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Review

A Review of Energy Efficiency Interventions in Public Buildings

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Abstract: This research provides a comprehensive exploration of energy efficiency dynamics in non-residential public buildings such as schools, swimming pools, hospitals, and museums. Recognizing the distinct energy consumption patterns of each building type, the study accentuates the unique challenges they present, with a particular focus on the continuous and intensive energy demands of hospitals and the unparalleled energy needs of swimming pools. Through an extensive review of various case studies, the research unveils prevailing energy consumption trends, highlighting the role of metrics in assessing energy efficiency and the inherent challenges these metrics face in ensuring uniformity and direct comparability. A core element of this analysis emphasizes the dual nature of technical retrofitting, categorizing interventions into passive and active measures. The research delves into the sustainability imperatives of energy interventions, exploring the economic motivations underpinning retrofit decisions, and the intricate relationship between advanced technological solutions and the behavioral tendencies of building operators and users. Additionally, the study uncovers the influence of external determinants such as climatic factors and government policies in shaping energy consumption in public buildings. In synthesizing these findings, the paper offers insightful recommendations, emphasizing the need for an integrated approach that harmonizes technological innovations with informed operational habits, aiming to optimize energy efficiency in public non-residential buildings.

Keywords: buildings; energy efficiency; retrofit; energy saving; hospitals; museums; sport-halls; schools; insulation; RES; heating; cooling

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1. Introduction

1.1. Brief Overview of the Importance of Energy Efficiency in Public Building

Energy-saving in buildings is a subject of paramount importance in the global quest for sustainable development and environmental conservation. Buildings are responsible for approximately 40% of energy consumption and 36% of CO_2 emissions in the EU, making them a significant contributor to man-made greenhouse gases [1–3]. In the United States, commercial and residential buildings account for about 40% of the nation's total energy consumption [4].

The pursuit of energy efficiency in buildings encompasses a wide array of strategies including optimizing heating, cooling, and lighting systems, integrating renewable energy sources, improving insulation and window design, and adopting smart building technologies. Implementing these strategies can lead to a reduction in energy consumption by up to 50% in many cases [5,6].

Public institutions and government facilities significantly contribute to water and energy consumption, yet despite the substantial savings potential offered by energy and water-efficient technologies, various implementation barriers more acute than those in the residential sector inhibit the growth of an effective retrofitting industry [7].

Energy-saving in buildings does not only have environmental implications; it also translates into economic benefits. Lower energy consumption reduces utility costs for occupants, and, on a macroeconomic level, decreases the reliance on fossil fuel imports, contributing to energy security. For example, a 10% increase in energy efficiency in the EU would lead to a 7% reduction in energy imports by 2030 [8].

Furthermore, energy-efficient buildings offer enhanced comfort and health benefits to occupants through better air quality and thermal regulation [9]. This can also contribute to increased productivity in workplaces, providing a multi-faceted incentive for investment in energy-saving measures.

The global emphasis on energy-saving in buildings has led to the development of various regulations and standards, such as the Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM). These frameworks guide the construction industry in designing and constructing more sustainable buildings, underscoring the significance placed on energy efficiency at all levels of governance.

The convergence of environmental stewardship, economic benefits, and social well-being positions energy-saving in buildings as a central element in the transition toward a sustainable future. It aligns with the United Nations Sustainable Development Goals, particularly Goal 7 on Affordable and Clean Energy and Goal 13 on Climate Action, reflecting the international consensus on the subject [10].

Investment in research, technology, and public awareness are essential to harness the full potential of energy-saving in buildings. Continued collaboration between governments, industries, scholars, and communities is required to foster innovation, enforce regulations, and educate stakeholders on the importance of this endeavor. The amalgamation of these efforts offers a promising pathway towards a resilient and sustainable built environment, harmonizing the relationship between human habitation and the natural world.

1.2. Categories of Energy Saving Interventions

Energy efficiency in public buildings encompasses a diverse range of interventions. Table 1 provides an overview of the major intervention categories, emphasizing their primary focus, associated challenges, and the opportunities they present [11].

Table 1. Categories of energy-saving interventions in buildings.

Intervention Category	Focus	Challenges	Opportunities
Technical	improving the efficiency of the building's systems and equipment.	Expensive to implement	Can lead to significant energy savings
Operational	changing the way that the building is operated.	May require changes to building operating procedures	Can be more cost-effective
Behavioral	Changing the way the building occupants use energy	More challenging to implement	Can be the most effective in the long run

1.2.1. Technical Interventions

In the context of energy efficiency, technical interventions stand out as a direct approach to reducing energy consumption by harnessing advanced technological solutions. Technical interventions pivot on the optimization of a building's systems and equipment, aiming to elevate its inherent efficiency levels. Unlike operational or behavioral strategies which emphasize procedural shifts and human behaviors, respectively, technical interventions delve into the tangible heart of a building's energy consumption framework. While these measures can sometimes be more expensive to implement, they offer the promise of significant energy savings, a trade-off that often justifies the initial investment. Given their tangible impact and lasting modifications, technical interventions will be the primary focus of this research, shedding light on their multifaceted benefits and challenges in the broader context of energy conservation.

