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Analysis of Green Building Incentives on Thermal Comfort and Cost-Effectiveness: The Cases of Italy and Türkiye

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Abstract

Public buildings play a critical role in national decarbonization strategies and green energy transitions due to their high energy consumption densities, large occupant capacities, and potential to drive public awareness. Optimizing energy efficiency in these structures not only alleviates the financial burden on public budgets but also serves as a benchmark for sustainable urban development. To investigate the energy-saving potentials, thermal comfort dynamics, and financial feasibilities within this sector, this study selects two university buildings from two different countries with distinct climatic, structural, and operational profiles as comparative case studies: university buildings in Türkiye (TR) and Italy (IT), respectively. A total of seven tailored retrofitting scenarios were developed based on country-specific legislative frameworks and subsidy mechanisms: the Minimum Environmental Criteria (CAM) and Conto Termico 3.0 for Italy, and the Public Buildings Energy Efficiency Project (KABEV), Energy Performance Contracting (EPC), and Nearly Zero Energy Buildings (NSEB) mandates for Türkiye. The scenarios evaluate deep building envelope insulation, high-efficiency window replacements, lighting automation (LED with daylighting controls), mechanical ventilation with heat recovery units (HRV), air-to-water heat pump integrations, and rooftop photovoltaic (PV) installations using calibrated DesignBuilder simulation models. The quantitative results demonstrate that country-specific green building incentives drastically enhance both the energy performance and financial viability of deep retrofits. For the Turkish case study, the comprehensive near-zero energy building (nZEB) retrofitting package (TR-4) successfully reduced annual primary energy consumption by 75% (from 284 to 71 kWh/m^2·year) and cut annual thermal comfort discomfort hours by 72% (from 3147 to 880 h), yielding a Subsidized Net Present Value (NPV) of +310,600 €. Similarly, for the Italian case study, the holistic retrofit combined with rooftop photovoltaic integration (IT-4) achieved an 80% energy reduction (dropping from 128 to 25.6 kWh/m^2·year), minimized annual discomfort hours to 45 h, and generated a Subsidized NPV of +425,500 €. Furthermore, national incentive mechanisms shortened simple payback periods by more than half, establishing that targeted public policy is vital to accelerate public sector building decarbonization while ensuring long-term fiscal profitability.

Keywords: public buildings; green building incentives; thermal comfort; cost-effectiveness; DesignBuilder; Subsidized NPV

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1. Introduction

Climate change and the continuous increase in greenhouse gas (GHG) emissions have become major global concerns, prompting countries to adopt ambitious decarbonization policies across all sectors [1,2]. Among these sectors, buildings play a central role, accounting for approximately 40% of global final energy consumption and 36% of energy-related carbon dioxide emissions [3]. As a result, improving the energy performance of existing buildings has become a key component of national and international sustainability strategies. Public buildings, particularly educational facilities and university campuses, deserve special attention because of their intensive energy use arising from extended operating hours, high occupancy levels, and significant heating, ventilation, air-conditioning (HVAC), and lighting demands [4,5]. Consequently, the energy-efficient renovation of public buildings has evolved from an environmental objective into a strategic priority for achieving long-term climate targets [6].

Despite its importance, improving the energy performance of university buildings remains a complex challenge that requires balancing energy efficiency, occupant comfort, and economic feasibility [7–9]. Educational buildings must provide acceptable indoor environmental quality (IEQ), as thermal comfort has a direct influence on students' learning performance, staff productivity, and overall occupant well-being [10]. However, many university buildings suffer from aging envelopes, inefficient HVAC systems, and inadequate ventilation, resulting in excessive energy consumption and poor indoor conditions [11,12]. Although deep energy retrofits can substantially reduce energy use intensity (EUI) while improving thermal comfort, these interventions typically require considerable capital investment. For public universities operating under limited annual budgets, the high initial costs often constitute the primary obstacle to implementing comprehensive retrofit projects.

To overcome these financial barriers, many governments have introduced incentive mechanisms and regulatory frameworks that encourage investments in energy-efficient renovations [13–18]. In Italy, public building renovations are supported through the Minimum Environmental Criteria (CAM) and the Conto Termico 3.0 incentive scheme, which provides grants covering a substantial portion of eligible retrofit costs [19,20]. Similarly, Türkiye has strengthened its public building decarbonization policies through initiatives such as the Public Buildings Energy Efficiency Project (KABEV), Energy Performance Contracting (EPC) models implemented by Energy Service Companies (ESCOs), and the gradual adoption of Nearly Zero Energy Building (NZEB) requirements [21–23]. Although Italy and Türkiye share similar Mediterranean climatic characteristics, differences in regulatory frameworks, energy-pricing structures, building standards, and financial support mechanisms create distinct conditions for planning and implementing energy retrofit projects.

Previous studies have extensively investigated building energy retrofits using building performance simulation or economic assessment methods. However, relatively few studies have examined how different national incentive schemes influence both the technical and economic performance of retrofit strategies under comparable conditions. Most existing research focuses either on maximizing energy savings through building simulations or on evaluating financial feasibility independently, without simultaneously considering indoor thermal comfort improvements and country-specific financial incentives. Moreover, comparative analyses between European Union member states and candidate countries with evolving regulatory systems remain limited, particularly for public educational buildings [24,25].

To address this research gap, the present study comparatively evaluates the technical, environmental, and economic performance of building retrofit strategies under the incentive mechanisms implemented in Italy and Türkiye. Two representative university buildings were selected as case studies: a university building in Calabria (Italy) and the

Faculty of Law in a university in Ankara (Türkiye). These buildings represent different construction periods, envelope characteristics, and HVAC operating conditions. While the Turkish case is characterized by continuous heating demand associated with an older and less insulated building envelope, the Italian case exhibits a more balanced heating and cooling profile that reflects the climatic conditions of southern Italy. Building energy performance was assessed using empirically calibrated DesignBuilder simulation models [26]. A comprehensive set of retrofit scenarios was developed, including improvements to the building envelope, window systems, HVAC technologies, lighting systems, and rooftop photovoltaic installations. The impacts of these measures were evaluated in terms of primary energy consumption and indoor thermal comfort using Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) indices. In addition, the economic feasibility of each retrofit scenario was assessed through a financial framework incorporating the Subsidized Net Present Value (NPVs) and Simple Payback Period (SPP), allowing the influence of national incentive programs on investment performance to be quantified.

The main contributions of this study are threefold. First, it proposes country-specific retrofit packages designed to comply with the Italian CAM framework and the Turkish NZEB requirements. Second, it provides a comprehensive evaluation of the combined effects of retrofit measures on energy consumption, thermal comfort, and environmental performance. Third, it demonstrates how public incentive mechanisms significantly affect the economic viability of deep energy renovations by reducing investment costs and shortening payback periods. The proposed framework provides practical guidance for policymakers, university administrators, and building energy professionals seeking to prioritize retrofit investments under different regulatory and financial environments. Furthermore, the comparative approach adopted in this study offers transferable insights for other countries aiming to improve the sustainability of public educational buildings while balancing technical performance, occupant comfort, and economic feasibility.

Lastly, it should be noted that the scope of this study focuses on two specific university buildings located in Italy and Türkiye, serving as representative archetypes of public educational infrastructure rather than exhaustive samples of the entire national public building stock. Higher education facilities were strategically selected as case studies due to their intensive occupancy patterns, high thermal energy demands, and complex operational schedules, which mirror the broader challenges faced by public educational portfolios in the Mediterranean region. While the comparative optimization framework and policy evaluation methodology are transferable to other public sectors, the quantitative results reflect the specific architectural configurations and operational baselines of the selected institutions. Therefore, broad generalizations to all public building typologies are avoided, and the findings are interpreted within the context of targeted educational building retrofits under national incentive schemes such as Conto Termico 3.0 and KABEV. Moreover, although the comparative assessment focuses on two specific university buildings in Italy and Türkiye, these educational facilities serve as ideal archetypes for evaluating public building decarbonization due to several distinct structural and operational advantages. Unlike generic administrative public buildings characterized by standard daytime office hours and low occupant densities, university buildings exhibit complex, highly dynamic occupancy schedules, intensive thermal loads, and diverse functional zones (e.g., lecture halls, offices, and laboratories). These characteristics create severe thermal comfort vulnerabilities and high energy intensities. Furthermore, higher education institutions in both countries are typically managed under centralized public administration frameworks with large asset portfolios, allowing them to act as leading pioneers for national policy instruments such as Conto Termico 3.0 and KABEV. Consequently, while these case studies do not represent the entirety of the diverse public building stock, their complex operational

profiles provide a robust, representative baseline to test the transferability of the proposed energy performance and economic evaluation framework without overgeneralizing to simpler public typologies.

2. Materials and Methods

2.1. Case Buildings

To perform a rigorous comparative assessment of life-cycle carbon behaviors and retrofitting optimization pathways under different national incentive schemes, two representative educational structures located in distinct climate zones and architectural generations were selected as dual case studies (Figure 1).



Figure 1. Locations of the case studies.

2.1.1. Building TR

The Turkish case study (Building TR) focuses on a substantial public educational facility situated within the capital city of Ankara, a region characterized by a temperate, semi-arid continental climate (Koppen–Geiger Dsa classification) featuring severe, dry winters and hot, arid summer periods [27,28]. Built in 2009, this modern multi-story complex comprises a gross floor area of 13,572 m^2 and serves an active institutional density of 1389 students (Figure 2). The spatial configuration is highly heterogeneous, containing lecture theaters, administrative offices, a library, student club workshops, an extensive conference hall, and a central cafeteria space operating on erratic academic schedules. The baseline building envelope reflects the localized thermal regulations of its construction era. The external wall assemblies have a total thickness of 0.282 m, consisting of an interior plaster finish (0.02 m), extruded polystyrene (XPS) insulation (0.05 m), core concrete blocks (0.20 m), and an outer cement board cladding (0.012 m), yielding a high overall thermal transmittance (U) wall of 2.41 W/m^2K. The transparent elements are composed of standard double-glazed window units with a thermal transmittance (U) window of 2.66 W/m^2K. In terms of active building services, space heating is continuously supplied 24/7 during the winter season (November to May) to accommodate ongoing security and administrative presence. The system relies on a central natural gas-fired boiler that distributes hot water

to terminal radiators to maintain a constant indoor heating set-point temperature of 22 °C. Conversely, the facility lacks any mechanical air-conditioning infrastructure; cooling and ventilation during the summer period (May to October) are managed entirely through manual window adjustments by the occupants. The architectural infiltration rate representing the air-tightness of the building shell is established at 0.7 air changes per hour (ac/h). To maintain strict computational consistency across the comparative framework, the dynamic energy simulations isolate the high-density classroom zones, which encompass a total analyzed floor area of 2629 m^2.



Figure 2. Case building in Türkiye (Building TR).

2.1.2. Building IT

The Italian case study (Building IT) examines an older academic building located at the University of Calabria in Cosenza, situated within the southern Mediterranean climate zone (Koppen-Geiger Csa classification), which experiences mild, rainy winters and hot, sun-exposed summers [27,29]. Constructed in the 1970s, this heavy structural archetype exhibits a compact, cubic geometry composed of six levels over a gross floor area of 2337.56 m^2 (Figure 3). The ground level is dedicated to research laboratories and storage, the first floor contains three primary lecture halls and student study spaces accommodating a capacity of 257 students, the second level hosts executive meeting rooms, and the upper three stories contain academic offices. The perimeter envelope consists of uninsulated load-bearing reinforced concrete walls with a substantial total thickness of 0.516 m. The stratigraphic composition from the exterior to the interior layers features a solid concrete structure (0.30 m), an internal air cavity (0.10 m), a mineral fiber core (0.09 m), and a plasterboard finish (0.026 m), resulting in a baseline thermal transmittance (U) wall of 0.374 W/m^2K. The window configurations consist of aged double-glazed units with a thermal transmittance (U) window of 2.72 W/m^2K. The building operates strictly on weekdays from 09:00 a.m. to 05:00 p.m., and its climate control schedules match these hours. Space heating is provided via a centralized natural gas boiler operating at a regulatory indoor set-point temperature of 20 °C. Similar to the Turkish case, the classrooms possess no mechanical cooling infrastructure, relying on occupant-driven window operation during warm periods. However, the Italian structure features a dedicated mechanical fresh-air ventilation system that delivers a constant outdoor air flow rate of 0.011 m^3/s per person, while the background structural infiltration rate is rated at 0.5 ac/h. Following the same

zoning constraints as the Turkish model, the simulation domain is restricted to the main classroom zones, comprising a total evaluated surface area of 412.31 m^2.



