPBD mandates that all new buildings must be nearly zero-energy buildings (nZEBs), while existing buildings undergoing major renovations must meet higher efficiency standards. Similarly, the rules on the efficient use of energy in buildings (PURES) in Slovenia sets ambitious targets for reducing thermal losses and integrating renewable energy in renovations.

However, a persistent gap remains between theoretical compliance and real-world performance, raising concerns about the accuracy of energy simulations used for certification and compliance. Current regulatory models primarily rely on static energy simulations, which fail to capture real-time energy consumption patterns, occupant behavior variations, and dynamic climate interactions [29,30]. This discrepancy can lead to suboptimal renovation strategies and misleading energy efficiency ratings.

The transition toward dynamic simulation methods presents an opportunity to enhance regulatory compliance accuracy by incorporating hourly energy demand fluctuations, thermal inertia effects, and renewable energy intermittency into performance assessments. Integrating dynamic models into policy frameworks could help bridge the performance gap by ensuring more reliable predictions of actual energy savings and decarbonization potential [31,32]. Additionally, improved simulation accuracy can better inform cost-effective renovation decisions, optimize renewable energy integration, and support the alignment of building policies with 2050 net-zero targets.

1.1.3. The Need for Accurate Energy Simulation Methods

Traditional compliance approaches rely primarily on static monthly calculation methods, which provide simplified estimations of energy performance. However, research has shown that these methods often fail to capture real-world energy dynamics, particularly in cases involving the following:

- Fluctuating weather conditions and climate change projections.
- Occupancy behavior and operational variations.
- Thermal mass effects and heat retention properties of building materials.
- Renewable energy generation profiles, which vary hourly and seasonally.

Static models, while widely used for regulatory compliance due to their efficiency and simplicity, often lead to overestimated energy savings and underestimated energy consumption, resulting in an energy performance gap. This misalignment between modeled and actual performance limits the effectiveness of current decarbonization strategies.

Dynamic simulation methods, which utilize hourly time-step calculations, recorded historical weather data, and occupancy-driven energy demand models, offer a more precise assessment of energy performance and decarbonization potential. By comparing static vs. dynamic simulation results, this study evaluated whether dynamic models provide a more reliable basis for achieving 2050 decarbonization targets and how their integration into policy frameworks could improve long-term sustainability outcomes.

Dynamic simulation is a powerful tool for accurately evaluating thermal demands in buildings and assessing the impact of energy refurbishment actions on final energy consumption. Conversely, semi-stationary models are widely adopted in commercial applications due to their simplified approach, which reduces calculation times and provides standardized results, albeit with deviations from real-world energy performance [33].

The semi-stationary method primarily focuses on building energy classification through a simplified approach. It is effective for fast and easy energy performance assessment, making it particularly useful for compliance checks and certification processes. This method is preferable for simple buildings with a limited number of thermal zones,

uniform occupancy profiles, and centralized heating systems. However, for larger buildings with heterogeneous occupancy profiles and diverse thermal zone end-uses, dynamic simulation tools should be employed.

While dynamic simulation tools are computationally intensive and require greater expertise, their application is justified when the goal extends beyond energy certification to a detailed estimation of energy demands, peak load behaviors, and economic feasibility of renovations. These tools are particularly valuable for evaluating long-term decarbonization strategies, optimizing energy refurbishment decisions, and enhancing the reliability of building energy policies aligned with net-zero targets [33].

1.2. Research Gap

Current national energy efficiency regulations, such as PURES in Slovenia, primarily rely on static simulation methods, which are steady-state or quasi-steady-state models that assume fixed boundary conditions and rely on standardized climate datasets and occupancy assumptions for assessing building energy performance. While these methods offer a simplified and standardized approach for regulatory compliance, they are inherently limited in capturing recorded operational variations, climate fluctuations, and user behavior dynamics.

Research has demonstrated that static models often underestimate actual energy consumption, leading to a misleading perception of building efficiency and potentially inadequate retrofitting measures. Calise et al. [33] highlight that semi-stationary models, commonly used in commercial applications and regulatory energy labeling, tend to overestimate primary energy savings compared to dynamic simulations, which offer a more precise estimation of energy demand. The study finds that the simplified steady-state approach overestimates primary energy savings by up to 64.7%, demonstrating the risk of over-reliance on static models.

Kotarela et al. [34] further reinforce this argument by analyzing energy performance certificates (EPCs), finding that static models overestimate energy savings, leading to an 85% discrepancy in CO₂ emissions predictions and an increase in retrofit cost of nearly 19.7%.

The implications of these inaccuracies extend beyond building-level analyses. Li et al. [35] highlight that in district heating networks, steady-state models fail to account for transport time delays in heat distribution, resulting in inaccuracies in temperature estimation for end users. The study introduces a quasi-dynamic model that improves the precision of supply temperature predictions, reducing errors by 20% compared to steady-state approaches. Lastly, Dalla Mora et al. [36] demonstrate how optimization tools using dynamic models provide a more holistic approach to cost-effective energy renovations by considering additional benefits such as thermal comfort, daylight availability, and indoor air quality, which are often overlooked in static simulations.

These studies collectively reinforce the limitations of static modeling in evaluating real-world energy performance. While static models provide a practical means for regulatory compliance, they frequently fail to capture the complexities of dynamic energy behavior, leading to inaccurate savings projections and suboptimal policy and investment decisions. To address these limitations, integrating dynamic simulations into energy performance assessments is essential for achieving reliable and data-driven energy renovation strategies.

As 2050 decarbonization goals impose increasingly stringent requirements for reducing operational energy use and CO₂ emissions, the limitations of static simulations could result in renovation strategies that fail to meet long-term climate commitments. The reliance on average weather conditions, predefined occupancy patterns, and fixed thermal properties in static models does not reflect the dynamic interplay of energy demand and

supply, particularly in buildings integrating renewable energy systems and advanced HVAC technologies.

Furthermore, as climate change accelerates, the ability to predict future energy performance under evolving weather conditions becomes critical. Dynamic simulations offer the capability to assess hourly energy variations, peak demand fluctuations, and seasonal mismatches in energy supply and consumption, making them a crucial tool for ensuring effective energy renovation strategies.

This study seeks to evaluate whether dynamic simulations can bridge this gap by offering more accurate, data-driven insights into long-term energy performance and supporting better policy and investment decisions. The integration of dynamic models into energy certification frameworks and renovation strategies has the potential to improve real-world energy savings, optimize carbon reduction efforts, and enhance the economic feasibility of decarbonization measures.