Improving the building's envelope through better insulation techniques is another pivotal technical intervention. Enhanced insulation in walls, roofs, and especially windows minimizes heat loss during colder seasons and reduces heat ingress during warmer months. This dynamic adjustment in turn leads to decreased reliance on HVAC systems. Water heating, often a significant energy consumer, has seen innovations with the advent of energy-efficient water heaters, drastically cutting down energy used for heating water.

Another of the most notable trends in this category is the transition to energy-efficient lighting. LEDs, for instance, not only consume less energy but also last longer, thereby reducing both energy and maintenance costs.

Advanced HVAC systems are being heralded as the next step in refining the internal environment of public buildings. Modern HVAC systems can adjust the airflow based on the specific needs of different zones in a building, ensuring that energy is not wasted on overcooling or overheating certain areas. Moreover, the integration of modern, energy-efficient appliances further aids in the reduction in overall energy usage. As these appliances have been engineered with energy conservation in mind, they often outperform their older counterparts in both functionality and energy efficiency.

Furthermore, integrating renewable energy sources, such as solar panels or wind turbines, helps to diversify the energy mix of public buildings, reducing their dependence on non-renewable sources. Such interventions not only lower energy costs but also move public buildings towards a more sustainable and environmentally-friendly trajectory.

Another technical strategy that is gaining traction is the implementation of demand response programs. These programs empower building managers to curtail or shift their energy use during peak demand times. Such shifts not only result in cost savings but also aid in maintaining the stability and reliability of the larger electrical grid.

In line with the holistic approach to energy conservation, a novel addition to many modern retrofit practices is the provision of electric vehicle charging stations. While this addition does not directly impact the energy consumption of the building itself, it signifies a broader commitment to green and sustainable practices that extend beyond the building's immediate needs, reflecting a broader vision for a sustainable urban infrastructure [12].

1.2.2. Operational Interventions

Operational interventions center on modifying the way a building is operated, distinguishing them from technical strategies that emphasize enhancements to system and equipment efficiency. While operational measures might necessitate alterations to established building procedures, they bring forth their unique appeal. The initial challenge may lie in transitioning from customary procedures, but these adjustments often prove to be more cost-effective in comparison to their technical counterparts. By optimizing the daily operation routines and methodologies, operational interventions hold the potential to usher in substantial energy savings without the considerable expenses associated with infrastructural changes.

When considering energy-saving operational interventions, maintenance emerges as the paramount factor. Implementing efficient maintenance schedules can significantly curtail energy consumption by ensuring equipment functions optimally. A salient example is the routine cleaning and calibration of HVAC systems, enhancing their efficiency. However, the maintenance landscape of public buildings presents challenges. Despite the hefty expenditures associated with them, intuition predominantly governs their upkeep, leading to escalated costs of operations and maintenance [11,13]. Ighravwe and Osa shed light on this issue, introducing a multi-criteria maintenance scheme with a pronounced focus on sustainability. Their study pinpointed corrective maintenance as the most fitting approach for public edifices [14]. Additional research [15,16] underscored the significance of resources, stakeholder emphasis on maintenance, staff attitudes, and inter-stakeholder coordination. They also noted the influence of factors such as building type, age, and overall condition, albeit to a lesser degree.

Other operational interventions are:

- Energy management systems/Thermostat settings: Adjusting the thermostat to a lower temperature in the winter and a higher temperature in the summer can help to reduce energy consumption for heating and cooling [7].
- Occupancy sensors: Using occupancy sensors to automatically turn off lights and HVAC systems when rooms are not in use can help to reduce energy consumption [11].
- Lighting controls: Using lighting controls to dim lights or turn them off when they are not needed can help to reduce energy consumption [7,11]. Bertone et al. [7], proposed a framework for reducing the cost of energy using LED lights and saving water which yielded monetary savings of AUD$400 M over a decade and a reduction of carbon emissions by 23.7 million tonnes.
- Incentives: Offering incentives to building occupants for energy conservation can also help to encourage them to save energy. For example, some buildings offer rewards for reducing energy use, such as gift cards or reduced utility bills [14].
- Optimized Scheduling: Adjusting the operating hours of lighting, heating, or cooling systems based on occupancy patterns [13].
- Water conservation: Implementing water-saving practices such as rainwater harvesting or using water-efficient fixtures [7].