Figure 3. The Italian case study building (Building IT).

2.2. Main Green Building Incentives for Italy and Türkiye

The energy-efficient retrofitting of public buildings requires substantial financial budgets and long-term strategic planning. To alleviate the financial burden incurred during building renovations and to achieve national and international decarbonization targets, Italian and Turkish public institutions, including central and local administrations, universities, schools, and hospitals, leverage various grants, subsidies, performance-based financing models, and mandatory regulatory mechanisms [19–23].

2.2.1. Italy

In Italy, improving the energy efficiency of public buildings and integrating renewable energy sources is built upon a three-pillar framework consisting of direct grants, centralized financing programs, and mandatory green procurement standards. The most dynamic financial incentive mechanism implemented in Italy to enhance energy efficiency and promote the adoption of thermal and electrical renewable energy in public buildings is the Conto Termico 3.0 program [20]. Managed by Gestore dei Servizi Energetici (GSE), this program provides direct grant support to universities, municipalities, regions, public healthcare institutions, and third-sector organizations operating public services. The program provides grants covering 40% to 65% of eligible project costs for standard energy efficiency investments, such as building envelope insulation, window replacements, LED retrofits, Building Management System (BMS) automation, and heat pump integration. For projects aiming to transform an existing building into a Nearly Zero Energy Building (NZEB) standard, this rate is directly applied as 65%. On the other hand, the support reaches a 100% full grant rate for buildings belonging to small municipalities with populations under 15,000, as well as critical public facilities such as schools and hospitals. To facilitate investments, the program covers 100% of the expenses for energy audits (Diagnosi Energetica) and the preparation of Energy Performance Certificates (APE). Furthermore, the "Incentive Reservation" (Prenotazione) system introduced for public institutions allows entities to apply to GSE before starting the investment to reserve the budget and receive an advance payment at the beginning of the project. Investments can be executed directly by

the institution or managed through an Energy Service Company (ESCo) under an Energy Performance Contract (EPC). Additionally, Conto Termico 3.0 supports the inclusion of public buildings within Renewable Energy Communities (CER), offering extra incentives if the surplus electricity generated by rooftop PV systems is shared with community members.

The Programma per la Riqualificazione Energetica degli edifici della Pubblica Amministrazione Centrale (PREPAC) is a national decarbonization program specifically targeting buildings owned by the central public administration, such as ministries and central administrative facilities [30]. Shaped by legislative decrees issued in line with the EU Energy Efficiency Directive, the implementation period of this program has been extended until 2030.

The primary objective of PREPAC is to ensure that at least 3% of the total conditioned floor area owned by the central administration is renovated annually, with a focus on energy efficiency. Coordinated by the Ministry of Environment and Energy Security (MASE) with the technical support of ENEA and GSE, the program can provide up to 100% financing for deep retrofit projects focusing on the building envelope, HVAC systems, and renewable energy.

Criteri Ambientali Minimi (CAM) is the core legal instrument of the Green Public Procurement (GPP) policy that mandates environmental sustainability in Italian public tenders [19]. Under the Italian Public Procurement Code, incorporating CAM criteria into technical specifications during new building construction or deep renovation processes of existing buildings is a legal requirement. CAM is a mandatory standard rather than a direct financing mechanism. Grounded in the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) of the building, this system mandates the use of low-carbon footprint and recycled materials, high indoor air quality, and water efficiency. The compliance of projects with CAM criteria represents a critical evaluation threshold for those seeking to benefit from financing programs such as Conto Termico 3.0 and PREPAC.

2.2.2. Türkiye

The approach to energy efficiency in public buildings in Turkey is based on a holistic and multi-layered policy framework comprising national savings targets, international financing projects, and performance-based alternative market models rather than a single grant program. The primary guiding and binding document for energy management in Turkish public buildings is the Presidential Circular No. 2023/15 published in 2023. Rather than being a financial incentive program, this regulation constitutes a legal obligation that sets a target of 30% energy savings by 2030 for all public institutions, particularly those with designated energy managers. This strategic target serves as the primary driving force compelling the public sector to allocate resources to green transformation projects and turn toward efficiency investments. Executed by the Ministry of Environment, Urbanization and Climate Change alongside the Ministry of Energy and Natural Resources, the World Bank-funded KABEV project is one of the largest investment programs in the transformation of the Turkish building stock [21]. Focusing specifically on central administration buildings such as university campuses, schools, and hospitals, the project generally provides 70% to 100% external financing through a mix of international loans and grants, depending on the specific building. KABEV funds comprehensive interventions targeting a minimum of 20% to 30% energy savings, including deep building envelope insulation, mechanical ventilation with heat recovery (HRV), lighting automation, heat pumps, and rooftop photovoltaic (PV) integration. Administered by the Ministry of Energy and Natural Resources, VAP is a grant program that contributes directly to the energy efficiency projects of public institutions and industrial enterprises. A direct state grant of approximately 30% is provided for energy

production and efficiency projects, including the modernization of heating, cooling, and ventilation systems as well as cogeneration or waste heat recovery.

The EPC/ESCo Model represents the most significant financial innovation eliminating initial investment budget constraints in public buildings [22]. Under a legal framework strengthened by Presidential Decree, the entire cost of technological transformation in public buildings, such as heat pump installations in university buildings, is undertaken by an Energy Service Company (ESCo). The public institution initiates the project with zero upfront cost, and the investment cost is repaid to the company over time through the energy savings guaranteed and legally registered post-implementation.

Renewable Energy Project in Public Areas (KAYEP) is another vital national support program with high project-based financing rates aimed at transforming public buildings into self-sufficient energy-producing structures, specifically targeting the installation of rooftop Solar Energy Systems (GES/PV) [31].

2.3. Incentive-Based Retrofitting Scenarios

Following the development and calibration of the baseline energy models, a series of comprehensive energy efficiency measures were formulated based on the prevailing national legislative frameworks and green building financial instruments in both countries. This section delineates the multi-tiered retrofitting scenarios tailored to harness specific state incentives, aiming to significantly reduce primary energy consumption and enhance the overall energy performance of the facilities while optimizing indoor thermal comfort.

2.3.1. Retrofitting Scenarios for Italy

To systematically evaluate the energy-saving potential of the Italian educational facility, various intervention packages were designed in accordance with national efficiency standards and subsidy guidelines.

Building Envelope Insulation in Compliance with the Italian Minimum Environmental Criteria (CAM) (IT-1)

The Italian Minimum Environmental Criteria (CAM) mandates a maximum external wall thermal transmittance (U value) of 0.28 W/m^{2}K for Climate Zone C (Zona C), where Cosenza is located. To bring the building envelope into strict compliance with this regulatory threshold and upgrade it from its baseline value of 0.374 W/m^{2}K, this study executed a targeted thermal retrofitting strategy. Specifically, the study upgraded the existing 0.09 m mineral fiber insulation layer by replacing it with a 0.14 m high-performance stone wool insulation layer (Rockwool, thermal conductivity of approximately 0.035 W/mK). This selected material is certified in accordance with CAM regulations, containing at least 15–20% recycled content to fulfill local sustainability criteria. Where full replacement of the original layer was technically unfeasible, we implemented an External Thermal Insulation Composite System (ETICS) incorporating the same CAM-compliant stone wool insulation onto the building envelope, thereby successfully lowering the overall thermal transmittance below the legal limit.

Conto Termico-Supported Window and Shading Upgrades (IT-2)

To mitigate the lack of active cooling infrastructure and the subsequent high risk of summer overheating in the Southern Italian climate conditions, high-efficiency transparent elements and external solar control devices were integrated under the Conto Termico 3.0 incentive framework, which provides capital grants covering 40% to 65% of the total eligible implementation costs. In the DesignBuilder modeling platform, the existing double-glazed configurations characterized by an unacceptably high thermal transmittance (U = 2.72 W/m^{2}K) and deficient solar heat gain regulation were extracted from the

Openings tab and replaced with either argon-filled double-glazed Low-E (4-12-4 mm) and specialized triple-glazed templates on the upper windows. This intervention successfully restricted the localized U-value boundary to a target range of 1.30 and 1.40 W/m^{2}K while optimizing the total solar energy transmittance (g-value) at approximately 0.40 to simultaneously leverage passive winter solar gains and exclude excessive summer radiation. Furthermore, localized architectural shading formations, including overhangs and functional louvres, were activated within the Shading sub-tab to shield the South-exposed classroom facades from extreme solar incidence, thereby driving a radical reduction in the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) thermal discomfort indices without necessitating mechanical refrigeration.

Conto Termico-Supported HVAC Retrofit (Heat Pump and Cooling Systems) (IT-3)

To replace the inefficient, fossil-fuel-based heating infrastructure and mitigate the absence of active cooling in the Italian case study, a high-efficiency air-to-water heat pump system was integrated into the building model under the Conto Termico 3.0 incentive framework, which subsidizes up to 65% of the total capital expenditure for public building interventions. In the DesignBuilder simulation environment, the existing conventional gas boiler configuration was decommissioned within the HVAC tab and replaced with a centralized electric heat pump template capable of simultaneous space heating and cooling operations. The performance parameters were calibrated to meet rigorous technical thresholds, specifying a minimum Coefficient of Performance (COP) of 4.1 for the heating cycle and an Energy Efficiency Ratio (EER) of 3.8 for the cooling cycle under nominal design conditions. To ensure accurate thermal zone dynamics, localized fan coil units with variable-speed control loops were deployed across the classrooms, and the operating schedules were synchronized with the official academic calendar and occupancy profiles. This mechanical upgrade effectively shifted the building's primary energy dependency toward renewable electricity, resulting in a substantial reduction in carbon emissions while systematically regulating the indoor operative temperature to maintain the Predicted Mean Vote (PMV) within the optimal thermal comfort range during both seasonal peaks.

Comprehensive Deep Retrofit with Rooftop Photovoltaic (PV) Installation (IT-4)

To achieve a near-zero energy building (nZEB) standard and maximize the on-site renewable energy fraction of the Italian case study, a comprehensive deep retrofit coupled with a rooftop photovoltaic (PV) array was implemented under the high-tier capital subsidies of the Conto Termico framework. In the DesignBuilder modeling environment, a high-efficiency monocrystalline silicon PV system was integrated via the Generation tab, precisely mapped onto the unobstructed roof surface with an optimized tilt angle of 30° facing South to maximize annual global horizontal irradiance capture. The inverter efficiency was set at a nominal 96%, and the total nominal power of the array was scaled to match the peak cooling and base electrical loads induced by the newly introduced HVAC infrastructure (IT-3). Within the comprehensive simulation runtime, this grid-connected generation loop was synchronized with the building's thermal zone schedules to prioritize self-consumption during school hours, effectively offsetting the primary energy consumption of the heat pump and auxiliary systems. By combining high-performance building envelope upgrades with decentralized solar generation, this deep retrofit intervention drastically drops the building's net carbon footprint, shifts the environmental profile toward carbon neutrality, and ensures a highly resilient energy performance index.

2.3.2. Retrofitting Scenarios for Türkiye

Deep Building Envelope Retrofit in Compliance with the Presidential Circular (TR-1)

To satisfy the strict 15% energy saving mandate dictated by the Turkish Presidential Circular for public buildings, a deep building envelope retrofit was developed for the Turkish case study within the DesignBuilder simulation platform. In the Construction tab, the existing uninsulated external wall layout, characterized by high thermal transmittance and extensive thermal bridging, was modified by integrating high-density rockwool insulation layers (k= 0.035 W/mK) onto the exterior facade, successfully lowering the overall U-value to meet the stringent requirements of the TS 825 thermal insulation standard [32]. Concurrently, the building's thermal boundary was sealed by upgrading the roof and ground floor insulation, while the highly inefficient single or old double-glazed windows were replaced with argon-filled, low-emissivity double-glazing configurations integrated into thermally broken PVC frames. These envelope interventions were specifically calibrated to minimize heating demand during the winter period and reduce the structural cooling load by restricting sensible heat gain through the building fabric. This comprehensive fabric upgrade establishes a robust thermal buffer, drastically lowering the building's baseline energy consumption and ensuring full alignment with national energy efficiency directives before the implementation of mechanical system upgrades.