1.3. Objectives

This study aimed to comprehensively assess the role of energy simulation models in achieving energy efficiency and decarbonization goals, focusing on their influence on regulatory compliance, financial feasibility, and real-world applicability. Specifically, this research sought to perform the following:

- Evaluate the accuracy of energy demand predictions by comparing static and dynamic simulation models across five renovation scenarios, identifying discrepancies and uncertainties in their projections.
- Assess the impact of simulation model selection on CO₂ emissions reduction, determining whether static models overestimate energy savings and underestimate real-world energy consumption.
- Analyze the financial implications of simulation inaccuracies, investigating how misleading performance predictions may lead to over- or under-investment in energy retrofitting projects.
- Explore the potential of dynamic simulations in optimizing decarbonization pathways, providing evidence-based recommendations for integrating advanced modeling techniques into regulatory frameworks to enhance long-term energy efficiency and sustainability outcomes.

The findings will establish a scientific foundation for incorporating dynamic simulations into energy compliance frameworks, ensuring more accurate performance assessments, cost-effective renovation strategies, and reliable decarbonization planning aligned with 2050 net-zero objectives.

2. Methodology

2.1. Assessing the Thermal Envelope's Performance in Renovated Buildings

This study examined the thermal transmittance (U-values) of building envelopes in 163 energy renovation projects, evaluating compliance with PURES 2010, which was adopted in 2010, and PURES 2022, which came into effect in 2022. PURES is Slovenia's national framework for improving energy efficiency in the built environment. It establishes mandatory performance criteria for new and existing buildings, aligning with the EPBD and the broader 2050 decarbonization goals.

The introduction of PURES 2010 established baseline energy efficiency criteria, setting limits on building envelope U-values to reduce heating and cooling demands. However, PURES 2022 introduced significantly stricter requirements, reflecting advancements in insulation technologies and the necessity to meet nZEB standards. These updated regulations

play a crucial role in reducing operational carbon emissions, making building retrofits essential for long-term sustainability.

Under the PURES 2022 framework, buildings undergoing renovation must meet lower U-value thresholds, ensuring improved thermal insulation and energy efficiency. These stricter limits impact renovation feasibility, as achieving compliance often requires additional insulation layers, high-performance glazing, and improved construction techniques.

A diverse sample of 163 buildings was analyzed, categorized by function, including primary schools (50 buildings), kindergartens (30 buildings), health centers (20 buildings), cultural centers (10 buildings), municipal buildings (5 buildings), sports halls (15 buildings), and other facilities (33 buildings). Educational institutions represented the largest portion, emphasizing the priority of improving energy efficiency in public sector buildings. Renovation measures included enhancements in insulation, window replacements, and the implementation of energy-efficient heating and lighting systems.

The study utilizes pre- and post-renovation U-value data collected from energy audit reports and project documentation. A comparative approach quantifies the extent of improvement and determines compliance with current energy performance requirements. The effectiveness of insulation measures is assessed by comparing recorded U-values against the threshold values prescribed in PURES 2022. Table 1 provides a comparative overview of the permissible U-values under PURES 2010 and PURES 2022 for different building components. The stricter limits introduced in PURES 2022, particularly for external walls, windows, and roofs, emphasize the need for higher insulation performance. Notably, the U-value requirement for external walls has decreased from 0.28 W/m²K under PURES 2010 to 0.18 W/m²K under PURES 2022, demonstrating the regulatory push toward better thermal performance. Similarly, the required U-value for windows has been lowered from 1.30 W/m²K to 1.00 W/m²K, indicating a focus on reducing heat loss through glazing elements.

Table 1. Comparative analysis of U-value requirements in renovated buildings between PURES 2010 and PURES 2022.

Building Component	PURES 2010 Limit [W/m ² K]	PURES 2022 Limit [W/m ² K]
Façade	0.28	0.18
Windows	1.30	1.00
Roof	0.20	0.15
Floors	0.30	0.35

Table 1 highlights that while most building components require lower U-values under PURES 2022, the regulation for floors presents an exception, with an increased allowable U-value from 0.30 W/m²K to 0.35 W/m²K. This adjustment likely reflects practical considerations related to construction feasibility and cost-effectiveness while still maintaining overall improvements in energy performance.

By integrating a broad range of building types, this analysis provides a comprehensive insight into the energy needs and opportunities for improvement in public buildings. The applied energy efficiency measures were tailored to the functional requirements of each category, ensuring an effective and sustainable approach to energy performance enhancement.

2.2. Case Study Buildings and Renovation Models

This study examined five selected buildings, each undergoing varying degrees of energy renovation. The case studies were chosen based on their renovation strategies, energy performance characteristics, and potential for decarbonization improvements. These

buildings represent different construction periods, typologies, and retrofit approaches, allowing for a comprehensive comparison between static and dynamic energy simulation methods. The five buildings were chosen based on the following key factors:

- **Building type and age:** A mix of residential, commercial, and public buildings with varying construction dates to capture diverse renovation needs.
- **Climate zone:** Buildings are situated in different microclimates to assess the influence of climate conditions on energy performance.
- **Renovation scope:** Selected buildings encompass a wide range of energy efficiency measures, including insulation, HVAC upgrades, and renewable energy integration.
- **Availability of energy performance data:** Each building has accessible pre- and post-renovation data, allowing for a comparative analysis of energy efficiency improvements.

2.2.1. Building Classification and Renovation Strategies

The five case study buildings are categorized according to their renovation approaches, focusing on three major intervention areas:

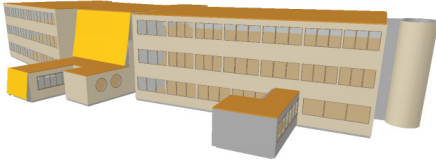
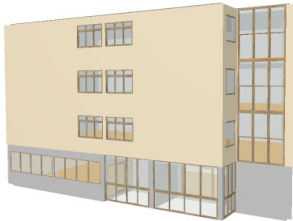
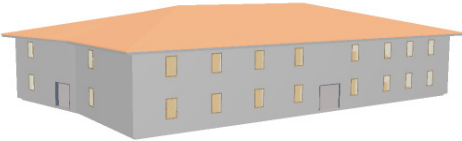
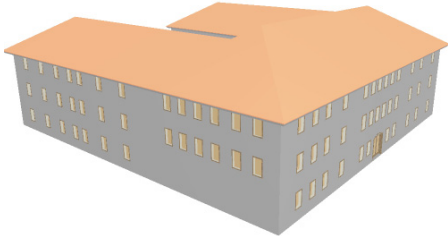
1. **Building Envelope Upgrades:** Thermal insulation improvements include upgrading walls, roofs, and floors with high-performance materials to reduce heat losses. Window and glazing replacement involve installing triple-glazed, low-emissivity windows to enhance thermal performance. Airtightness improvements focus on sealing thermal bridges and minimizing air infiltration losses to improve overall building efficiency.
2. **HVAC System Modernization:** Heat pump installations replace fossil fuel-based heating systems with air-source or ground-source heat pumps, significantly improving efficiency. District heating integration connects buildings to district heating networks, reducing dependence on individual heating units. Mechanical ventilation with heat recovery was implemented to optimize indoor air quality while minimizing heat losses.
3. **Renewable Energy Integration:** PV systems are deployed on rooftops or integrated into external walls to generate on-site electricity. Battery storage solutions enhance energy self-consumption and grid interaction. Solar thermal collectors provide renewable heating for domestic hot water systems, reducing reliance on fossil fuel-based heating sources.