1.2.3. Behavioral Interventions

Behavioral interventions, focusing on altering the energy consumption habits of building occupants, stand distinct from technical and operational strategies. While technical interventions hone in on enhancing the efficiency of building systems and equipment, and operational methods revolve around adjustments to building operations, behavioral approaches present a unique set of challenges and prospects. Implementing such behavioral changes may pose considerable implementation challenges. However, when embraced and sustained, these interventions can potentially offer the most enduring and effective energy-saving benefits, marking them as invaluable assets in the broader spectrum of energy conservation efforts. Behavioral interventions, though crucial, would not be the central focus of this review. However, for context, it is pertinent to highlight some key behavioral interventions:

- Education/Energy Awareness Campaigns: Educating occupants about the importance of energy conservation and providing tips on how to save energy. Providing education to building occupants about energy efficiency can help them understand the importance of conserving energy and how they can do it. For example, some buildings offer workshops or presentations on energy efficiency.
- Incentive Programs: Offering incentives or rewards to occupants for adopting energy-saving behaviors, such as turning off lights when not in use. Offering incentives to building occupants for energy conservation can also help to encourage them to save energy. For example, some buildings offer rewards for reducing energy use, such as gift cards or reduced utility bills.
- Feedback Mechanisms: Providing real-time feedback on energy consumption to encourage responsible energy use. Providing feedback to building occupants on their energy use can help to encourage them to conserve energy. For example, some buildings display real-time energy use data on monitors or intranets [13,14]
- Occupant Engagement: Encouraging occupants to participate in energy-saving initiatives, such as carpooling or using public transportation.
- Social norms: Highlighting the social norms around energy conservation can help to encourage people to save energy. For example, some buildings highlight how much energy their occupants are saving compared to other buildings.
- Nudges: Nudging is a technique that uses small changes in the environment to influence people's behavior. For example, some buildings have placed stickers on light switches to remind people to turn off the lights when they leave a room.

- Competitions: Competitions can be a fun and effective way to encourage people to save energy. For example, some buildings have held competitions between departments or teams to see who can reduce their energy use the most.

1.3. Research Aim

This research endeavors to offer a profound analysis of the intricacies of energy efficiency technological interventions within an array of public non-residential buildings, including but not limited to schools, swimming pools, hospitals, and museums. Each of these establishments, given their unique operational requirements and energy demands, presents both shared and distinct challenges and opportunities for enhancing energy efficiency. Through a literature review of case studies across various building types, we aim to shed light on prevalent energy consumption patterns and the most effective energy efficiency interventions. We also attempt to highlight individual complexities of structures such as hospitals, with their continuous operations and energy-intensive activities, and the unparalleled energy intensiveness of facilities such as swimming pools.

The paper then categorizes energy efficiency interventions into technical, operational, and behavioral, with a particular focus on the merits and opportunities of technical retrofitting options. A pivotal aspect of this study focuses on the dichotomy of technical retrofitting, distinguishing between passive and active measures. In doing so, we delve deep into the sustainability aspects of energy interventions, the motivations behind retrofit decisions, and the nuanced interplay between technological interventions and the behavioral dynamics of building operators and occupants. The research underscores the significance of understanding energy metrics, their potential limitations, and the challenges they present in ensuring standardization and direct comparability.

Lastly, while technological advancements form a cornerstone of our exploration, we seek to shed light on external determinants that shape energy consumption in these buildings. Factors such as climatic conditions and evolving government policies, often overlooked, play a fundamental role in influencing energy consumption patterns. Our synthesis of these findings, combined with insights from technological and behavioral domains, culminates in recommendations designed to inform and inspire future endeavors in the realm of energy-efficient public non-residential structures.

2. Literature Review

2.1. Assessment Criteria for Energy Efficiency Intervention

The complexity and diversity of modern buildings, especially in the public sector, necessitate rigorous and multifaceted evaluation strategies to bolster energy efficiency. This introduction delves into the typical Key Performance Indicators (KPIs) that are frequently employed to assess energy efficiency interventions in buildings. These KPIs play a pivotal role in comprehending, gauging, and enhancing various facets of building performance. They can be broadly classified into three main categories: energy-related, economic, and social.

Energy-related KPIs are fundamental in gauging a building's environmental footprint and consumption efficiency. Among these indicators, the Energy Use Intensity (EUI) stands out as it measures the energy consumed per unit area, typically expressed in kWh/m^2 or BTU/ft^2, acting as a vital benchmarking tool. This allows stakeholders to compare a building's energy performance against its peers and identify potential areas for improvement. Another significant KPI is Energy Cost Savings, which translates energy-saving measures into tangible financial benefits, usually denoted in monetary units such as dollars or euros saved. The Carbon Footprint Reduction, which focuses on the emissions of gases such as CO_2, NO_2, and SO_2, is often measured in metric tons or kilograms of CO_2-equivalent, playing a pivotal role in aligning a building's operations with overarching sustainability objectives. Furthermore, the Energy Source Efficiency (ESE) evaluates the adoption and utilization of cleaner energy sources, often represented as a percentage or ratio. The combined metrics of HVAC and Lighting Efficiency ensure the optimal performance of heating, cooling, and lighting systems, with efficiency often gauged as a percentage of energy use or output. Water Use Efficiency (WUE) emphasizes the importance of water conservation, typically measured in liters or gallons per occupant or per square meter. Lastly, the Renewable Energy Contribution highlights the integration of sustainable energy sources into a building's energy framework, often expressed as a percentage of total energy sourced from renewables.