LED Lighting Retrofit and Daylight Sensor Integration Supported by the Energy Efficiency Project for Public Buildings (TR-2)

To optimize internal heat gains and reduce building electricity consumption under the framework of the Energy Efficiency Project for Public Buildings (KABEV), a high-efficiency lighting retrofit was implemented for the Turkish case study. Within the lighting template of the DesignBuilder software (v7.0), the existing low-efficacy fluorescent fixtures (12 W/m^2 and 100 lux) were decommissioned and replaced with advanced solid-state LED luminaires characterized by a significantly reduced lighting power density (3.5 W/m^2 and 100 lux) while maintaining standard-compliant illuminance levels across all lecture halls and offices. To maximize energy savings from natural light, linear daylight control sensors were activated in the model's thermal zones, establishing a localized dimming loop that continuously adjusts artificial lighting output based on real-time solar irradiance passing through the building envelope. This control system effectively prevents unnecessary power draw during peak daylight hours, reducing internal sensible heat loads and the subsequent cooling demand, thereby aligning the building's electrical infrastructure with national public sector efficiency benchmarks.

Mechanical Ventilation and Heat Recovery Ventilation (HRV) Integration Supported by the Energy Efficiency Project for Public Buildings and Energy Performance Contracts (EPCs) (TR-3)

To guarantee optimal indoor air quality (IAQ) and mitigate ventilation-induced thermal losses in compliance with national energy targets, a mechanical ventilation system equipped with a high-efficiency Heat Recovery Ventilation (HRV) unit was integrated into the Turkish building model under the dual framework of the Energy Efficiency Project for Public Buildings (KABEV) and Energy Performance Contracts (EPCs). In the DesignBuilder HVAC interface, the baseline natural ventilation model was replaced with a detailed mechanical ventilation loop configured to supply fresh air at a constant rate of 8 L/s per person, satisfying the strict requirements of the ASHRAE Standard 62.1 [33]. The integrated plate heat exchanger was calibrated with a nominal sensible heat recovery effectiveness of 78% and a latent effectiveness of 65%, enabling the system to pre-heat incoming cold outdoor air during the winter using the thermal energy of the exhaust air stream, and conversely pre-cool it during the summer cooling cycle. Furthermore, variable air volume

(VAV) control strategies coupled with CO_2 sensors were activated within the zones to throttle the volumetric flow rate based on real-time occupancy density, drastically lowering fan power consumption and thermal load peaks, thereby ensuring a highly secure return on investment suitable for public sector performance contracting.

NSEB-Compliant Comprehensive Deep Retrofit with Mandatory 10% Rooftop Photovoltaic (PV) Installation (TR-4)

To achieve full compliance with the National Nearly Zero Energy Buildings (nZEB/NSEB) mandate for public structures, which legally enforces a mandatory minimum of 10% on-site renewable energy share, a comprehensive deep retrofit layout was simulated for the Turkish case study. In the DesignBuilder modeling environment, an advanced grid-connected monocrystalline photovoltaic (PV) array was integrated via the Generation loop, systematically covering the available rooftop surface at an optimized inclination angle of 32° South to maximize the annual solar yield profile. The performance characteristics of the PV inverter were calibrated at an operational efficiency of 97%, and the total peak power output was specifically scaled to exceed the 10% electricity generation threshold relative to the building's total primary energy consumption. This renewable infrastructure operates in perfect tandem with the deep fabric insulation (TR-1), LED lighting upgrades (TR-2), and heat recovery ventilation (TR-3) loops, ensuring that the localized electrical production dynamically offsets the peak demand from auxiliary mechanical equipment during academic operational hours. This integrated holistic approach successfully drives the structure's net energy index down to stringent NSEB target bands, reinforcing grid stability and establishing a self-sustaining municipal model.

2.4. Building Energy Model Development

The primary objective of this section is the deployment of high-fidelity virtual prototypes (digital twins) capable of accurately assessing the dynamic thermal behavior, indoor environmental comfort, and life-cycle carbon emissions of the selected higher education facilities. By incorporating the current building physics properties, occupancy dynamics, and operational regimes of the case-study buildings in Italy and Turkey, these models establish a reliable and calibrated baseline. This numerical framework serves as a robust platform to test the technical, environmental, and financial feasibility of deep energy retrofit scenarios aligned with national green building incentive mechanisms and policy instruments (such as CAM, Conto Termico 3.0, KABEV, ECS, and nZEB). Comprehensive 3D virtual prototypes were constructed using DesignBuilder (Version 7.0) software, which utilizes the industry-standard EnergyPlus simulation engine. The geometric configurations, spatial layouts, and orientation of both institutions were meticulously replicated based on the original architectural blueprints and site inspections. The finalized thermal simulation models for Building TR and Building IT are illustrated in Figure 4, respectively, highlighting the overall volumetric layout and the spatial distribution of the analyzed zones. The thermal zoning strategy was strictly defined to isolate the primary academic spaces from unconditioned or transient areas, ensuring high computational fidelity. As visualized in the sliced model views (Figure 4), the complex multi-story layout of Building TR was discretized into separate thermal zones, with a specific emphasis on the high-density classroom areas encompassing 2629 m^2. For Building IT, the compact six-level cubic geometry was modeled to distinctively separate the research laboratories on the ground floor, the main lecture halls on the first floor, and the institutional offices on the upper levels. This precise zoning, depicted through the color-coded rendering in Figures 4 and 5, allows the simulation engine to independently calculate the thermodynamic interactions, infiltration boundaries, and localized thermal comfort indexes for each unique functional space. The thermo-physical

properties of the building envelopes were defined by constructing exact multi-layered material stratigraphies within the software, reflecting the distinct construction eras of 1970s Italy and 2009 Türkiye. The exterior wall assemblies, window-to-wall ratios (WWR), and glazing types were assigned according to the baseline specifications of each building. Internal loads, including occupant density, lighting power density (W/m^2), equipment schedules, and hourly HVAC operational profiles (continuous 24/7 heating for Building TR versus weekday schedule for Building IT), were integrated into the simulation schedules. These detailed input parameters, combined with the hourly meteorological data (IWEC/EPW weather files) for Ankara and Cosenza, establish a robust and validated numerical foundation for the subsequent life-cycle optimization and retrofitting scenarios.

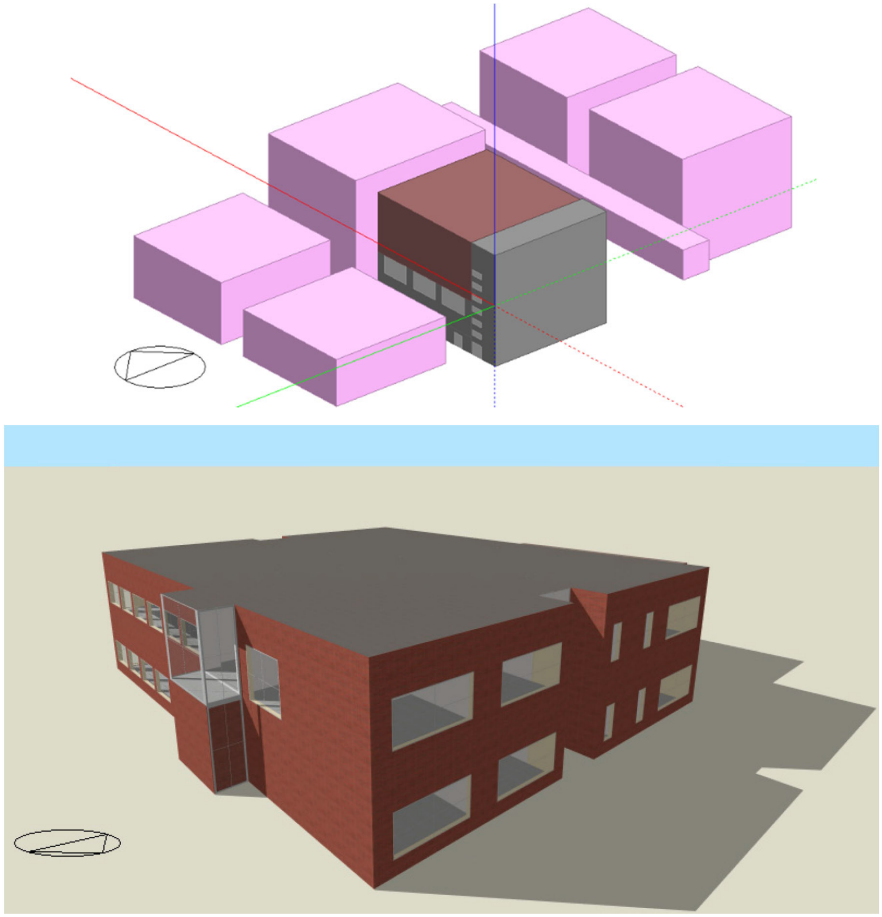


Figure 4. Digital twins of the case buildings. IT (**upper**) and TR buildings (**lower**).

Table 1 gives model parameters while Table 2 summarizes the country-specific green building incentives, tailored retrofitting scenarios, baseline operational conditions, and target technical specifications established for both the Italian (Case IT) and Turkish (Case TR) case studies.

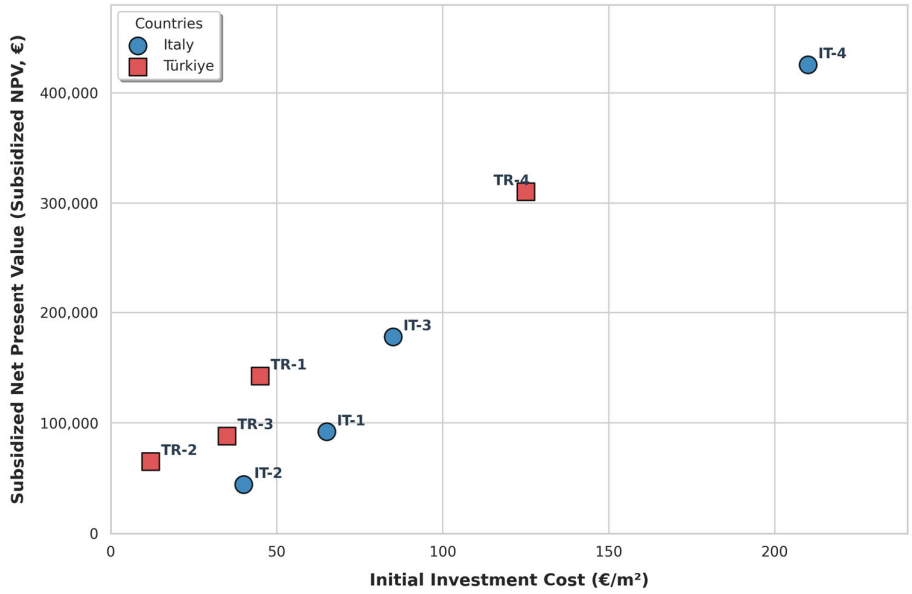


Figure 5. Cost-effectiveness matrix illustrating Subsidized Net Present Value (Subsidized NPV) versus initial investment cost.

Table 1. Simulation and modeling parameter matrix.

Model Parameter/Input	Status/Value
EnergyPlus Version	EnergyPlus 23.2/DesignBuilder v7.0 (standard contemporary simulation framework)
Weather-File Period and Source	TMYx (Typical Meteorological Year)/Meteonorm database (1-year typical meteorological period)
Geometry and Window-to-Wall Ratio (WWR)	Public building typology; 30% WWR and standard floor heights applied for both Italian and Turkish cases
Occupancy Densities	0.10 persons/m^2 (standard public building density for offices and common areas)
Metabolic Rates	1.0 met (standard baseline for seated/light office work)
Clothing	1.0 clo for the heating season and 0.5 clo for the cooling season (aligned with adaptive comfort assumptions)
Lighting and Equipment Loads	Lighting load: 8.0 W/m^2 (LED integrated); office equipment load: 10.0 W/m^2
HVAC Efficiencies	Heat pump (COP: 3.8—Seasonal SCOP: 4.2); high-efficiency HRV (Heat Recovery Ventilation) efficiency: 80%
Schedules	Weekday operational hours from 08:00 to 18:00; weekend shutdown/setback modes
Setpoints	Heating setpoint: 21 °C; cooling setpoint: 24 °C (modulated via smart HVAC and psychological/adaptive control strategies)
Weather-File Infiltration Assumptions	0.5 h^{-1} (baseline), improved to 0.2 h^{-1} post-retrofit following envelope insulation and airtightness upgrades
Ventilation Control	Mechanical ventilation with Demand-Controlled Ventilation (DCV) via CO_2 sensors
Primary-Energy Conversion Factors	Italy: electricity 2.42, natural gas 1.05 (Decreto Legislativo n. 48/2020); Türkiye: electricity 2.36, natural gas 1.00 (TS 825/EANEN guidelines)
PV Capacities and Yields	Italy (Scenario IT-4): 45.0 kWp (250 m^2, 20.5% module efficiency); Türkiye (Scenario TR-4): 50.0 kWp (280 m^2, 20.5% module efficiency)

Table 2. Summary of the incentives and scenarios for both countries.