Table 2 provides a visual comparison between real-life case study buildings and their corresponding Building Energy Models (BEMs) used in the simulation process. These BEMs were developed to assess the impact of renovation measures on energy performance. The images illustrate the geometry and envelope characteristics of each building, helping to contextualize the simulation results. Each case study building was analyzed using both static and dynamic simulation methods:

- **Renovated buildings (Id-2, Id-3, Id-5):** The impact of real renovation measures was assessed, including thermal insulation improvements, HVAC upgrades, and renewable energy integration.
- **Non-refurbished buildings (Id-1, Id-4):** Proposed renovation strategies were evaluated to determine potential improvements in energy performance.

By integrating these elements, Table 2 serves as a reference for understanding the relationship between actual buildings and their corresponding digital models, emphasizing the influence of renovation strategies on building energy performance.

Table 2. Overview of five selected case studies in real life and as a BEM.

Building Id	Photo	Model
Id-1		
Id-2		
Id-3		
Id-4		
Id-5		

2.2.2. Overview of Assessed Buildings

This study evaluated five selected buildings, three of which have already undergone energy renovation to different extents, while two remain in their original state. These case studies represent different building types, construction periods, and renovation scopes, providing a diverse dataset for analyzing the impact of renovation strategies on energy efficiency. The selection of buildings includes educational, healthcare, and office facilities, each presenting unique challenges and opportunities for energy optimization.

The renovations implemented across these buildings include improvements to the building envelope, HVAC systems, and integration of renewable energy sources. These measures aim to enhance thermal performance, reduce energy demand, and lower carbon emissions, aligning with the PURES 2022 regulatory framework and long-term 2050 decarbonization goals.

On-site data collection was conducted to obtain detailed insights into the buildings' energy performance and operational conditions. The following types of data were gathered:

- Envelope Performance Data: Infrared thermography and blower door tests were conducted to assess thermal insulation effectiveness, air leakage, and thermal bridging.
- HVAC System Performance: Operational data from heating, ventilation, and cooling systems were recorded, including temperature setpoints, efficiency levels, and control strategies.
- Energy Consumption Data: Historical energy consumption patterns were collected through smart meters, energy management systems, and manual logbooks.
- Indoor Environmental Quality (IEQ) Parameters: Temperature and humidity measurements were taken to evaluate occupant comfort and ventilation effectiveness.

A structured data collection protocol was followed, ensuring consistency across all case study buildings. This protocol included the following stages:

1. Preliminary Building Survey: Reviewing architectural plans, renovation history, and existing energy audit reports.
2. Instrumented Measurements: Using calibrated sensors and meters to record energy and environmental parameters.
3. Occupant Interviews and Observations: Gathering qualitative feedback from building users to identify operational inefficiencies.
4. Data Validation and Cross-Checking: Comparing collected data with existing documentation and simulation models.

Table 3 provides a summary of the five Slovenian case study buildings, outlining their key characteristics, implemented renovation measures, and available energy-related data sources used for evaluation.

Table 3. Key characteristics, renovation measures, and used data of case study buildings.

Building Id	Type	Year Built	Conditioned Area [m ²]	Renovation Measures (Actual or Proposed)	Energy Data Used
Id-1	Elementary School	1976 (partly renovated 1994)	3174	Insulation, window replacement, LED lighting, heat pump	EPC, BIM, Energy Audit, Consumption Data
Id-2	Health Center	1980 (renovated 2019)	3630	Heating system upgrade, district heating, energy management system	EPC, BIM, Energy Audit, Consumption Data
Id-3	Office Building	1956 (renovated 2013)	605	ESCO model, energy monitoring, lighting retrofit	EPC, BIM, Energy Audit, Consumption Data
Id-4	School	1675 (façade renovated 1970, roof 1994)	2527	Cultural heritage constraints, energy-inefficient systems	EPC, BIM, Energy Audit, Consumption Data
Id-5	Elementary School	1960 (renovated 2022)	3977	Insulation, LED lighting, district heating, PV system	EPC, BIM, Energy Audit, Consumption Data

2.2.3. Simulation and Renovation Roadmap Development

The assessment follows a structured methodology, integrating energy audit reports, project documentation, EPC tools, and BEMs developed using IDA ICE version 5.0 software. The process begins with a baseline energy performance analysis, utilizing EPC and audit reports to develop standardized static models, while simultaneously constructing dynamic BEMs to provide in-depth energy performance assessments.

On-site data collection was conducted through site visits and consultations with energy and facility managers to refine energy efficiency measures. These discussions ensured that proposed interventions align with real building conditions, particularly regarding renewable energy integration and monitoring system upgrades.

An action plan was formulated to assess the feasibility of renovation strategies, estimating potential energy savings and financial viability for the two buildings that remain unrenovated (Id-1, Id-4). The plan considers key performance indicators, including ex-

pected energy demand reductions, CO₂ emission reductions, and return on investment, ensuring that proposed renovation measures align with long-term decarbonization goals.

2.3. Simulation Methods and CO₂ Emission Reduction Assessment

This study employed both static and dynamic simulation methods to assess energy performance before and after renovation. Static simulation relies on monthly steady-state calculations, providing simplified estimations for compliance assessments. These methods follow predefined standard conditions without accounting for variations in occupancy, weather fluctuations, and the dynamic behavior of building materials. In contrast, dynamic simulation utilizes hourly based energy performance analysis, allowing for a more accurate representation of energy demand fluctuations. Tools such as IDA ICE model complex interactions between internal loads, HVAC system operations, and recorded historical weather data. By incorporating detailed thermal mass effects, renewable energy generation profiles, and peak power demand variations, dynamic simulations offer a refined assessment of energy savings potential.

The comparison between these methods is based on key performance indicators, including total energy demand (kWh/m²/year), seasonal heating and cooling loads, and peak power demand variations. These metrics help determine the impact of building renovations on energy efficiency, thermal comfort, and demand-side management strategies. By integrating static and dynamic modeling, this study quantified the performance gap between compliance calculations and real-world energy consumption, providing insights into the suitability of dynamic simulations for improving energy certification accuracy and supporting decarbonization strategies.