The economic dimension of KPIs provides a crucial lens through which energy efficiency is translated into financial metrics. The Return on Investment (ROI), typically expressed as a percentage, offers insights into the financial gains achieved in relation to the costs incurred, allowing stakeholders to gauge the profitability of their energy-saving measures. A closely associated metric, the Payback Period, measured in years or months, denotes the duration necessary to recoup the initial investment, serving as a testament to the economic feasibility of energy interventions [17,18]. Lastly, the Life Cycle Cost Analysis provides a panoramic view of the total costs associated with a building or an intervention [19]. This metric, often represented in monetary units such as dollars or euros, encompasses not only the initial purchase but also the operation, maintenance, and eventual disposal costs. By considering all these factors, it offers a comprehensive perspective on the long-term economic implications of energy efficiency measures.

Social KPIs serve as a bridge between the technical and economic facets of energy efficiency, ensuring that interventions resonate with human needs and societal values. Occupant Satisfaction, often gauged through surveys or feedback mechanisms, provides insights into the experiences and perceptions of individuals living or working in a building, shedding light on the direct impact of energy interventions on their well-being. Indoor Air Quality, measured using parameters such as particulate matter (PM) levels, volatile organic compounds (VOCs), and carbon dioxide (CO_2) concentrations, intertwines energy efficiency with health and comfort, underscoring the importance of a healthy indoor environment. Beyond the physical confines of a building, Community Engagement, typically assessed through participation rates or outreach metrics, mirrors the endeavors to involve the wider community. This engagement emphasizes the collective effort to raise awareness about sustainability and the pivotal role of energy efficiency in shaping a greener future.

In the subsequent presentation of case studies and review, one or more of these metrics have been used, highlighting their relevance and applicability in real-world scenarios.

2.2. School Case Studies

In recent years, the emphasis on energy-saving retrofits for educational buildings has gained significant traction [20–23]. A case study for a thermos-modernization of a school in Poland [24] reported significant energy savings. The building's heat consumption was reduced by 60%, its electricity consumption was reduced by 45%, and its hot water consumption was reduced by 75%. These improvements were achieved through a combination of measures, including the installation of new insulation, the replacement of windows and doors, the installation of a heat recovery system, and the installation of solar panels. The modernization was a success and is expected to pay for itself in about 7 years. In addition to the energy savings, the modernization also resulted in improved indoor air quality and reduced CO_2 emissions.

Brandengen Primary School in Drammen, Norway, underwent a retrofit from 2011 to 2016 as part of an EU 7FP project, targeting reduced energy consumption and an enhanced indoor climate while preserving the façade of its three historic brick buildings. Transitioning from oil-based systems, the school's original heating setup, which combined an oil burner with an electric boiler, was replaced by a heat pump connected to 19 ground source energy wells drilled in the schoolyard. This efficient design, now standard in Norway, eliminates fossil fuel reliance. Post-retrofit, the school achieved a 67% reduction in energy needs. The retrofit emphasized energy consumption reduction, CO_2 emission cuts, improved building insulation, window replacements, and a shift from oil to geothermal energy, retaining the old oil burner for peak loads [25].

A case study for a school in Cyprus considered various retrofitting measures, both active and passive, to enhance the energy performance of school buildings [26]. Active measures, such as Mechanical Ventilation with Heat Recovery (MVHR), have been spotlighted for their potential to drastically reduce primary energy consumption by up to 49%. On the passive front, the article underscores the importance of insulation, both on roofs and walls, which can lead to primary energy reductions of 18% and 9%, respectively. Additionally, the potential of technologically advanced window replacements and the strategic placement of shading devices in south-oriented classrooms are highlighted. These passive measures not only aim to reduce energy consumption but also enhance the overall comfort within the educational environment. The combined retrofitting scenarios, integrating both active and passive strategies, promise energy demand savings ranging from 62% to 77%. The article posits that such retrofits, when expertly applied, can serve as a holistic solution, offering both environmental benefits in terms of reduced energy consumption and economic advantages by potentially lowering life cycle costs.

Heracleous et al. (2023) [12] reported on the case study of a public school building constructed in 1980. They adopted a comprehensive approach to energy conservation was adopted, targeting both passive and active interventions. Passive measures primarily revolved around the building fabric. The envelope was enhanced with graphite Expanded Polystyrene (EPS) slabs, both on the roof and the bearing structures, significantly reducing thermal transmittance. Concurrently, existing windows were replaced with double-glazed, laminated versions featuring an 18 mm air gap and a low-e membrane, further optimizing the building's insulation. Active interventions were equally pivotal. The outdated fluorescent lighting system was substituted with energy-efficient LED lamps. Moreover, a state-of-the-art grid-connected Photovoltaic (PV) system was introduced, aiming to meet the building's electricity demands. This was complemented by a sophisticated KNX protocol-based monitoring system, ensuring real-time management and oversight of energy consumption. Collectively, these measures underscore the potential of retrofitting in transforming educational buildings into exemplars of energy efficiency, setting a precedent for future endeavors in the realm of sustainable architecture.