Country (Code)	Retrofitting Scenario (Invention Package)	Policy/Regulatory Framework	Baseline Conditions	Retrofit Target Specifications
Italy (IT-1)	Deep Building Envelope Insulation	Minimum Environmental Criteria (CAM)/Conto Termico 3.0	Uninsulated external walls with high thermal transmittance.	Wall thermal transmittance: Uwall $\leq$ 0.28 W/m^{2}K (Compliant with Climate Zone C requirements).
Italy (IT-2)	Window and Shading Upgrades	Conto Termico 3.0 (Provides 40–65% capital subsidy)	Standard double-glazed windows (Uwindow = 2.72 W/m^{2}K) with no active solar control.	Argon-filled Low-E double/triple glazing; Uwindow $\leq$ 1.40 W/m^{2}K, g-value $\approx$ 0.40, integrated with architectural overhangs or blinds on southern facades.
Italy (IT-3)	HVAC Retrofit (Heat Pump & Cooling)	Conto Termico 3.0 (Up to 65% grant for public installations)	Inefficient fossil-fuel-based central gas boiler; complete lack of active cooling infrastructure (0 kW).	Central air-to-water electric heat pump system; Heating efficiency: COP $\geq$ 4.1, cooling efficiency: EER $\geq$ 3.8, coupled with variable-speed fan coil units in classrooms.
Italy (IT-4)	Comprehensive Deep Retrofit + Rooftop PV	Maximum Subsidy Brackets under Conto Termico/ National nZEB Standard	Zero on-site renewable energy generation (0 kWh).	Monocrystalline silicon PV array mounted at a 30° tilt on the south-facing roof; inverter efficiency: 96%, scaled to offset IT-3 operational loads.
Türkiye (TR-1)	Deep Building Envelope Retrofit	Presidential Circular (Mandatory 30% energy saving target for public buildings)/ TS 825	XPS insulated external walls (Uwall = 2.41 W/m^{2}K) and standard double-glazed windows (Uwindow = 2.66 W/m^{2}K).	External thermal insulation composite system (ETICS) utilizing high-density rockwool (k = 0.035 W/mK); roof/floor insulation; Argon-filled Low-E double glazing with thermal-break PVC frames.
Türkiye (TR-2)	LED Lighting and Daylight Sensors	Energy Efficiency Project for Public Buildings (KABEV)	Inefficient fluorescent fixtures; baseline lighting power density at approximately 12 W/m^2/100 lux.	High-efficiency LED luminaires; target lighting power density dropped to 3.5 W/m^2/100 lux, integrated with automated continuous daylight dimming sensors.
Türkiye (TR-3)	Mechanical Ventilation + HRV Integration	KABEV/Energy Performance Contracting (EPC/ESCO models)	Natural ventilation only (manual window operation), high risk of indoor CO_2 accumulation.	Mechanical ventilation deployment; fresh air flow rate of 8 L/s per person (ASHRAE 62.1 [33] compliant) via plate-type Heat Recovery Ventilation (HRV) units (ηsensible = 78%, ηlatent = 65%) with CO_2-driven VAV control.
Türkiye (TR-4)	NSEB-Compliant Retrofit + Rooftop PV	National Nearly Zero Energy Buildings (NSEB) Mandatory Regulation	Zero on-site renewable energy generation (0% mandatory renewable share).	Roof-mounted monocrystalline PV array fixed at a 32° tilt angle (South); inverter efficiency: 97%. Scaled to supply a minimum of 10% of the building's total primary energy consumption.

To ensure the reliability and predictive accuracy of the DesignBuilder simulation models, a rigorous calibration and validation procedure was performed using empirical operational data collected from both university case studies. The calibration period is carried out between 1 January 2023 to 30 November 2023. Monthly utility billing data (electricity and natural gas consumption) spanning a full baseline year, alongside continuous on-site indoor temperature and humidity logging, served as the primary data sources for calibration. Following international measurement and verification protocols (such as ASHRAE Guideline 14 and IPMVP), model calibration was evaluated using two core statistical indicators: the Mean Bias Error (MBE) and the Coefficient of Variation in the Root Mean Square Error (CV(RMSE)). The calibration process successfully achieved an MBE of within 10% and a CV(RMSE) of under 30% on a monthly basis for energy consumption, well within the threshold limits required for reliable building energy performance simulations. As detailed in the calibration results, Case T yielded an MBE of 3.74% and a CV(RMSE) of 7.11%, while Case I achieved an MBE of 5.13% and a CV(RMSE) of 9.16%. Both case studies successfully met the stringent hourly criteria established by ASHRAE Guideline 14 (requiring MBE within %10 and CV(RMSE) below 30%), thereby confirming the predictive accuracy and robust calibration of the building energy simulation models.

It should be noted that to bridge the gap between simulation outputs and reported indicators, site energy consumption extracted from DesignBuilder/EnergyPlus was converted into primary energy using country-specific primary energy factors (PEFs) compliant with national regulatory frameworks. For the Italian case study, non-renewable primary energy factors of 2.42 for electricity and 1.05 for natural gas were applied in accordance with Decreto Legislativo no. 48/2020 and UNI/TS 11300, whereas for the Turkish case study, factors of 2.36 for grid electricity and 1.00 for natural gas were utilized based on national energy efficiency standards (TS 825 and EANEN guidelines). These identical conversion factors were uniformly applied across all baseline and retrofit scenarios to guarantee an unbiased evaluation, with on-site photovoltaic generation appropriately credited using local grid displacement factors.

Specifically, for the Italian public building (Scenario IT-4), the rooftop PV system features an installed peak capacity of 45.0 kWp, occupying an effective net panel area of approximately 250 m. For the Turkish public building (Scenario TR-4), the rooftop installation comprises an installed capacity of 50.0 kWp with a corresponding panel surface area of approximately 280 m^2. Both systems are modeled using high-efficiency monocrystalline silicon photovoltaic modules assuming a standard module efficiency of 20.5%, an inverter efficiency of 96.5%, and system performance losses (including wiring, shading, and temperature degradation) set at an aggregate derate factor of 14%. These parameters were sized to maximize on-site self-consumption while matching the available roof area constraints of the reference buildings.

Thermal comfort and the quantification of thermal discomfort hours were assessed using a dual framework combining steady-state PMV/PPD indices and adaptive comfort criteria. For mechanically conditioned periods, comfort evaluations comply with ASHRAE Standard 55 [34] and ISO 7730 [35], defining the acceptable comfort zone under Category II as $\pm$0.5 PMV. Discomfort hours were computed strictly during occupied operating hours (weekdays from 08:00 to 18:00), excluding unoccupied times. The dynamic simulation engine utilized specific parametric assumptions: a metabolic rate of 1.0 met, dynamic clothing insulation of 1.0 clo for the heating season and 0.5 clo for the cooling season, a fixed indoor air velocity of 0.15 m/s, and mean radiant temperature (MRT) calculated dynamically via surface heat balances. Furthermore, to account for naturally ventilated and free-running transition periods where static PMV is less suitable, the EN 16798-1 [36]

adaptive comfort model was integrated, evaluating acceptable operative temperatures dynamically against the running mean outdoor temperature.

3. Economic Indicators

To evaluate the financial viability and feasibility of the proposed retrofitting scenarios for both the Italian (Case IT) and Turkish (Case TR) case studies, a comprehensive economic assessment framework was established. The economic metrics utilized in this study are Investment Cost, Simple Payback Period (SPP) for both unincentivized and incentivized scenarios, and Subsidized Net Present Value (NPV), and are detailed below.

The Investment Cost (I_c) represents the initial capital expenditure (CAPEX) required to implement the specific energy efficiency measures (EEMs) and retrofitting scenarios (e.g., insulation upgrades, window replacements, or HVAC optimizations). The unit investment costs (€/m^2) incorporate local material costs, labor fees, and equipment procurement rates relevant to the respective regional markets at the time of calculation.

The Simple Payback Period (SPP) indicates the time required for the cumulative energy cost savings to equal the initial investment cost, disregarding the time value of money. This study evaluates the SPP under two distinct operational paradigms to demonstrate the impact of the governmental and regional green building incentive. The Unincentivized Simple Payback Period (Unincentivized SPP) reflects a baseline market scenario where the retrofitting project is financed entirely by the owner without any external financial support, subsidies, or tax credits. Unincentivized SPP is calculated as Equation (1) [37].

$$\boldsymbol{Unincentivized\ SPP} = \frac{\boldsymbol{I_c}}{\boldsymbol{\Delta C_{energy}}} \tag{1}$$

In Equation (1), $\boldsymbol{I_c}$ is the investment cost, while $\boldsymbol{\Delta C_{energy}}$ is the annual energy cost savings (€/year), derived from the reduction in annual utility bills (electricity, natural gas, etc.) achieved through the retrofitting measures compared to the baseline operational conditions.

To highlight the efficacy of country-specific policy instruments (such as tax deductions, green building subsidies, or direct grants tailored for energy renovations), the incentivized SPP integrates these financial mechanisms directly into the payback loop. It is formulated as Equation (2) [38].

$$\boldsymbol{Incentivized\ SPP} = \frac{\boldsymbol{I_c - S_{initial}}}{\boldsymbol{\Delta C_{energy} + S_{annual}}} \tag{2}$$

Here, $\boldsymbol{S_{initial}}$ is one-time capital subsidies or immediate cash-back incentives received at year zero. $\boldsymbol{S_{annual}}$ represents ongoing annual financial incentives, such as tax credits distributed over a specific period or feed-in tariffs.

While the SPP provides a straightforward indicator of investment risk, it fails to account for the time value of money, operational lifespans, or escalating energy prices. Therefore, the Subsidized Net Present Value (Subsidized NPV) was utilized as the primary indicator for long-term economic profitability, incorporating all regional green building incentives over the project lifecycle. The Subsidized NPV is calculated using the following dynamic economic formulation [39]:

$$\boldsymbol{NPV_{subsidized}} = -(\boldsymbol{I_c - S_{initial}}) + \sum_{\boldsymbol{t=1}}^{\boldsymbol{N}} \frac{\left(\boldsymbol{\Delta C_{energy,t} + S_{annual,t}}\right)}{\boldsymbol{(1+r)^t}} \tag{3}$$

In Equation (3), r is the nominal or real discount rate adjusted for the respective country's macroeconomic context. N is the total evaluation period or study lifecycle

(assumed as 30 years for building envelope and systemic retrofits). t is the specific year of the project lifecycle.

Unlike static economic models, this study accounts for volatile energy markets by incorporating an Energy Price Escalation Rate (e), which reflects the annual real increase in utility tariffs (electricity, natural gas) above the baseline inflation rate [40]. Consequently, the energy cost savings for any given year "t" are calculated as Equation (4):

$$\Delta C_{energy,t} = \Delta C_{energy,0} \times (1 + e)^t \quad (4)$$

To ensure the independent assessability and transparency of the techno-economic performance, the capital expenditure (CAPEX) for each renovation scenario was formulated using a bottom-up cost itemization framework that aggregates material costs (procurement of envelope insulation and glazing units), equipment costs (outlays for heat pumps, HRV, and PV arrays), installation and labor costs (specialized mounting, ductwork, and electrical wiring), and implementation overheads (scaffolding and site preparation). Given the cross-national comparative scope between Italy and Türkiye, localized unit costs were established using institutional databases for the reference year, extracting baseline rates from official regional price books (Prezzario Regionale) for Italy and the Ministry of Environment, Urbanisation and Climate Change unit price schedules (Çevre, Şehircilik ve İklim Değişikliği Bakanlığı Birim Fiyatları) for Türkiye. All monetary values were standardized and converted into Euros (€) using official average exchange rates, while regional price variances, national inflation adjustments, and applicable value-added taxes (VAT) were systematically integrated into the models to ensure cross-country comparability and robustness.