The impact of different energy modeling approaches on CO₂ emissions was assessed by comparing avoided emissions from the static monthly method and the dynamic simulation method. Energy demand for heating was simulated using both the ISO 13790 [37] static model and the IDA ICE dynamic simulation model. The conditioned floor area of each building was used to estimate total energy savings. The static model operates on steady-state assumptions, while the dynamic model incorporates hourly energy demand variations, real operational conditions, and transient heat transfer effects.

To calculate CO₂ emissions, emission factors were assigned based on the energy source used in each building. The heating system information was gathered from a combination of sources, including the energy performance certificate (EPC) database, Eco Fund subsidies, and modeling based on [38,39]. Buildings Id-1 and Id-4 used a factor of 0.27 kg CO₂/kWh for heating oil-based systems. Buildings Id-2, Id-3, and Id-5 used 0.235 kg CO₂/kWh for electricity-based systems, with values adopted from regulatory emission guidelines and validated through modeling results. Total avoided emissions were derived by comparing the pre- and post-renovation energy demand for each building and applying the corresponding emission factors.

A building-level comparison determined how each modeling approach influenced CO₂ reduction estimates. The static model generally predicted higher avoided emissions due to its overestimation of baseline energy demand and energy savings post-renovation. The dynamic model, in contrast, accounted for real-time variations in energy performance, resulting in more realistic and conservative CO₂ reduction estimates.

2.4. Methodology for Financial Analysis of Incorrect Simulations

The financial implications of incorrect energy predictions were analyzed using a pay-back period comparison between static and dynamic models. The methodology involved a break-even analysis, investment optimization, and visualization of financial impacts.

A break-even analysis was performed to determine at what point overestimated energy savings would lead to financial losses. The financial feasibility of energy efficiency measures was evaluated based on investment costs, energy cost savings, and annual financial returns. The renovation cost was set at 300 EUR/m², based on publicly available construction cost databases, industry reports, and already implemented energy renovation projects in Slovenia [40]. Given that renovation costs can fluctuate based on regional and economic factors, a sensitivity analysis was conducted to assess how variations in investment costs influence financial viability. Energy cost savings were calculated using actual energy prices, with electricity priced at 0.168 EUR/kWh for Buildings Id-2, Id-3, and Id-5, while heating oil (Buildings Id-1 and Id-4) was valued at 1132 EUR per 1000 L and converted into EUR/kWh. The payback period was determined by dividing total investment costs by annual cost savings, with a threshold of 15 years set as the acceptable limit for cost-effective investments.

To assess how dynamic modeling improves cost-effectiveness, projected payback periods under static and dynamic models were compared. Overestimated returns in static models often led to misallocated resources and unrealistic investment expectations. The long-term feasibility of renovations was particularly analyzed in buildings with significant renovation costs.

A comparative payback period analysis was conducted to illustrate the financial implications of incorrect simulations. The results were visualized using bar charts comparing static and dynamic model predictions, with the 15-year payback threshold marked to highlight financially viable and unviable investments. The financial analysis demonstrated that static models consistently underestimate payback periods, leading to overly optimistic investment decisions. In contrast, dynamic models provided a more accurate projection, ensuring that resources were allocated efficiently to projects with the highest energy savings and economic impact.

This methodology ensures that CO₂ reduction estimates and financial feasibility assessments align with realistic performance expectations, enabling better decision making in energy efficiency investments.

3. Results and Discussion

3.1. Findings on U-Value Compliance and Performance

The analysis of U-values for external walls, windows, roofs, and ground-contact floors provides key insights into compliance and performance trends. Table 4 summarizes the average U-values for each building envelope component, along with their compliance with the PURES 2010 and PURES 2022 thresholds. The average U-value for external walls is 0.205 W/m²K, indicating strong alignment with PURES 2010 standards (≤ 0.28 W/m²K). Most projects have U-values between 0.17 W/m²K and 0.24 W/m²K, but only a smaller portion meets the stricter PURES 2022 requirement (≤ 0.18 W/m²K). The distribution of U-values for external walls is relatively narrow, with only a few projects exceeding the upper standard limits. Similarly, the average U-value for windows is 1.087 W/m²K, demonstrating compliance with PURES 2010 (≤ 1.30 W/m²K) in most cases. However, adherence to the stricter PURES 2022 requirement (≤ 1.00 W/m²K) is less consistent, as window U-values range widely from 0.15 W/m²K to 1.50 W/m²K, reflecting variability in insulation quality and performance.

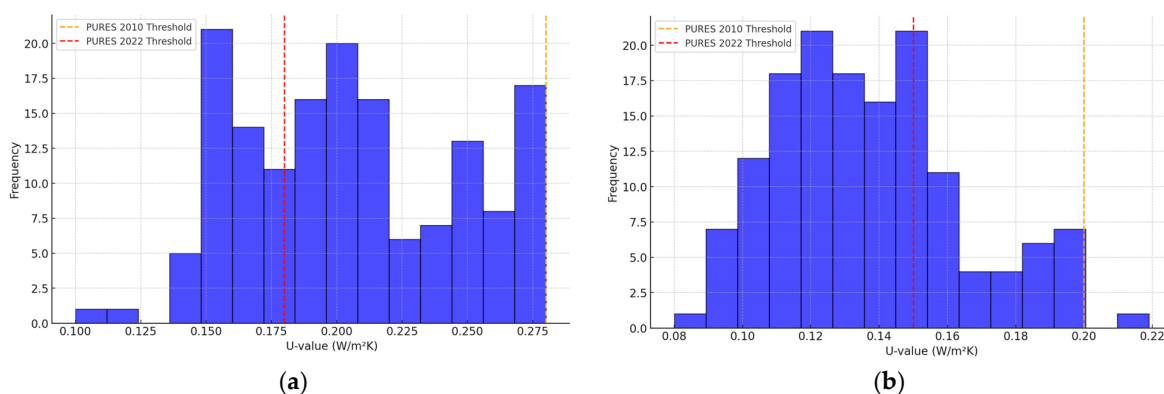
Table 4. Summary of U-values and compliance with PURES standards.

Building Component	Average U-Value [W/m ² K]	PURES 2010 Limit [W/m ² K]	PURES 2022 Limit [W/m ² K]	Compliance Observation
Façade	0.205	0.28	0.18	Partial compliance, requires additional retrofits
Windows	1.087	1.30	1.00	High variability, inconsistent compliance with PURES 2022
Roof	0.136	0.20	0.15	Strong compliance across most projects
Floors	0.259	0.30	0.35	Generally compliant, though some projects exceed thresholds

For roofs, the average U-value is 0.136 W/m²K, ensuring that the vast majority of projects comply with both PURES 2010 (≤ 0.20 W/m²K) and PURES 2022 (≤ 0.15 W/m²K). Most roof U-values range between 0.12 W/m²K and 0.15 W/m²K, indicating well-optimized thermal insulation. Ground-contact floors, with an average U-value of 0.259 W/m²K, generally meet PURES 2022 requirements (≤ 0.35 W/m²K), which are slightly more lenient compared to PURES 2010 (≤ 0.30 W/m²K). However, the U-value range for floors is broader, with some projects exhibiting very low values indicative of high-performance insulation, while others remain near the upper standard limits.