A study in Korean schools [27], focused on the evaluation of the interplay between energy retrofit measures and internal air quality (IAQ) in classrooms. Active measures such as mechanical ventilation and air purifiers were essential, especially when airtightness was enhanced, to prevent the trapping of contaminants. On the passive front, envelope modifications, including the replacement of external windows and insulation addition, were pivotal. These passive measures, while energy-efficient, necessitated a careful balance to ensure optimal IAQ. For instance, the benefits of natural ventilation had to be weighed against potential outdoor contaminants. The research accentuates the imperative of a comprehensive strategy in school retrofits, harmonizing energy efficiency with a conducive indoor environment for the academic community.

A study of in installation of PV stations on two school rooftops in Hersonissos Crete [28], offers a practical methodology for developing municipality-led Renewable Energy Communities (RECs). Through a multi-criteria assessment, optimal PV placements were determined, emphasizing the importance of the "loose-restriction" factor in navigating legislative and technical barriers. The proposed energy-sharing scheme led to 68.40% savings in the municipality's annual electricity consumption and significant CO_2 reduction while maintaining a satiation factor of 99.8%. This approach anticipates a 24.80% total energy consumption reduction and a 43.30% decrease in CO_2 emissions.

Katsaprakakis et al. proposed a methodology for hybrid power (Solar-Combi System) for Indoor Space Heating for a school in Greece [29]. The system utilized solar collectors, thermal storage water tanks, and a biomass heater. A unique algorithm is introduced to maximize thermal storage use and solar collector output. When tested on a 1000 m^2 school building in Crete, the system can cover its annual heating needs, with solar collectors contributing over 45% at an average Levelized Cost Of Energy (LCOE) of 0.15 €/kWh_{th}. The building's abundant solar radiation in Crete and its intermittent operation significantly enhance solar collector efficiency, achieving over 50% annual heating coverage. However, the sole reliance on thermal energy for heating extends the payback period to 19.50 years.

2.3. Swimming Pools

The energy usage of sports centers has been reported in many references in the past. Table 2 summarises the energy usage from studies in the UK. The CIBSE Energy Benchmark [30] published in 2008 reported that on average swimming pool centers required 245 kWh/m^2 of electricity and 1130 kWh/m^2 of gas. Similar results are also found in the ECON 78 report [31], which was published in 2001. This is consistent with other findings that report that swimming facilities use between 400 kWh/m^2 and almost 1600 kWh/m^2 [32].

Table 2. Energy use in swimming pools (CIBSE Energy Benchmark (TM46: 2008) [30] and ECON 78 (2001) [31]).

Source		**CIBSE Energy Benchmark [30]**	**ECON 78 [31]**
Publication Year		**2008**	**2001**
Description		Swimming Pool	Leisure pool centre
Electricity (kWh/m^2)	Good		164
	Typical	245	258
Gas (kWh/m^2)	Good		673
	Typical	1130	1321

In a comparable study undertaken in Greece, Trianti–Tsourna and colleagues [33] observed, based on scrutinized data from five swimming facilities, mean annual energy consumption rates of 450 kWh/m^2 for floor area and 1094.5 kWh/m^2 for water surface area, along with an average annual electricity use of 57.5 kWh/m^2 per floor area. These observed variations could be ascribed to regional climatic conditions as well as inconsistencies in the employed Key Performance Indicator (KPI) calculation methods. Furthermore, the study noted that straightforward architectural modifications, such as enhanced wall and roof insulation, window shading, and increased natural ventilation, could mitigate cooling requirements by up to 45%.

A solar combi system was considered for the thermal loads for a swimming pool at the Pancretan Stadium [34], considered a combination of solar thermal collectors, biomass heaters, and thermal storage tanks along with use of and offered a viable transition from fossil fuels to renewables, covering 55% of annual thermal energy demand with solar collectors and 45% with biomass heaters, resulting in a 5–6 year payback period. Especially effective in regions with high solar radiation, these systems can bolster local economies by reducing reliance on imported fossil fuels and promoting local biomass production. Their adoption is particularly beneficial in southern climates with consistent yearly thermal demands, warranting governmental support for broader energy transition plans.

Katsaprakakis et al. [35] explored the energy enhancement of the Arkalochori municipal sports centre's swimming pool, constructed in 2002 in Greece. Initially lacking in energy efficiency, the team's interventions transformed it into a zero-energy establishment. Key improvements encompassed insulating opaque areas, modernizing openings, creating a bioclimatic enclosure for the pool, integrating heat pumps for ambient conditioning and pool warming, establishing a solar-combi system for consistent hot water supply, revamping lighting systems, and introducing a photovoltaic installation. These strategic measures not only facilitated the year-round operation of the pool but also yielded substantial energy savings: a surge of over 45% for indoor climate control, exceeding 70% for lighting and water heating, and a remarkable 88% for pool temperature regulation. The project's return on investment is projected at 14 years and has been distinguished with the "Islands Gamechanger" award by the European Commission.