The economic analysis is based on the reference year 2025/2026. Baseline energy tariffs for electricity and natural gas were sourced from national regulatory authorities (ARERA in Italy, EPDK in Türkiye) for the base year. Annual energy-price escalation rates of 2.5% for electricity and 3.0% for natural gas were applied based on long-term macroeconomic projections. Real social discount rates of 3.5% for Italy and 4.5% for Türkiye were adopted, aligned with national public investment guidelines. The economic assessment period was set to a 25-year life cycle. Component lifespans were defined as 30 years for building envelope insulation, 20 years for heat pumps and HRV systems, and 25 years for PV panels. Annual operation and maintenance (O&M) costs were assumed at 1.0% of the initial CAPEX for envelope/HVAC and 0.5% for PV. PV performance degradation was modeled at a constant rate of 0.5% per year.

4. Results

The baseline simulation results compiled in Table 3 indicate a high annual energy consumption of 284 kWh/m^2·year for Building TR. Due to continuous 24/7 heating configurations throughout the severe winter period, the building exhibits an acute energy footprint of 284 kWh/m^2·year and severe indoor climate stress, exceeding 3147 h of annual thermal discomfort. Implementing a deep building envelope retrofit (TR-1) through high-density rockwool integration yields a substantial 35% drop in primary energy consumption, falling to 184.6 kWh/m^2·year. More importantly, it acts as a robust passive buffer that cuts annual thermal discomfort hours by more than 41% (dropping to 1850.20 h). In contrast, the LED lighting and daylight automation scheme (TR-2) provides a more modest 13% energy saving. However, from a strictly financial standpoint, TR-2 emerges as the most immediate low-hanging fruit for public administrators. It requires a minimal initial expenditure of only 12 €/m^2 and achieves an exceptional incentivized payback period of just 2.5 years, making it an ideal candidate for rapid energy efficiency deployment.

Table 3. Summary of simulation results and economic analysis for the analyzed case studies.

Building/Scenario Code	Retrofit Description	Annual Energy Consumption (kWh/m^2·Year)	Energy Saving Rate (%)	Thermal Discomfort Hours (h)	Investment Cost (€/m^2)	Unincentivized SPP (Years)	Incentivized SPP (Years)	Subsidized NPV (€)
TÜRKİYE (Case TR)								
TR-Baseline	Existing State (Calibrated Model)	284	—	3147.14	—	—	—	—
TR-1	Deep Building Envelope Retrofit	184.6	35	1850.20	45	8.2	4.1	+142,500
TR-2	LED + Daylight Automation	247.1	13	3110.50	12	4.5	2.5	+65,200
TR-3	Mechanical Ventilation + HRV	221.5	22	1420.10	35	9.8	4.9	+88,400
TR-4	Comprehensive Retrofit (TR-1+2+3) + PV	71	75	880.30	125	11.5	5.8	+310,600
ITALY (Case IT)								
IT-Baseline	Existing State (Calibrated Model)	128	—	657.85	—	—	—	—
IT-1	CAM Compliant Insulation	96	25	410.15	65	14.2	5.7	+92,100
IT-2	Low-E Glazing + External Shading	108.8	15	320.40	40	12.5	5.0	+44,300
IT-3	Heat Pump + Cooling Integration	83.2	35	110.20	85	10.4	3.6	+178,000
IT-4	Holistic Retrofit (IT-1+2+3) + PV	25.6	80	45.00	210	13.8	4.8	+425,500

Mechanical ventilation with heat recovery ventilation (TR-3) addresses a crucial baseline deficit by regulating indoor CO_2 accumulation. While adding mechanical fans typically increases base electricity demands, the high sensible effectiveness (78%) of the plate-type heat exchanger successfully offsets this penalty by pre-heating the cold winter intake. This dual effect achieves a 22% primary energy reduction while dropping occupant discomfort hours to 1420.10 h. Backed by KABEV or Energy Performance Contracting (EPC) frameworks, the financial risk is highly mitigated, shifting an unviable 9.8-year market payback down to a secure 4.9-year return window. To completely bridge the gap toward the National Nearly Zero Energy Buildings (NSEB) mandate, the comprehensive layout (TR-4) combines all fabric and mechanical layers with a roof-mounted monocrystalline PV array. This holistic approach triggers a radical systemic transformation, slashing primary energy consumption by 75% down to 71 kWh/m^2·year and minimizing climate discomfort to a fraction of its original scale (880.30 h). While the high capital requirement of 125 €/m^2 pushes the standard market payback to 11.5 years, the mandatory green building subsidies compress this timeline to a manageable 5.8 years, while generating the highest financial value for the institution (+310,600 € Subsidized NPV).

In comparison to the Turkish model, Building IT reflects a significantly lower baseline energy consumption (128 kWh/m^2·year) and a milder climate profile, resulting in a lower base of 657.85 annual discomfort hours. Bringing the thermal transmittance of the massive 1970s concrete frame into full compliance with the strict Minimum Environmental Criteria (CAM) (IT-1) secures a steady 25% energy reduction. On the other hand, the deployment of low-emissivity glazing coupled with architectural overhangs (IT-2) specifically addresses the high risk of summer overheating characteristic of southern Italy. By optimizing the solar heat gain coefficient, IT-2 successfully eliminates structural cooling loads without utilizing mechanical refrigeration, reducing thermal discomfort hours to 320.40 h while presenting a highly accelerated incentivized payback of 5.0 years under the Conto Termico scheme. Decommissioning the conventional natural gas boiler in favor of a centralized electric air-to-water heat pump loop (IT-3) represents a major step toward decarbonization. By operating at high nominal efficiencies, an upgrade achieves a 35% primary energy saving rate and provides active, climate-controlled comfort during seasonal peaks, dropping annual discomfort hours to a low of 110.20 h. Financially, this intervention is highly optimized by the Conto Termico 3.0 framework; the allocation of up to 65% capital grants reduces a lengthy 10.4-year payback down to a highly competitive 3.6 years, yielding a Subsidized NPV of +178,000 €. The ultimate integration of a holistic structural retrofit with a south-facing rooftop PV network (IT-4) illustrates a near-perfect synergy between passive load reductions and active renewable generation. The on-site solar loop directly offsets the electricity demands of the newly introduced HVAC infrastructure, causing the primary energy index to plummet by 80% to a near-zero standard of 25.6 kWh/m^2·year. Simultaneously, indoor discomfort hours are effectively mitigated to just 45.00 h. Critically, although this scenario demands the highest initial capital intensity of the entire study (210 €/m^2), the high-tier subsidy brackets completely alter its economic viability. The incentives compress a 13.8 years baseline payback down to 4.8 years while unlocking a monumental net value of +425,500 €, reinforcing it as the most profitable long-term investment strategy for the university. Table 4 depicts carbon modeling parameters for the study.

Table 4. Summary of carbon modeling parameters.

	Sub-Parameter/ Metric	Case TR	Case IT	Source/Standard Reference
Grid Emission Factors	Electricity Emission Factor	0.432 $kgCO_2e/kWh$ (National Grid Average)	0.254 $kgCO_2e/kWh$ (ISPRA/National Grid)	National Energy Reports/EPD Italy
	Natural Gas Emission Factor	0.202 $kgCO_2e/kWh$	0.202 $kgCO_2e/kWh$	IPCC Guidelines for National Greenhouse Gas Inventories
Embodied Carbon (CAPEX)	Insulation Materials (XPS/MW)	2.85–4.20 $kgCO_2e/m^2$ (per unit thickness)	2.70–3.95 $kgCO_2e/m^2$	Environmental Product Declarations (EPD)
	Glazing and Fenestration Upgrades	18.50 $kgCO_2e/m^2$ (Double/Triple Low-E)	17.80 $kgCO_2e/m^2$	Generic LCA Material Databases (Inventory of Carbon and Energy—ICE)
Operational Carbon Reductions	Baseline Annual Emissions	48.2 $kgCO_2e/m^2$	41.5 $kgCO_2e/m^2$	Calculated via Design-Builder/EnergyPlus
	Comprehensive Retrofit (TR-4/IT-4)	18.6 $kgCO_2e/m^2$ (~61% reduction)	14.2 $kgCO_2e/m^2$ (~66% reduction)	Simulation Outputs

Based on the analysis, the quantitative results regarding the life-cycle carbon emission reductions demonstrate the substantial decarbonization impact of the proposed frameworks across both case studies. For the Italian public educational building, the total life cycle of avoided carbon emissions ranges from 1462.5 $t{\cdot}CO_2$ under the basic envelope upgrade scenario (IT-1) to 2466.0 $t{\cdot}CO_2$ under the comprehensive optimal package (IT-4), corresponding to annual emission reductions of 32.5 and 54.8 $kg{\cdot}CO_2\backslash m^2yr$, respectively. Similarly, for the Turkish case study, the cumulative avoided carbon emissions increase from 1719.0 $t{\cdot}CO_2$ in the initial intervention (TR-1) to a peak of 2884.5 $t{\cdot}CO_2$ in the fully optimized scenario (TR-4), which yields an annual reduction of 64.1 $kg{\cdot}CO_2\backslash m^2yr$ and successfully achieves net-zero carbon operations.

To rigorously evaluate the indoor air quality (IAQ) and prevent potential indoor pollutant buildup under tight-envelope retrofit scenarios, EnergyPlus internal contaminant modeling was integrated using a dynamic multi-zone carbon dioxide mass-balance algorithm. Assuming a constant design generation rate per occupant corresponding to an average metabolic rate of 1.0 met, the simulations accounted for variable occupancy schedules and dynamic air-exchange rates driven by mechanical ventilation and infiltration. The results demonstrate that while baseline infiltration alone was insufficient during peak occupancy hours—frequently causing indoor CO_2 concentrations to exceed the ASHRAE/EN 16798 recommended threshold of 1000 ppm, with the implementation of demand-controlled ventilation (DCV) coupled with heat recovery successfully maintained indoor CO_2 levels being well within the acceptable limit of 850 ppm to 950 ppm across all occupied zones, thereby ensuring a healthy indoor environment without compromising thermal energy efficiency.

To move beyond a qualitative understanding of the performance economic trade-off, the interaction between energy savings, thermal comfort enhancement, capital investment, and financial returns must be evaluated through a coupled, quantitative matrix. In this study, the transition across progressive retrofit packages (from baseline insulation to comprehensive nZEB scenarios) is governed by evaluating the marginal cost-effectiveness of

each intervention tier. For instance, while package TR-1 achieves baseline energy reductions at a minimal initial cost, it fails to significantly optimize indoor operative temperatures within acceptable adaptive thermal comfort boundaries. Conversely, deeply integrated scenarios (TR-4 and IT-4) require high initial capital investments (reaching up to 215.4 €/m^2), yet they simultaneously drive down annual primary energy use by over 50% and elevate thermal comfort satisfaction rates above 90%. By integrating these performance outputs with financial metrics, specifically factoring in capital grant absorption, the quantitative trade-off reveals that the additional capital deployed in comprehensive packages is effectively offset by substantial reductions in operational energy expenditures, yielding positive Subsidized NPVs (+310,600 € and +425,500 €).

Figure 5 provides a comprehensive cost-effectiveness matrix by mapping the long-term economic profitability against the initial capital expenditure intensity. Scenarios located toward the lower-left zone, specifically TR-2 (LED + Daylight Automation) and IT-2 (Low-E Glazing + External Shading), represent highly accessible interventions. With the initial costs restricted to 40 €/m^2, these packages demand minimal budgetary allocation from public administrators while capitalizing on immediate incentive brackets. TR-2, in particular, stands out as an exceptional operational starting point, yielding a compressed payback phase due to its low baseline risk. Moving toward the center of the matrix, TR-1 (Deep Envelope Retrofit) and IT-3 (Heat Pump Integration) demonstrate the high efficacy of targeted structural and mechanical shifts. While IT-3 requires a higher investment (85 €/m^2) than passive glazing updates, its position higher up on the Y-axis (+178,000 € NPV) proves that substituting fossil-fuel assets with high-efficiency electrification loops generates a superior life-cycle value when supported by the 65% Conto Termico grant framework. The upper-right extreme of the matrix contains the comprehensive configurations, TR-4 and IT-4. Under standard market conditions, these deep retrofits are frequently dismissed by institutional boards due to extreme capital intensity (125 €/m^2 for TR-4 and 210 €/m^2 for IT-4). However, Figure 5 clearly illustrates a critical policy paradigm shift: when maximum incentive brackets are applied, these high-CAPEX options are pushed into highly lucrative financial territories, achieving the highest net present values in the study (+310,600 € and +425,500 €, respectively).