The distribution of U-values for each building envelope component is further illustrated in Figures 1 and 2. The analysis highlights varying degrees of compliance with PURES 2022 standards. While many projects demonstrate significant reductions in U-values, aligning with stricter efficiency requirements, certain building envelope components still fail to meet optimal insulation performance. External walls exhibit the highest compliance rates, as they are often prioritized in renovation projects. In contrast, roof and window upgrades show greater variability, with some buildings struggling to achieve required insulation levels. Floor insulation improvements are observed less frequently, suggesting that this aspect is often overlooked in retrofit strategies.

Overall, the findings indicate that projects completed under PURES 2010 will require additional upgrades to meet current energy efficiency targets. The variation in implementation strategies underscores a lack of standardization in renovation measures, contributing to performance gaps between expected and actual energy savings. Ensuring consistent adherence to updated insulation standards will be essential for achieving long-term sustainability and maximizing energy efficiency improvements in renovated buildings.

**Figure 1.** Distribution of U-values for building envelope components: (a) external walls; (b) roofs.

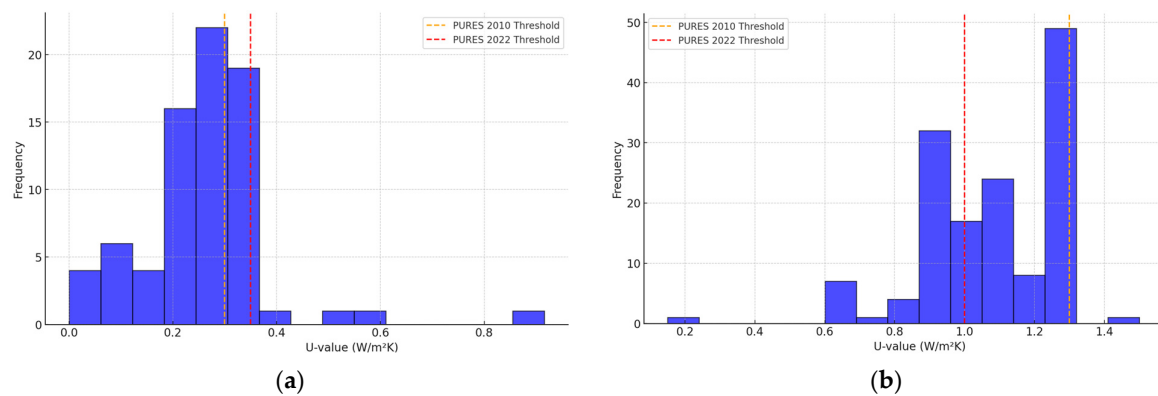


Figure 2. Distribution of U-values for building envelope components: (a) floors; (b) windows.

Figure 3 presents a boxplot visualization of the U-values for key building envelope components, including external walls, windows, roofs, and floors. The boxplots display the spread, central tendency, and variability of U-values across different building elements, offering insights into the overall performance and compliance of renovations.

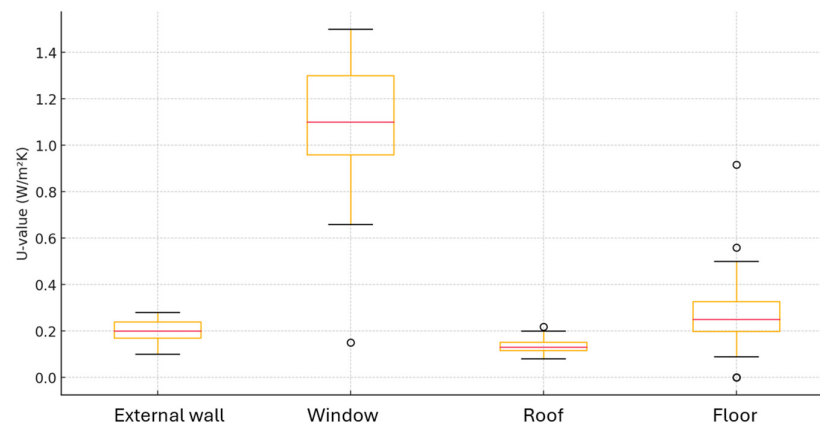


Figure 3. Boxplot of U-values for building elements.

The U-values for external walls are relatively low, with a narrow interquartile range (IQR), indicating consistent insulation performance. Most values fall well below the PURES 2010 thresholds, though a few outliers suggest minor deviations. Windows exhibit the highest U-values among all building elements, with a wider range and greater variability. The median U-value remains above the PURES 2022 requirement, indicating that window insulation improvements have not been as uniformly applied as for other elements.

The U-values for roofs are consistently low, with a tight distribution and minimal outliers. This suggests that roof insulation measures are generally effective and meet regulatory standards. Floor U-values show a moderate spread, with some extreme outliers indicating variability in insulation quality. While most projects meet regulatory requirements, certain cases display relatively high U-values, suggesting potential areas for improvement.

Overall, the boxplot highlights disparities in the insulation performance of different building elements. While external walls and roofs demonstrate strong compliance with energy efficiency standards, windows and floors exhibit greater variability, underlining the need for more targeted insulation measures in these areas.

3.2. Comparison of Energy Performance Predictions

3.2.1. Differences in Energy Consumption Estimates Between Static and Dynamic Models

The comparison of energy consumption estimates between static and dynamic simulation models highlights significant discrepancies in predicted primary energy use across

different building types. Static models, based on steady-state assumptions, offer simplified calculations that do not account for time-dependent factors such as fluctuating climate conditions, occupancy patterns, and internal heat gains. In contrast, dynamic models incorporate these variations, providing a more realistic representation of actual energy demand.

The results demonstrate a consistent overestimation of energy consumption in static models compared to dynamic simulations (Table 5). For instance, in primary schools, the static model predicts an average consumption of 75.0 kWh/m², whereas the dynamic model estimates 63.3 kWh/m², reflecting a 15.6% overestimation. The discrepancy is even more pronounced in office buildings, where the static model forecasts 32.3 kWh/m², while the dynamic model calculates 23.8 kWh/m², leading to a relative error of 26.3%. The largest deviation is observed in combined primary and secondary school buildings, with static models predicting 102.2 kWh/m², whereas dynamic simulations suggest 64.6 kWh/m², resulting in a 36.8% difference.