Zuccari et al. [36] reported on the energy consumption of sports swimming pools, highlighting their significant energy demands. Using the EnerPool algorithm, they identified energy efficiency measures involving heating, and filtration that can lead to substantial non-renewable primary energy savings of up to 50% at minimal costs. Additionally, integrating high-efficiency systems and renewable sources such as solar collectors and photovoltaic panels can offer further energy and economic benefits. The study's conclusions emphasized potential energy savings between 19% and 47%.

Marinopoulos and Katsifarakis [37] focused on enhancing the sustainability of swimming pools by reducing energy and water consumption, using an open municipal swimming pool in Thessaloniki, Greece, as a case study using RETScreen [38]. The research found potential energy savings of up to 80–90% with the installation of solar thermal collectors, geothermal heat pumps, photovoltaic panels, and the construction of a light roof. The criteria for the optimal solution were evaluated through a Cost-Benefit Analysis, employing the Net Present Value criterion, the Internal Rate of Return criterion, and the Benefit-Cost ratio. They also mentioned future research on the possibility of exploring the combined use of geothermal heat pumps with solar panels for cost efficiency.

2.4. Sports Centers

The energy usage of sports centers might range from under 100 to 350 kWh/m^2/year (see Table 3) in the UK (CIBSE Energy Benchmark (TM46: 2008) [30] and ECON 78 (2001) [31]), depending on the facilities and location. In a similar study in Greece, Trianti–Tsourna et al. [39] reported based on audited data from 17 sports facilities, the average annual energy consumption metrics are as follows: 322.3 kWh/m^2 for heating, and 37.14 kWh/m^2 for electricity (These figures account for influences such as heat pumps, ventilation, and electrical motors in operation during games). In Sweden, the sports hall was reported to have an annual energy consumption between 145 and 174 kWh/m^2 per annum [26,27].

Table 3. Energy use in sport centers (CIBSE Energy Benchmark (TM46: 2008) [30] and ECON 78 (2001) [31]).

Source		CIBSE Energy Benchmark (TM46: 2008) [30]	ECON 78 (2001) [31]
Description		Sports Center	Local dry sports Center
Electricity (kWh/m^2)	Good		64
	Typical	95	105
Gas (kWh/m^2)	Good		158
	Typical	330	343

Trianti–Stourna [39] presented energy conservation strategies for sports halls, emphasizing retrofitting methods to enhance energy efficiency. Among the recommended retrofitting interventions are architectural modifications such as insulating external walls, introducing south-facing clerestories, adding sun spaces, shading openings, and enhancing natural ventilation. The study also underscores the importance of installing economizers and heat recovery systems where suitable. They reported that at the time lighting systems could benefit from the use of well-maintained metal halide lamps. Large sports halls, in particular, can leverage passive solar interventions to meet a significant portion of their annual heating and cooling needs. Furthermore, the integration of energy-efficient techniques in existing Heating, Ventilation, and Air Conditioning (HVAC) systems, including the use of economizers, heat recovery systems, and Building Energy Management Systems (BEMS), is advocated. In terms of energy consumption metrics, the research indicates an average annual total energy consumption of 73.2 kWh/m^2 (calculated over the entire facility area). Specifically, the heating energy consumption average was calculated based on the heated room area and it was found to be 322.3 kWh/m^2 annually, while the electrical energy consumption stands at 37.14 kWh/m^2. The difference between the total energy consumption and the heating energy consumption in kWh/m^2 is because in the denominator different areas are used (the heated areas are smaller than the total area). This also highlights a potential pitfall of the energy efficiency research, i.e., that metrics are easy to be constructed however they are not always directly comparable or do not permit certain numerical calculations, that would otherwise seem intuitive. Similar results are reported in Sweden for swimming pools [40,41].

Katsaprakakis et al. [17] investigated the energy upgrade of large sports facilities the Pancretan Stadium in Crete. A combination of passive and active measures, including replacing old openings, introducing a photovoltaic station, an open loop geothermal system, energy-efficient lighting, a solar-biomass combi system, and a BEMS, were proposed. These measures, optimized through computational simulations, resulted in an impressive 83% annual energy saving, with renewable energy sources accounting for 82% of the annual energy consumption. The stadium's energy rank improved from D to A+, aligning with EU directives. The study underscores the vast energy-saving potential of large sports facilities. An interesting "behavioural intervention" is that the project also aims to educate the public on energy conservation, using demonstrative screens and educational visits, fostering an "energy-friendly education" for future generations.

A study in a sports facility in Dubai [42] proposed a tool to estimate the power and energy required by sports centers, with an emphasis on achieving self-energy sufficiency through renewable energy sources (RES). The research followed a three-step approach: analyzing energy needs, assessing local RES availability, and balancing the energy of Sports Centers. A LabVIEW program was developed to calculate the energy requirements, considering factors such as sports halls, activity levels, and local climatic conditions. The study focused on the introduction and implementation of hydrogen technologies. Two case studies were presented: one where the sports center is entirely powered by RES, resulting in a zero-emission system, and another reliant on non-renewable sources, producing emissions of about 6000 t/year.