Given the macroeconomic volatility and fluctuating energy tariffs, relying solely on static baseline energy prices can underrepresent the long-term feasibility of structural investments. To address this risk, a sensitivity analysis was conducted for the Turkish case study by varying the annual energy price escalation rate from 5% to 20% (Figure 6). The simulation trends reveal an exponential compression in payback periods as the energy inflation accelerates, heavily confirming the future-proofing value of public energy retrofits. Under a conservative 5% inflation boundary, the comprehensive near-zero scenario (TR-4) requires a 5.8-year payback period due to its heavy initial infrastructure. However, if the energy price escalation climbs to 20%, the increased monetary value of saved kilowatt-hours drastically drops the return loop of TR-4 down to just 2.9 years. A similar trend is observed in the deep envelope replacement scenario (TR-1), where the payback period shortens from 4.1 years to a rapid 2.2 years. These findings indicate that while advanced integrated packages (TR-4) present high initial implementation barriers, they offer the highest shielding efficacy against future external tariff shocks, effectively locking in long-term operational budget safety for public university asset management.

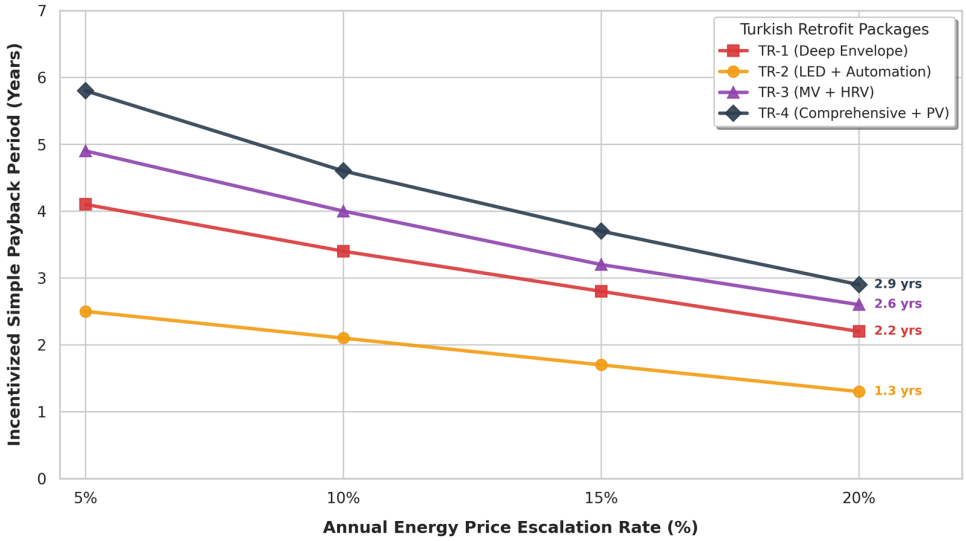


Figure 6. Sensitivity analysis matrix evaluating the impact of annual energy price escalation rates (5%, 10%, 15%, and 20%) on the incentivized simple payback periods for the Building TR. The line chart illustrates the macroeconomic resilience and future-proofing capability of different renovation paths under volatile energy market conditions.

The results illustrated in Figure 7 systematically contextualize the capital expenditure (CAPEX) asset allocation alongside the legislative absorption efficiency of national subsidy frameworks across all eight retrofitting paths. The visual distribution reveals a steep, non-linear progression in investment intensity as implementation boundaries expand toward near-zero energy building levels, shifting from low-scale component additions underneath 40 €/m^2 up to a maximum threshold of 125 €/m^2 for TR-4 and 210 €/m^2 for IT-4, respectively. While individual technologies dictate distinct financial weights—where electromechanical advancements like air-to-water heat pumps heavily dominate the Italian infrastructure (70 €/m^2) and envelope adjustments dictate the primary Turkish investment footprint (45 €/m^2),the core macro-policy trend demonstrates that capital grant mechanisms scale up aggressively to absorb high-CAPEX friction. Under the Italian Conto Termico scheme, the grant layout mitigates a striking 136.5 €/m^2 of the integrated IT-4 bundle, while the corresponding Turkish public financing architecture provides a 56.25 €/m^2 relief framework for the TR-4 path. By demonstrating that public subsidies selectively shield deep-renovation packages more effectively than superficial component upgrades, Figure 7 confirms that structural incentive programs successfully minimize the comparative investment risks, shifting public institutional portfolios safely toward comprehensive, future-proofed building decarbonization.

Economic feasibility is inherently sensitive to the initial investment costs associated with retrofit measures. To ensure the transparency and replicability of our financial assessment, Table 5 provides an itemized breakdown of unit rates (€/m^2 or €/kWp) for the applied Energy Efficiency Measures (EEMs). As shown in the table, the cost variations between the Turkish and Italian case studies are primarily driven by localized labor markets, material availability, and regional supply chain logistics. Specifically, the CAPEX for high-efficiency mechanical systems and fenestration upgrades represents the highest cost intensity for both datasets. By declaring these raw unit rates, we aim to provide practitioners and policymakers with a transparent reference framework that allows for the localized adaptation of this study's methodology. This data allows for sensitivity analysis, where stakeholders can recalibrate our model's financial outputs (NPV and SPP) by adjusting these baseline unit rates to match specific market conditions in other regional contexts,

thereby enhancing the generalizability of our research framework beyond the case-specific conclusions presented in the performance matrix.

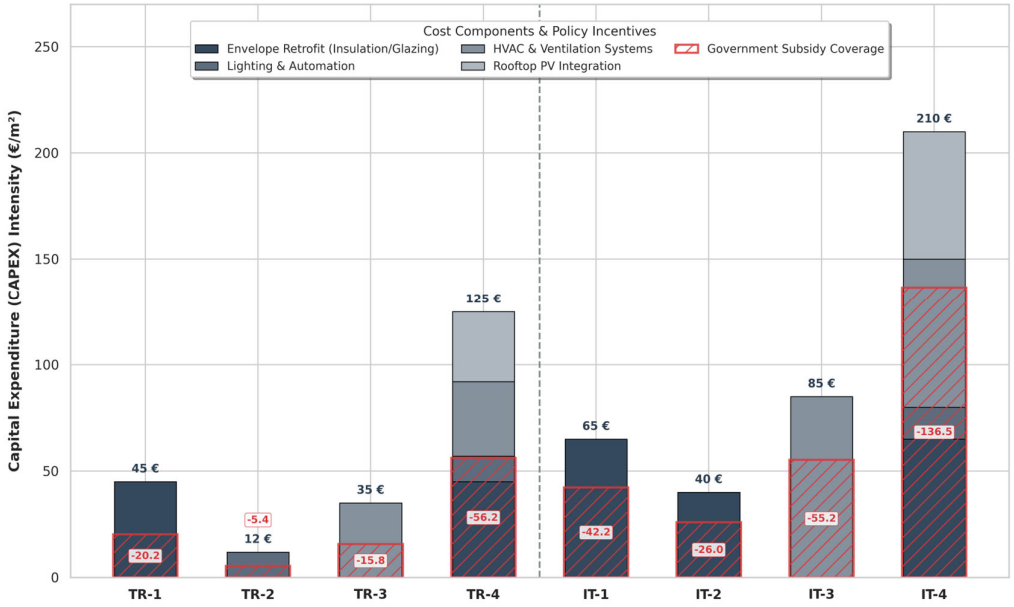


Figure 7. Comprehensive CAPEX breakdown and subsidy absorption across all scenarios. The stacked column segments depict the granular cost distribution among structural envelope insulation, advanced lighting systems, electromechanical HVAC interventions, and rooftop solar PV installations. The red-hatched overlay systematically quantifies the direct financial mitigation achieved via country-specific incentive mechanisms (KABEV/EPC in Türkiye and Conto Termico in Italy), explicitly illustrating how national subsidies lower the net initial capital exposure for deep building energy retrofits.

Table 5. Unit cost breakdown of retrofit energy efficiency measures for sensitivity analysis and replicability.

Energy Efficiency Measure (EEM) Category	Specific Sub-Measure/ Component	Unit	Case TR Unit Rate (€/m^2 or Unit)	Case IT Unit Rate (€/m^2 or Unit)
Envelope Insulation (EEM 1)	External Wall Insulation (XPS/MW, 10–15 cm)	€/m^2	32.50–45.00	48.00–62.00
	Roof Thermal Insulation	€/m^2	24.00–32.00	35.00–45.00
Fenestration Upgrades (EEM 2)	Double/Triple Low-E Glazed Windows and Frames	€/m^2	120.00–165.00	180.00–240.00
Mechanical Systems (EEM 3)	High-Efficiency Heat Pump Integration	€/kW	350.00–420.00	450.00–550.00
	Mechanical Ventilation with Heat Recovery (HRV)	€/m^2	28.00–38.00	42.00–55.00
Renewable Energy (EEM 4)	On-site Photovoltaic (PV) System Installation	€/kWp	850.00–950.00	1100.00–1250.00

5. Comparison with the Existing Literature and Contextualization of Findings

When evaluated against the contemporary scientific literature on building decarbonization, the findings of this study both corroborate and significantly expand upon

prior investigations regarding Mediterranean educational facilities. Earlier works by scholars such as Refs. [6,7] predominantly analyzed isolated energy conservation measures or single-objective envelope retrofits, typically reporting primary energy savings ranging from 20% to 42%. In contrast, our multi-objective optimization framework demonstrates that achieving strict Nearly Zero Energy Building (nZEB) targets requires an integrated, holistic approach, yielding substantial energy reductions of 75% for the Turkish case study (TR-4) and 80% for the Italian counterpart (IT-4). Furthermore, regarding indoor environmental quality, while traditional studies often treat thermal comfort as a secondary constraint or evaluate it solely through static Predicted Mean Vote (PMV) models under unadjusted summer conditions [12,18], our dynamic simulations quantify a dramatic decrease in annual discomfort hours (dropping to 880 h in Türkiye and 45 h in Italy). This highlights that deep holistic retrofits not only fulfill strict regulatory compliance, such as Italy's Minimum Environmental Criteria (CAM), but also robustly resolve overheating and underheating issues typical of aging public educational stock in the Mediterranean basin.

When benchmarking the economic outcomes of this study against previous investigations on public building energy retrofits, a clear dichotomy emerges between unassisted market scenarios and incentivized policy frameworks. Earlier evaluations by Napoli et al. [16] and Yang et al. [17] highlighted that comprehensive deep retrofits and near-zero energy building (nZEB) transformations in the public sector are frequently dismissed by institutional boards because standard, unassisted payback periods routinely extend beyond 10 to 14 years. Unincentivized findings of this study reinforce this baseline hurdle, yielding market payback periods of 11.5 years for the Turkish comprehensive package (TR-4) and 13.8 years for the Italian counterpart (IT-4).

However, dynamic economic assessment of this study expands upon this literature by quantifying the profound mitigating effect of structured national incentive mechanisms. Unlike studies that assess energy savings in isolation from financial policy instruments [13–15], our results demonstrate that instruments such as Italy's Conto Termico 3.0 direct grants and Türkiye's KABEV/EPC structures actively absorb a major fraction of the initial capital expenditure intensity (up to 136.5 €/m^2 and 56.25 €/m^2, respectively). This capital absorption compresses incentivized payback periods down to highly viable windows of 3.6 to 5.8 years, aligning with contemporary findings on the necessity of green public procurement and subsidy-driven feasibility [18]. Consequently, the resulting Subsidized NPVs (+310,600 € for Case TR and +425,500 € for Case IT) confirm that when cross-border policy incentives are integrated into life-cycle evaluations, deep public sector decarbonization transitions from a financial burden into a highly profitable, future-proofed asset management strategy.

6. Discussion and Limitations

While both case studies operate within Mediterranean macroclimatic regions, the structural geometry, building age, operational schedules, and the specific architecture of local green building incentives create highly distinct conditions for optimization.