Table 5. Comparison of energy consumption estimates from static and dynamic models.

Building Code	Static Model [kWh/m ² a]	Dynamic Model [kWh/m ² a]	Absolute Error [kWh/m ² a]	Relative Error [%]
Id-1	75.0	63.3	11.7	15.6
Id-2	95.6	80.0	15.6	16.3
Id-3	32.3	23.8	8.5	26.3
Id-4	102.2	64.6	37.6	36.8
Id-5	115.2	86.1	29.1	25.3

These findings underscore the limitations of static modeling in accurately estimating energy consumption, particularly in buildings with complex operational schedules and diverse thermal loads. The reliance on steady-state calculations in static models leads to inflated primary energy use predictions, which can misguide energy efficiency planning and investment decisions. By contrast, dynamic simulations provide a more precise estimation, supporting better-informed strategies for optimizing building performance.

These results highlight the importance of incorporating dynamic modeling in energy performance assessments, as it offers a more accurate estimation of actual energy demand and helps in aligning renovation strategies with realistic efficiency targets.

3.2.2. Evaluation of Prediction Errors and Implications on Energy Efficiency Planning

The predictive error analysis performed highlights the limitations of static models in accurately reflecting actual energy performance. The Mean Absolute Percentage Error (MAPE) across all building types is calculated at 24.06%, indicating a significant deviation between static model estimates and more precise dynamic simulations.

Buildings with higher energy consumption, such as primary and secondary schools, show larger relative errors, suggesting that static models tend to overpredict energy demand in these cases. On the other hand, office buildings exhibit substantial deviations, with static models predicting considerably higher energy use than that observed in dynamic simulations. Such discrepancies can lead to suboptimal energy efficiency planning, where overestimation may result in excessive investments in insulation and HVAC systems without proportionate energy savings, while underestimation could lead to inadequate efficiency measures and increased operational costs.

To enhance planning accuracy, a hybrid approach that integrates real-time data calibration with dynamic modeling techniques is recommended. This method would help in

better aligning energy efficiency investments with actual building performance, ensuring optimal resource allocation and sustainability target.

Figure 4 illustrates the probability density functions (PDFs) of heating energy demand predictions for the five analyzed buildings (SI-01, SI-02, SI-03, SI-05, and SI-08) using two calculation methods: the static monthly method (ISO 13790) and the dynamic simulation method (IDA ICE). Each building is represented by two curves: the solid lines correspond to static model predictions, while the dashed lines depict results from the dynamic model.

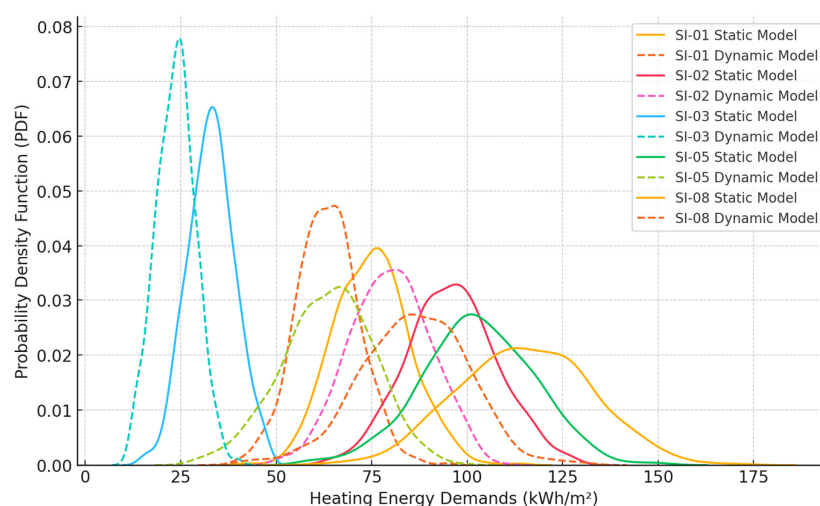


Figure 4. Probability density function (PDF) of heating energy demand predictions for individual buildings.

The results reveal that the static model systematically overestimates heating energy demand compared to the dynamic simulation, with its distributions consistently shifted toward higher values. This overestimation is most pronounced for SI-05 (a combined primary and secondary school) and SI-08 (a primary school), where the static model predicts significantly higher heating demand than the dynamic model. The discrepancy is attributed to the steady-state assumptions in the static model, which fail to capture transient effects such as internal heat gains, occupant behavior, and real climate variations.

The variability of heating energy demand predictions also differs between the two models. The dynamic simulation produces broader distributions for all buildings, reflecting a greater sensitivity to operational and environmental variations. This contrasts with the narrower peaks in the static model, which assumes averaged climate conditions and standard usage patterns. The largest variability is observed in SI-05, indicating that dynamic modeling provides a more nuanced assessment of heating demand for complex buildings with mixed-use spaces.

These findings highlight the limitations of relying solely on static models for energy performance assessments, as they may lead to over-dimensioned heating systems and inaccurate energy savings estimates. By incorporating transient effects, dynamic simulations offer a more realistic evaluation of building energy performance, leading to better-informed energy efficiency strategies and investment decisions.

3.3. Impact on CO₂ Emission Reductions

The impact of different energy modeling approaches on CO₂ emissions was assessed by comparing avoided emissions from the static monthly method and the dynamic simulation method. Using the estimated heating energy demands and emission factors of 0.27 kg CO₂/kWh for Buildings Id-1 and Id-4, and 0.235 kg CO₂/kWh for Buildings Id-2, Id-3, and

Id-5, the total avoided emissions were calculated based on each building's conditioned floor area.

The results indicate that the static model tends to overestimate avoided emissions, as it assumes higher baseline energy consumption. Across all analyzed buildings, the absolute difference in CO₂ emissions between static and dynamic models varied significantly. For instance, Building Id-4 (a school) exhibited the highest discrepancy, with a total annual CO₂ reduction of 25,654 kg CO₂/year, while Building Id-3 (an office building) showed a smaller reduction of 1,208 kg CO₂/year. The largest elementary school, Id-5, achieved 27,196 kg CO₂/year in reductions, whereas the health center (Id-2) reached 13,307 kg CO₂/year. These findings suggest that static models may exaggerate potential decarbonization benefits, leading to the potential misallocation of resources in energy efficiency planning.

The reliance on static models for CO₂ emission reductions raises concerns about their alignment with long-term decarbonization goals. Since static models consistently overestimate energy savings, they may create an unrealistic perception of progress toward net-zero targets. The dynamic model, by integrating real-world operational conditions and transient effects, provides a more reliable estimation of CO₂ reductions.

By ensuring that projected CO₂ savings align with actual energy performance, dynamic simulations enable policymakers and stakeholders to make data-driven decisions regarding building retrofits. This helps in optimizing investments, ensuring that decarbonization efforts are targeted effectively.