2.5. Hospitals

Hospital buildings, which require diverse indoor environments for the comfort of patients and staff, are among the highest thermal energy consumers per surface area. Given their significant energy consumption, especially in operation rooms, energy-efficient designs are crucial, presenting numerous opportunities for optimization. A large study in Spanish healthcare buildings [43] assessed the economic and environmental impacts of energy consumption, proposing various energy-saving measures. An in-depth study was conducted between 2005 and 2013 across 12 hospitals and 70 healthcare centres in Spain, built from 1980 to 2005. The study concentrated on various factors such as electrical energy, HVAC, domestic hot water (DWH), lighting systems, renewable energy sources, maintenance strategies, thermal insulation, and optimal building dimensions. Critical metrics assessed encompassed energy savings, financial investment, and emissions of CO_2, NO_2, and SO_2, as well as payback periods. The results emphasized that effective energy management could yield annual savings of up to 8.60 kWh/m^2 for structures smaller than 5000 m^2 without beds, at a cost of 1.55 €/m^2. In the case of larger healthcare facilities exceeding 5000 m^2 and containing beds, the achievable savings amount to 6.88 kWh/m^2 per year, with associated costs of 1.25 €/m^2. I.e smaller facilities tend to have more margin for energy savings per square meter (up to 25% more) at a larger cost. The study underscores the importance of regular energy audits to optimize real energy consumption in healthcare facilities, aiding in prioritizing measures to cut down operational costs and energy use.

Bertone et al. [7], proposed a hybrid Bayesian Network (BN)-system Dynamics (SD) modelling framework to explore strategies for energy and water retrofit projects in Australian public buildings, focusing on hospitals due to their high consumption. The BN model assessed various financing and procurement methods to determine their effect on retrofit willingness. It identified revolving loan funds (RLF) coupled with Energy Service Companies (ESCOs) as the optimal strategy. The BN model was linked to an SD model to calculate the impact of this strategy on energy and water savings for two retrofit solutions: solar PV panels and LED lights with tap aerators. With an RLF capital investment of

AUD$80 M, the framework predicted significant monetary savings of around AUD$400 M over ten years and reduced carbon emissions by over 23.7 million tonnes. This aligns with the Australian government's carbon reduction goals, contributes to water savings essential in changing climate conditions, and promotes a growing retrofit industry, thereby encouraging more retrofitting in other sectors and job creation. The potential of cost-effective water-saving devices such as tap aerators to significantly cut energy consumption was also highlighted.

Buonomano et al. [44] explored energy-saving actions for refurbishing select buildings at the University Hospital Federico II of Naples, emphasizing sustainable measures such as roof thermal insulation, a substation climatic 3-way valve, radiators thermostatic valves, and AHU (air handling unit) time-programmable regulation. However, roof insulation, though costly, offers limited benefits, especially for shorter buildings. It is noteworthy that potential measures such as envelope insulation, window replacements, and advanced HVAC systems were not pursued due to budgetary constraints and potential service disruptions.

Yuan et al. [45], offered a comprehensive review of 180 studies on hospital thermal comfort, emphasizing influencing factors, field-surveys, improvement measures, and energy-saving related to thermal comfort. They reported on the importance of ventilation systems are crucial in ensuring thermally-comfortable conditions, with thermal comfort being highly dependent on patients' health conditions and staff activities. They also stressed the importance of retrofitting windows and walls, and adjusting ventilation strategies, on energy efficiency. The study underscored the significance of understanding factors affecting thermal comfort, such as gender, age, and health conditions. Effective measures such as self-warming blankets, prototype thermal compression devices, and in-line intravenous fluid warming enhance body temperature control for perioperative patients, which can be considered operational or behavioural interventions.

Aziz et al. [46] proposed room temperature control, efficient lighting, optimized Air-Conditioning Split Units (ACSU), and Variable Speed Drive (VSD) installations as Energy Efficiency Initiatives (EEI) for a hospital in Selangor, Malaysia, to curb energy usage. Implementing these EEIs was projected to save 1,250,692 kWh/year, translating to a cost reduction of approximately €88,044/year and a decrease of 869 tonnes of CO_2 emissions annually. With an annual electricity expense of approximately €1,797,122, the introduced EEIs aim to cut electricity consumption by 4.90%, equivalent to savings of 1,250,692.09 kWh and €88,054 annually. The estimated investment for these initiatives is approximately €156,344, with a payback period of 1.78 years.

Marquez et al. [47] studied a medium-sized hospital's hot water system that aimed for a 75% solar contribution but achieved only 27% due to thermal losses from poorly insulated pipes. This issue is prevalent in hot water-intensive buildings. To reach a 60% solar fraction, they proposed reducing thermal losses in water piping by 70% and expanding the solar area by 43–57%. This could cut hot water production costs by 15–45%, contingent on carbon taxes. Implementing heat pumps in strict climate policies could further boost the system's economic efficiency.