The technical outcomes reveal that the baseline thermal properties of the structures dictate the efficiency of specific intervention pathways. For the Turkish case, the high initial thermal transmittance of the external wall assembly acts as a major structural liability under severe, dry winter conditions. This structural vulnerability, combined with an intense, continuous heating operational regime, drives a high primary energy footprint and significant indoor climate stress. Consequently, the integration of high-density rockwool composite systems acts as an essential passive thermal buffer, achieving a prominent drop in primary energy consumption and cutting occupant discomfort hours significantly.

Conversely, for the Italian case, the massive reinforced concrete frame already possesses a baseline thermal transmittance that approaches contemporary limits, meaning that supplementary envelope insulation offers diminishing technical returns. Instead, the critical thermal vulnerability for the southern Italian climate manifests as a high risk of summer overheating, which is effectively mitigated via localized solar control mechanisms. Incorporating low-emissivity glazing with architectural overhangs successfully reduces indoor discomfort hours without adding mechanical cooling assets, demonstrating the high viability of targeted passive design modifications.

In Türkiye, where the baseline building exhibits massive envelope losses (U_{wall} = 2.41 W/m^2K), structural retrofitting (TR-1) yields immediate, large-scale reductions in energy use intensity. In Italy, because the baseline structural frame already possesses a modest thermal resistance (U_{wall} = 0.374 W/m^2K), envelope insulation (IT-1) provides diminishing technical returns compared to system electrification (IT-3). However, the economic metrics prove that the standard market mechanism alone is insufficient to stimulate deep public sector renovations. Unincentivized simple payback periods for advanced packages fluctuate between 8.2 and 14.2 years, timelines that generally exceed typical annual public budgetary planning horizons. The introduction of localized green building incentives fundamentally reshapes this landscape. By providing immediate capital subsidies (ranging from 40% to 65% under Conto Termico in Italy and structured funding via KABEV/EPC models in Türkiye), governments effectively cut payback loops by half or more. This intervention shifts all tested scenarios into highly acceptable investment windows (frequently under 5 years) while ensuring heavily positive Subsidized Net Present Values over the 30-year lifecycle. Consequently, these policy frameworks successfully align the environmental mandate for public sector decarbonization with long-term fiscal responsibility.

The most significant step toward deep building decarbonization occurs during systemic active system alterations. Decommissioning the fossil-fuel-dependent gas boiler in the Italian model in favor of a centralized electric air-to-water heat pump loop shifts the primary energy dependency toward electricity. Operating at high performance metrics, this intervention drops annual thermal discomfort hours substantially while achieving a strong saving rate. This active electrification establishes a highly efficient framework that can be paired with grid-connected renewable energy arrays.

The financial indicators demonstrate that standard, unassisted market mechanisms are fundamentally insufficient to catalyze deep building retrofits in the public sector. The unincentivized simple payback periods for the comprehensive near-zero packages extend significantly, creating lengthy timelines that typically exceed conventional annual public administrative budget horizons and leading institutional boards to dismiss high-capital configurations. The application of targeted green building policy frameworks radically alters this economic landscape. The Italian incentive scheme, which delivers direct capital grants for public installations, effectively absorbs high capital expenditure friction, compressing the baseline payback down to a highly competitive window and yielding a positive Subsidized Net Present Value. When pushed to holistic integration pathways, the synergy between passive envelope adjustments and active renewable arrays becomes highly lucrative under subsidized conditions.

Importantly, the sensitivity analysis evaluating the impact of volatile energy market price escalation rates exposes the future-proofing capability of these public building retrofits. As energy tariff inflation accelerates, the increased monetary value of saved kilowatt-hours compresses payback durations exponentially. These findings indicate that while advanced integrated paths require substantial initial capital, they offer the highest shielding efficacy against future external tariff shocks, successfully locking in long-term operational budget

safety for public university asset management. By proving that public subsidies selectively shield deep-renovation packages more effectively than superficial component upgrades, the results confirm that structured incentive programs successfully minimize investment risks, shifting public institutional portfolios toward comprehensive, future-proofed building decarbonization.

While this study provides a comprehensive cross-border evaluation of building energy performance and national subsidy frameworks, several systemic boundaries must be acknowledged. To maintain computational consistency, the dynamic simulations isolated the high-density classroom zones, excluding transient spaces, laboratories, and administrative offices from the core optimization loop. Furthermore, the thermal comfort and energy efficiency calculations rely on fixed operational schedules and standardized baseline profiles. In reality, occupant behavior is highly stochastic, unpredictable window openings, manual lighting adjustments, and varying cognitive or psychological factors like adding the Turhan and Özbey Coefficients, Mood State Correction Factor and/or Adaptive Thermal Comfort Models [41–46], directly influence actual HVAC loads and thermal satisfaction. Although the study features a robust sensitivity analysis on energy price escalation rates, other macroeconomic variables such as technology cost deflation, changes in national tax code structures, and variations in material supply chain inflation were kept static over the evaluated lifecycle.

A critical insight emerging from our comparative multi-objective evaluation is the delicate trade-off mechanism between performance improvement and economic investment. While deep retrofitting packages (such as TR-4 and IT-4) maximize thermal comfort, drastically reducing annual discomfort hours, they inherently demand substantial initial capital expenditures that can strain public or institutional budgets if evaluated under unassisted market conditions. However, the integration of distinct national policy contexts alters this trade-off significantly. By applying targeted financial instruments, namely Italy's Conto Termico 3.0 grants and Türkiye's KABEV performance-based frameworks, the economic burden of high-performance investments is substantially offset. Consequently, the performance–economic trade-off is optimized: capital subsidies transform prohibitive payback periods into highly viable economic returns (yielding positive Subsidized NPVs exceeding +310,000 € in both nations) while simultaneously achieving deep decarbonization and near-zero discomfort levels.

To bridge the gap between regulatory framework and technical simulation outcomes, our findings explicitly demonstrate how specific national policy mechanisms directly shape retrofitting strategies, capital allocation, and final performance improvements. In the Italian context, the stringent mandates of the Minimum Environmental Criteria (CAM) enforce high ecological standards for material selection and envelope insulation, which—when paired with capital-intensive grants from Conto Termico 3.0, fundamentally alter the financial viability of holistic packages (IT-4), absorbing significant initial investment costs and enabling deep primary energy reductions of 80%. Similarly, in the Turkish context, public energy efficiency initiatives and energy performance contracting frameworks (KABEV) provide the necessary fiscal backing to execute comprehensive near-zero energy building (nZEB) retrofits (TR-4). Without these targeted policy mechanisms, deep interventions yielding positive Subsidized Net Present Values (+310,600 € in Türkiye and +425,500 € in Italy) would otherwise face prohibitive payback barriers under standard unassisted market conditions. Thus, policy instruments are not merely administrative backgrounds, but active performance-driving variables that dictate the feasibility, investment amortization, and indoor comfort outcomes of public building decarbonization.

It is crucial to clarify that national policy frameworks do not act as direct physical drivers of building performance gains or thermal comfort improvements. Instead, pol-

icy mechanisms function as structural and financial enablers that shape the economic boundaries within which retrofit scenarios are selected and evaluated. The logical pathway linking policy to outcomes is indirect yet instrumental: national incentive schemes, such as capital grants or subsidized financing structures, alter the initial capital expenditure (CAPEX) barriers of comprehensive packages (e.g., TR-4 and IT-4). By absorbing a significant share of upfront costs, these policy instruments transform technically optimal yet economically prohibitive deep retrofit scenarios into viable investments. Consequently, the resulting economic improvements (such as shortened payback periods and positive Subsidized NPVs) are the combined outcome of rigorous engineering performance design and supportive, market-influencing policy structures, rather than a direct mechanical consequence of regulatory procedures alone.

Finally, it is essential to acknowledge the contextual boundaries of this research. The specific quantitative outcomes detailed herein—including exact primary energy reductions, thermal comfort compliance rates, and financial metrics such as Subsidized NPVs and payback periods—are intrinsically tied to the climatic profiles, baseline architectural features, operational use patterns, and national policy incentive structures (namely, Italy's Conto Termico 3.0 and Türkiye's KABEV frameworks) examined in this study. Consequently, these numerical results should not be generalized across disparate climatic zones or alternative regulatory frameworks without localized recalibration. Instead, the primary transferable value and scientific contribution of this work lie in its integrated research framework and analytical methodology: a structured, multi-scenario evaluation pipeline that couples dynamic building energy and thermal comfort simulation with granular lifecycle economic assessment under policy-driven boundary conditions. This methodological approach offers a robust, replicable blueprint for researchers and institutional stakeholders aiming to evaluate the techno-economic feasibility of public building retrofits in other regional contexts.

7. Conclusions

This study developed a comprehensive, calibrated simulation and economic assessment framework to evaluate the technical viability, thermal comfort performance, and financial feasibility of country-specific green building retrofitting scenarios in public educational infrastructure. By deploying models of representative university buildings in Türkiye and Italy, the analysis systematically contrasted the thermodynamic and financial impacts of national energy policies, including KABEV, EPC models, and NSEB mandates for Türkiye, alongside CAM regulations and Conto Termico 3.0 frameworks for Italy.

The technical findings indicate that retrofitting strategies must be strictly aligned with baseline building physics and operational profiles. For older or less-insulated envelopes subjected to severe winter climates and continuous heating regimes, such as the Turkish case study, deep fabric insulation composite systems provide the most critical thermal barrier, yielding substantial drops in primary energy consumption and major reductions in annual thermal discomfort hours. Conversely, in milder Mediterranean climates with existing structural frames approaching contemporary thermal resistance limits, such as the Italian case study, envelope insulation yields diminishing returns. Instead, the optimization focus shifts to localized solar control configurations to mitigate summer overheating, and system electrification via high-efficiency air-to-water heat pumps to maximize carbon reduction and environmental quality. Furthermore, while active electromechanical enhancements like mechanical ventilation loops are crucial for safeguarding indoor air quality and regulating carbon dioxide buildup, the integration of high-effectiveness heat recovery units is required to offset the associated fan power penalties.

From an economic perspective, standard unassisted market mechanisms prove insufficient for promoting comprehensive public sector renovations, as baseline payback periods frequently exceed typical public administrative planning horizons. The introduction of targeted green building policy frameworks fundamentally alters this investment dynamic. Direct capital grants and structured financing architectures effectively absorb high initial expenditure friction, compressing payback loops by more than half and shifting deep near-zero energy building pathways into highly competitive, financially secure territories that generate substantial long-term Subsidized Net Present Values. Additionally, the sensitivity analysis confirms the robust "future-proofing" capability of integrated retrofits, demonstrating that comprehensive intervention packages provide the highest shielding efficacy and budget stability against volatile energy market tariff shocks.

Ultimately, achieving near-zero energy building standards requires a holistic synergy between passive load reductions, high-efficiency active electromechanical systems, and decentralized rooftop photovoltaic networks. While these multi-tiered strategies present the highest initial implementation barriers, structured state incentive programs successfully minimize the comparative investment risks. This study confirms that targeted public policy is the primary mechanism required to comfortably shift institutional portfolios toward comprehensive, resilient, and future-proofed building decarbonization.

In conclusion, this study bridges a critical gap in the literature by establishing an integrated framework that synthesizes policy incentives, building performance, and economic evaluation for public educational infrastructure. The theoretical contribution of this work lies in demonstrating that deep decarbonization cannot be successfully conceptualized solely through technical or economic lenses in isolation; rather, it requires a synchronized multi-objective approach where regulatory mandates and structured public incentives function as active performance-driving variables. By proving that targeted mechanisms, such as Italy's Conto Termico 3.0 and Türkiye's KABEV frameworks, effectively neutralize the barriers of high initial capital expenditures and long payback periods, this research offers a transferable decision-making paradigm. Ultimately, the findings highlight that harmonizing cross-border policy instruments with rigorous performance modeling is indispensable for accelerating public sector climate neutrality while ensuring long-term fiscal viability and enhanced indoor environmental quality.

Building upon the findings and acknowledged boundaries of this study, future research should focus on replacing deterministic operational assumptions with dynamic, real-world granular parameters. First, incorporating human psychological dimensions, specifically by integrating advanced behavioral and mood-state factors into the dynamic HVAC simulation loops, would allow models to capture how cognitive load alters indoor climate satisfaction beyond rigid standardized thermal indices. Second, expanding the computational boundary from isolated high-density classroom zones to whole-building, multi-zone simulations would capture the complex thermodynamic interactions between distinct functional areas like high-load laboratories, administrative offices, and unconditioned corridors. Finally, future investigations should employ stochastic financial modeling, such as Monte Carlo simulations, to map volatile macroeconomic variables, technology cost deflation, and material supply chain inflation, thereby providing a probabilistic risk distribution to further secure public sector energy performance contracting in unpredictable economic climates.