3.4. Financial Implications of Incorrect Simulations

The financial break-even point in energy efficiency investments is crucial for ensuring that projected savings align with actual performance. The analysis compares static and dynamic energy modeling approaches to assess when incorrect predictions lead to financial losses. Static models often overestimate savings, resulting in shorter projected payback periods than what is realistically achievable. This misalignment can lead to situations where investments that appear viable under static assumptions fail to reach profitability when real energy performance is accounted for.

For example, in Building Id-4, the static model predicts a payback period of ~65 years, while the dynamic model suggests much longer at ~105 years. This indicates that an investment decision based on static modeling alone could result in a financially unfeasible project, where energy savings are insufficient to recover the investment cost within an acceptable timeframe. Similarly, while Buildings Id-2 and Id-3 show acceptable payback periods under both models, the static approach still overestimates energy savings, making the return on investment appear more favorable than it is in practice.

Figure 5 compares the payback periods for static and dynamic models across different buildings. The red bars represent static model predictions, while the blue bars show the dynamic model results. The dashed gray line represents the 15-year payback threshold, which is commonly used as an acceptable limit for energy efficiency investments.

The visualization clearly demonstrates how static models consistently underestimate payback periods, making projects appear more financially viable than they actually are. The discrepancy is especially large in projects with long-term energy savings assumptions, such as Id-4, where the static model fails to capture the real performance limitations.

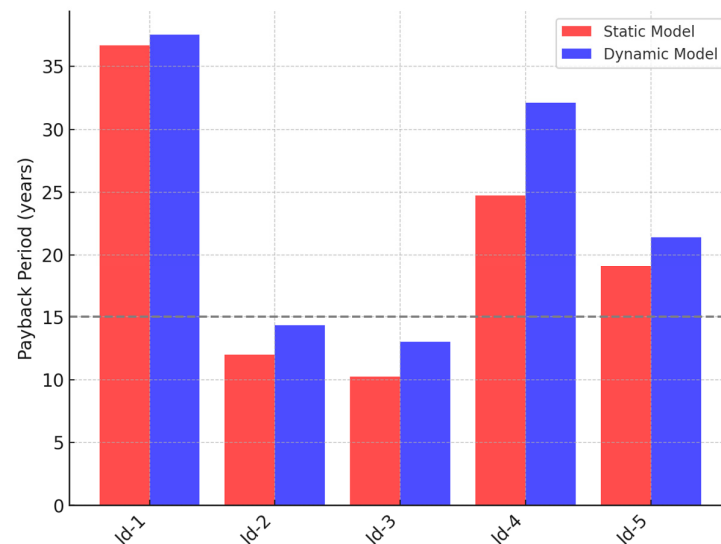


Figure 5. Comparison of payback periods: static vs. dynamic models.

This analysis underscores the importance of using dynamic modeling for investment decision making, ensuring that financial risk is minimized and return expectations are based on realistic performance outcomes.

Dynamic modeling provides a more realistic assessment of energy performance, reducing the risk of overestimated savings and ensuring that financial investments in energy retrofits are cost-effective. By integrating hourly energy demand variations, internal heat gains, and actual occupancy patterns, dynamic simulations produce more accurate predictions of actual energy savings and financial returns. This prevents the common overinvestment in energy efficiency measures that do not yield proportional savings.

In cases like Id-1 and Id-5, the dynamic model predicts longer payback periods than the static model, but these projections are more aligned with real-world performance. This allows decision-makers to prioritize cost-effective investments, ensuring that capital is allocated efficiently to projects with the highest impact on both energy savings and financial returns.

The sensitivity analysis of investment costs and their impact on the payback period provides critical insights into the financial feasibility of energy renovation projects under varying cost conditions. The results, as illustrated in Figure 6, demonstrate that fluctuations in renovation costs significantly influence the economic viability of energy efficiency investments.

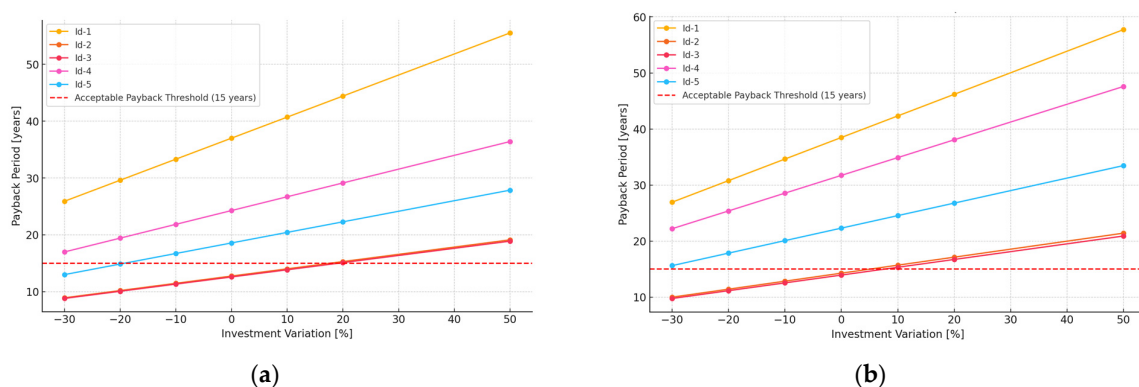


Figure 6. Sensitivity analysis of investment costs vs. payback period: (a) static simulation; (b) dynamic simulation.

The analysis reveals that increasing investment costs by 50% extends the payback period considerably, causing several buildings to exceed the commonly accepted 15-year threshold for cost-effective investments. Conversely, a reduction of 30% in investment costs improves the financial feasibility of most renovation projects, allowing them to meet or fall below the acceptable payback period. This finding underscores the importance of cost control in energy renovation strategies, as even minor variations in investment expenditures can determine whether a project remains financially viable.

A comparison between static and dynamic simulation results highlights notable differences in sensitivity to cost variations. Static simulation models exhibit a more stable payback period across different investment levels, whereas dynamic models demonstrate greater fluctuations. This disparity suggests that static models, which rely on simplified assumptions, may underestimate the financial risks associated with energy efficiency projects by failing to capture operational energy variations accurately. The dynamic simulations, which account for hourly energy demand fluctuations, emphasize the necessity of using more refined methodologies for financial evaluations.

Furthermore, an important factor influencing investment cost feasibility is inflation, which can significantly affect both renovation costs and energy price trajectories over time. Inflationary pressures on construction materials, labor, and technology costs can increase renovation expenses, further extending the payback period beyond initial projections. Conversely, inflation-driven increases in energy prices may accelerate the return on investment for energy efficiency improvements by enhancing the value of avoided energy costs. This dynamic interaction suggests that incorporating inflation-adjusted financial models could improve the accuracy of economic assessments for energy renovations.

Building-specific findings further reinforce these observations. Buildings Id-2 and Id-3, which underwent significant renovation measures, maintain stable payback periods across different cost scenarios, remaining within the 15-year threshold in most cases. In contrast, Buildings Id-1 and Id-4, which rely on heating oil-based systems, display high sensitivity to cost fluctuations, with payback periods extending beyond 30 years in certain scenarios. This suggests that without additional financial support or policy incentives, deep renovations for these buildings may not be economically justifiable. Meanwhile, Building Id-5, which integrates renewable energy systems, exhibits relatively strong financial performance but remains susceptible to cost variations, highlighting the need for additional financial mechanisms to support renewable energy adoption.

From a policy and investment perspective, these findings emphasize the necessity of financial incentives and support mechanisms to enhance the economic feasibility of large-scale energy renovations. Given that high investment costs can lead to extended payback periods, financing schemes such as subsidies, low-interest loans, and performance-based incentives could mitigate financial risks for building owners. Additionally, the analysis underscores the importance of incorporating dynamic simulation models and inflation-adjusted cost projections in economic assessments, as traditional static models may overestimate cost-effectiveness and underestimate financial risks.

Overall, the sensitivity analysis underscores the critical role of cost assumptions in determining the viability of energy renovations. While energy efficiency improvements offer long-term benefits in terms of CO₂ reduction and operational savings, their economic success is contingent on investment cost structures, inflationary trends, and financing conditions. Future research should explore the integration of incentive mechanisms, alternative financing models, and inflation-adjusted economic assessments to ensure that energy renovation projects remain financially sustainable in varying economic conditions.

4. Conclusions

This study critically evaluated the preparedness of renovated buildings in achieving the 2050 decarbonization goals by assessing their adherence to current energy performance standards and their potential for further optimization. The findings from Section 3.1 underscore a significant divergence in compliance, where the majority of renovated buildings align with PURES 2010 standards, yet a substantial proportion fail to meet the more stringent PURES 2022 requirements, particularly in terms of window insulation. This variation in compliance suggests that additional retrofit interventions are imperative to elevate the thermal performance of these structures, ensuring their viability in a low-carbon future.

The U-value analysis performed further highlights disparities in compliance across different building envelope components. While external walls and roof insulation generally exhibit good adherence to regulatory standards, windows and floor insulation emerge as the weakest elements in thermal performance. A significant proportion of buildings fail to meet the stricter PURES 2022 U-value thresholds for windows, which remain a persistent source of heat loss. Additionally, floor insulation improvements have been less frequently implemented, despite their considerable impact on reducing energy demand. These inconsistencies underline the necessity for stricter regulatory oversight, targeted financial incentives, and the adoption of best practices to ensure the uniform implementation of energy efficiency measures across all building components.

Despite advancements in thermal insulation, disparities persist in the effectiveness of renovation measures. Floor and window insulation remain critical areas requiring enhanced retrofitting approaches to mitigate heat losses and improve overall energy efficiency. Although many building envelopes exhibit near-compliance with PURES 2022, the observed inconsistencies in renovation quality highlight the necessity for enhanced regulatory enforcement, financial incentives, and the adoption of standardized best practices to ensure the uniform implementation of energy efficiency measures.

The application of dynamic simulations has provided deeper insights into the limitations of current renovation strategies. The comparative analysis between static and dynamic modeling approaches reveals a systematic overestimation of energy savings in static models, which can lead to suboptimal investment decisions and inefficient policy planning. By incorporating transient thermal behaviors, occupancy variations, and recorded historical climate interactions, dynamic simulations offer a more precise prediction of energy consumption patterns. This, in turn, enables a more effective allocation of resources and better-informed decision-making processes in building renovations. However, while dynamic simulations provide a higher level of accuracy, their widespread adoption faces challenges due to higher computational demands, increased modeling complexity, and the need for extensive input data. These practical barriers often hinder their use in smaller-scale renovations, limiting their feasibility across different stakeholder groups.

The financial analysis performed further underscores the implications of inaccurate energy performance estimations. The sensitivity analysis of investment costs carried out demonstrates that variations in renovation expenses significantly impact financial feasibility, with higher costs leading to extended payback periods. Static models frequently predict shorter payback periods, potentially leading to unrealistic investment expectations and the suboptimal allocation of financial resources. Conversely, dynamic modeling provides a more rigorous economic assessment, ensuring that energy efficiency investments are optimized by aligning financial projections with real-world energy savings. These findings reinforce the necessity of integrating dynamic simulation models into financial assessments to enhance the reliability of economic evaluations. Additionally, a hybrid approach that combines static modeling efficiency with key dynamic elements may offer a practical and scalable solution, balancing accuracy with usability in real-world applications.

Furthermore, the discrepancies between static and dynamic models impact various stakeholders differently. Homeowners, contractors, and policymakers each face unique challenges in adopting advanced simulation methodologies. For homeowners, the initial cost and complexity of dynamic modeling can deter its application in smaller projects. Contractors may require additional training and technological resources to effectively implement such models. Policymakers, on the other hand, play a crucial role in incentivizing the adoption of data-driven decision-making tools to improve long-term energy performance assessments.

In conclusion, while considerable strides have been made in enhancing the energy performance of renovated buildings, the current trajectory suggests that additional policy refinements, technological advancements, and regulatory enforcements are required to bridge the gap between projected and actual energy savings. Future efforts should prioritize the integration of advanced simulation methodologies into compliance frameworks, the enhancement of data-driven monitoring systems, and the promotion of holistic energy renovation strategies that align with long-term climate neutrality objectives. Furthermore, the sensitivity analysis highlights the necessity of cost-effective investment planning, emphasizing the role of targeted financial incentives and adaptive policy mechanisms in supporting deep energy renovations. Additionally, addressing the practical challenges of dynamic modeling adoption and exploring hybrid modeling approaches will be key to improving the accuracy and feasibility of energy performance assessments. Only through these comprehensive measures can the built environment be effectively transformed to meet the ambitious 2050 decarbonization goals, ensuring a sustainable and resilient future for the sector.

Funding: This research was partially funded by LIFE IP CARE4CLIMATE (LIFE17 IPC/SI/000007) and H2020 TIMEPAC (GA Nr. 101033819).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: Boris Sučić, Rajko Leban, and Boštjan Mljač.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BIM	Building Information Modeling
BEM	Building Energy Model
BPS	Building performance simulation
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
ESCO	Energy Services Company
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air conditioning
LED	Light-emitting diode
nZEB	Nearly zero-energy buildings
PURES	Rules on efficient use of energy in buildings
PV	Solar photovoltaic
ZEB	Zero-emission buildings

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