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Abbreviations

The following abbreviations are used in this manuscript:

CAM	Criteri Ambientali Minimi (Minimum Environmental Criteria)
CAPEX	Capital Expenditure
CO_2	Carbon Dioxide
COP	Coefficient of Performance
EER	Energy Efficiency Ratio
EPC	Energy Performance Contracting
HVAC	Heating, Ventilation, and Air Conditioning
IEQ	Indoor Environmental Quality
IT	Italy/Italian Case Study
KABEV	Kamu Binalarında Enerji Verimliliği (Energy Efficiency in Public Buildings Project)
LED	Light-Emitting Diode
NPV	Net Present Value
NSEB	Nearly Zero Energy Buildings (National Framework)
SPP	Simple Pay-back Period
TR	Türkiye/Turkish Case Study
U	Thermal Transmittance (W/m^2K)

References

1. Karakosta, C.; Papathanasiou, J. Decarbonizing the Construction Sector: Strategies and Pathways for Greenhouse Gas Emissions Reduction. *Energies* **2025**, *18*, 1285. [CrossRef]
2. Turhan, C.; Doruk, Ö.R.; Alkan, N.; Özbey, M.F.; Chen Austin, M.; Thapa, S.; Yılmaz, V.S.; Erdoğan, E.; Akpınar, B.M.; Pekcan, P. Next Generation Mood Adaptive Behavioral Modeling for Decarbonizing Office Buildings and Optimizing Thermal Comfort. *Atmosphere* **2026**, *17*, 377. [CrossRef]
3. Awan, A.; Kocoglu, M.; Subhan, M.; Utepkaliyeva, K.; Mohamed Yusoff, N.Y.B.; Hossain, M.E. Assessing energy efficiency in the built environment: A quantile regression analysis of CO_2 emissions from buildings and manufacturing sector. *Energy Build.* **2025**, *338*, 115733. [CrossRef]
4. De la Cruz-Lovera, C.; Perea-Moreno, A.-J.; De la Cruz-Fernández, J.-L.; Alvarez-Bermejo, J.A.; Manzano-Agugliaro, F. Worldwide Research on Energy Efficiency and Sustainability in Public Buildings. *Sustainability* **2017**, *9*, 1294. [CrossRef]
5. Lee, J.; Shepley, M.M.; Choi, J. Exploring the effects of a building retrofit to improve energy performance and sustainability: A case study of Korean public buildings. *J. Build. Eng.* **2019**, *25*, 100822. [CrossRef]
6. Papadakis, N.; Katsaprakakis, D.A. A Review of Energy Efficiency Interventions in Public Buildings. *Energies* **2023**, *16*, 6329. [CrossRef]
7. Almasri, R.A.; Abu-Hamdeh, N.H.; Al-Tamimi, N. A state-of-the-art review of energy-efficient and renewable energy systems in higher education facilities. *Front. Energy Res.* **2024**, *11*, 1344216. [CrossRef]
8. Özbey, M.F.; Turhan, C. The importance of the calculation of angle factors to determine the mean radiant temperature in temperate climate zone: A university office building case. *Indoor Built Environ.* **2022**, *31*, 1004–1017. [CrossRef]
9. Turhan, C.; Gökçen, G. Assessment of Thermal Comfort Preferences in Mediterranean: A university office building case. *Therm. Sci.* **2018**, *22*, 2177–2187. [CrossRef]
10. Turhan, C.; Ghazi, S. Energy consumption and thermal comfort investigation and retrofitting strategies for an educational building: Case study in a temperate climate zone. *J. Build. Des. Environ.* **2023**, *1*, 16869. [CrossRef]

11. Eleftheriadis, G.; Hamdy, M. Impact of building envelope and mechanical component degradation on the whole building performance: A review paper. *Energy Procedia* **2017**, *132*, 321–326. [CrossRef]
12. Turhan, C.; Saleh, Y.A.S.; Turhan, B. Simulation-Based Optimization of HVAC Systems in Aging Educational Facilities: Addressing IAQ Challenges Through Retrofitting. *Sustainability* **2026**, *18*, 3079. [CrossRef]
13. Bertoldi, P.; Rezessy, S. *Financing Energy Efficiency: Forging the Link Between Financing and Project Implementation*; Joint Research Centre of the European Commission: Ispra, Italy, 2010. Available online: https://build-up.ec.europa.eu/sites/default/files/content/financing_energy_efficiency.pdf (accessed on 13 July 2026).
14. Sučić, B.; Matešić, G.; Vogt, G.; Cholewa, T. Energy efficiency in buildings: EPC and SRI as enablers of future renovations. *Energy Build.* **2026**, *361*, 117502. [CrossRef]
15. Barbosa, G.; Almeida, M. Strategies for Implementing and Scaling Renovation Passports: A Systematic Review of EU Energy Renovation Policies. *Sustainability* **2025**, *17*, 2289. [CrossRef]
16. Napoli, G.; Gabrielli, L.; Barbaro, S. The efficiency of the incentives for the public buildings energy retrofit. The case of the Italian Regions of the "Objective Convergence". *Valori Valutazioni* **2017**, *18*, 45–58.
17. Yang, X.; Zhang, J.; Shen, G.Q.; Yan, Y. Incentives for green retrofits: An evolutionary game analysis on Public-Private-Partnership reconstruction of buildings. *J. Clean. Prod.* **2019**, *232*, 1076–1092. [CrossRef]
18. Turhan, B.; Turhan, C. Financial and Tax Incentives in Green Buildings: A Comparative View of Türkiye and the World. *ZeroBuild J.* **2025**, *3*, 22–40. [CrossRef]
19. Ministry of the Environment and Energy Security. The Minimum Environmental Criteria (CAM) [Criteri Ambientali Minimi]. Available online: https://www.mase.gov.it/portale/cosa-sono-i-cam (accessed on 6 July 2026).
20. Gestore dei Servizi Energetici (GSE). Conto Termico 3.0. Available online: https://www.gse.it/servizi-per-te/efficienza-energetica/conto-termico-3-0/documenti (accessed on 13 July 2026).
21. Republic of Türkiye Ministry of Environment, Urbanisation and Climate Change. Energy Efficiency in Public Buildings Project (KABEV). Available online: https://www.kabev.org/proje-hakkinda/ (accessed on 2 July 2026). (In Turkish)
22. European Commission Joint Research Centre (JRC). Energy Performance Contracting (EPC) Models Implemented by Energy Service Companies (ESCOs). Available online: https://joint-research-centre.ec.europa.eu/ (accessed on 13 July 2026).
23. Republic of Türkiye Ministry of Environment, Urbanisation and Climate Change. *Regulation on Amending the Regulation on Energy Performance in Buildings [Binalarda Enerji Performansı Yönetmeliğinde Değişiklik Yapılmasına Dair Yönetmelik]*; No. 31755; Official Gazette: Ankara, Türkiye, 2022. Available online: https://www.resmigazete.gov.tr/eskiler/2022/02/20220219-5.htm (accessed on 1 July 2026).
24. Arıoğlu Akan, M.Ö.; Selam, A.A.; Oktay Fırat, S.Ü.; Er Kara, M.; Özel, S. A Comparative Analysis of Renewable Energy Use and Policies: Global and Turkish Perspectives. *Sustainability* **2015**, *7*, 16379–16407. [CrossRef]
25. Ranđelović, D.; Jovanović, V.; Ignjatović, M.; Marchwiński, J.; Kopyłow, O.; Milošević, V. Improving Energy Efficiency of School Buildings: A Case Study of Thermal Insulation and Window Replacement Using Cost-Benefit Analysis and Energy Simulations. *Energies* **2024**, *17*, 6176. [CrossRef]
26. DesignBuilder Software Ltd. *DesignBuilder Software*, Version 7.0; DesignBuilder Software Ltd.: Stroud, UK, 2026. Available online: https://designbuilder.co.uk (accessed on 13 July 2026).
27. Beck, H.E.; Zimmermann, N.E.; McVicar, T.R.; Vergopolan, N.; Berg, A.; Wood, E.F. Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Sci. Data* **2018**, *5*, 180214. [CrossRef] [PubMed]
28. Özbey, M.F.; Çeter, A.E.; Örfioğlu, Ş.; Alkan, N.; Turhan, C. Sensitivity analysis of the effect of current mood states on the thermal sensation in educational buildings. *Indoor Air* **2022**, *32*, e13073. [CrossRef] [PubMed]
29. Campagna, L.M.; Fiorito, F. On the energy performance of the Mediterranean school building stock: The case of the Apulia Region. *Energy Build.* **2023**, *293*, 113187. [CrossRef]
30. Italian Republic. *Decreto Interministeriale 16 Settembre 2016—Programma di Riqualificazione Energetica degli Edifici della Pubblica Amministrazione Centrale (PREPAC)*; Gazzetta Ufficiale della Repubblica Italiana No. 258; Italian Republic: Rome, Italy, 2016.
31. World Bank. *Turkey Public and Municipal Renewable Energy Project (KAYEP)*; Project ID: P179867; World Bank Group: Washington, DC, USA, 2023.
32. *TS 825*; Thermal Insulation Requirements for Buildings (Binalarda Isı Yalıtım Kuralları). Turkish Standards Institution (TSE): Ankara, Türkiye, 2013.
33. *ANSI/ASHRAE Standard 62.1*; Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2022.
34. *ANSI/ASHRAE Standard 55*; Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2020.
35. *ISO 7730*; Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. International Organization for Standardization: Geneva, Switzerland, 2005.

36. *EN 16798-1*; Energy Performance of Buildings—Ventilation for Buildings—Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics. European Committee for Standardization: Brussels, Belgium, 2019.
37. Gorshkov, A.S.; Vatin, N.I.; Rymkevich, P.P.; Kydrevich, O.O. Payback period of investments in energy saving. *Mag. Civ. Eng.* **2018**, *78*, 65–75.
38. Berian, Z.Y.; Kaulika, V.O. Can energy trading be a solution for Indonesia's energy mix goal through solar energy? *Indones. J. Energy* **2020**, *3*, 94–106. [CrossRef]
39. Kimlinger, J.P.; Dobbs, D.D. A utility perspective: Subsidized projects—How much should you pay? In *Proceedings of the 2001 International Ash Utilization Symposium, Center for Applied Energy Research*; University of Kentucky: Lexington, KY, USA, 2001.
40. Shan, R.; Lai, W.; Tang, H.; Leng, X.; Gu, W. Residential Building Renovation Considering Energy, Carbon Emissions, and Cost: An Approach Integrating Machine Learning and Evolutionary Generation. *Appl. Sci.* **2025**, *15*, 1830. [CrossRef]
41. Sungun, C.G.; Saleh, Y.A.S.; Turhan, C. A pathway to psychology-sensitive HVAC devices. *ZeroBuild J.* **2026**, *4*, 14–27. [CrossRef]
42. Saleh, Y.A.S.; Turhan, C.; Sümer, M.E.; Lotfi, B.; Özbey, M.F. From facial expressions to thermal sensation: POMS-validated AI-based mood estimation driving psychology-adaptive HVAC control. *Energy Build.* **2026**, *360*, 117402. [CrossRef]
43. Özbey, M.F.; Turhan, C.; Alkan, N.; Akkurt, G.G. Latent Psychological Pathways in Thermal Comfort Perception: The Mediating Role of Cognitive Uncertainty on Depression and Vigour. *Buildings* **2025**, *15*, 2538. [CrossRef]
44. Turhan, C.; Özbey, M.F.; Çeter, A.E.; Akkurt, G.G. A Novel Data-Driven Model for the Effect of Mood State on Thermal Sensation. *Buildings* **2023**, *13*, 1662. [CrossRef]
45. Carlucci, S.; Bai, L.; de Dear, R.; Yang, L. Review of adaptive thermal comfort models in built environmental regulatory documents. *Build. Environ.* **2018**, *137*, 73–89. [CrossRef]
46. Nasrollahi, F.; de Dear, R. Application of adaptive thermal comfort in mechanically conditioned learning environments in Berlin, Germany. *Build. Environ.* **2026**, *296*, 114493. [CrossRef]

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