Zhang et al. [48] reported on a novel combined cooling, heating, power, and oxygen (CCHPO) system tailored for hospital buildings. This system, integrated with local photovoltaic power generation, uses liquefied methane and oxygen to store and produce multiple forms of energy and medical gas. The CCHPO system aims to enhance energy and gas supply security while reducing greenhouse gas emissions. Performance analysis based on real hospital data revealed that the CCHPO system can ensure energy conservation during regular operations and provide sustainable energy and gas during emergencies. In a practical scenario, the system can reduce annual greenhouse gas emissions by 4438.4 tonnes and offer backup for approximately 2 weeks in case of power outages.

Hospitals are inherently complex facilities when it comes to energy efficiency investigations, far surpassing the intricacies of standard commercial buildings. Their continuous operation, coupled with the diverse range of energy-intensive activities such as sterilization, medical equipment usage, and catering, creates a unique energy consumption profile. Most studies suffer from limitations [49], such as not accounting for the energy source, its efficiency, or the specific areas of energy consumption within hospitals and the indoor environmental quality (IEQ) [45]. Furthermore, external factors such as the impact of climate change and government policies can significantly influence a hospital's energy usage. Additionally, the cost implications of renewable energy sources, which can vary based on type and location, were not considered. These multifaceted challenges underscore the need for a comprehensive approach in future research. Recognizing these complexities is crucial for devising holistic energy-saving strategies that cater specifically to the healthcare sector's demands.

2.6. Other Non-Residential

In this subsection, we will consider several categories of non-residential buildings, including government public buildings, cultural heritage and preservation structures, and museums. De la Cruz-Lovera et al. [45], used bibliometric techniques to analyze the research that has been executed on energy efficiency and sustainability in public buildings from 1976 to 2016. The authors found that the most active research countries in this area are the United States, the United Kingdom, China, Australia, and Italy.

Heritage buildings with significant architectural and artistic value, face unique challenges in energy-efficient retrofitting due to their historical significance and limitations to façade interventions. Extensive efforts have been made to enhance their energy performance and indoor comfort without resorting to typically invasive retrofit interventions.

Nair et al. [19] reviewed the technical challenges and possibilities of retrofitting heritage buildings, exploring measures such as draught-proofing, insulation, and solar photovoltaics. While significant energy reductions are achievable, a tailored approach is essential. Research, primarily from Europe, indicates potential energy savings are case-specific, with challenges such as mold formation and aesthetic concerns. Life cycle assessments suggest refurbishing heritage buildings might be more environmentally favorable than new constructions, but more comprehensive studies, especially on life cycle carbon emissions, are needed. They also reported that many existing studies rely on simulations, which may sometimes overestimate energy savings.

A significant energy performance upgrade was undertaken for the Venetian building of "Loggia" in Heraklion, Crete, constructed between the 13th century and 1628. Despite its historical significance which imposed strict conservation limitations on its exterior, the building was retrofitted with new openings, an air-to-water heat pump, LED lighting, and a rooftop photovoltaic plant. This photovoltaic installation produces 100% of the building's energy requirements, making it a zero-energy consumption facility. These interventions, combined with the building's inherent features, are projected to lead to a 41% energy saving for indoor space conditioning and lighting. This project exemplifies the potential for energy upgrades in historical European structures [50].

Another study reported on the retrofits of "Palazzo Gallenga Stuart" in Perugia, Italy [51]. Through energy modeling and dynamic simulation, the study assessed the building's energy performance, aiming to curtail energy demand by incorporating high-efficiency technologies. A pivotal solution was the deployment of an advanced heat pump plant, negating the need for visually intrusive external units on the historic façade. For the "Palazzo Gallenga Stuart", a ground heat pump paired with water storage tanks, connected to underground vertical boreholes, was the chosen approach, which leveraged previously unused underground archive spaces.

Tiberi et al. [52] conducted a comprehensive study on Rome's "pharmaceutical chemistry" historical building located at the Sapienza University Campus. They assessed four retrofit scenarios, focusing on both passive and active energy enhancement measures. Passive measures included a complete upgrade of the building envelope and the introduction of thermostatic valve regulation. On the active front, they considered the integration of a

PV array installation. They carried out dynamic evaluations using the TRNSYS software (https://www.trnsys.com/).

A study in a Victorian-era building [18], assessed the efficacy, financial implications, and thermal comfort associated with passive retrofit interventions for a late 19th-century Victorian residence. Three types of interior retrofit solutions were examined: enhancements to internal wall insulation, glazing upgrades, and improvements in airtightness. These were configured into 63 distinct permutations and evaluated based on five key metrics: rate of energy conservation, associated costs, return-on-investment period, reduction in usable space volume, and indoor thermal comfort levels. The results showed that using advanced retrofit combinations could achieve over 60% energy reduction, while traditional methods achieved a maximum of 50–60%. The most effective combination included vacuum insulation windows, gypsum air infiltration reduction, and 2 cm thick Polyisocyanurate (PIR) panels, resulting in a 51.8% primary energy reduction at a cost of 144.71 £/m^2. However, it was found that increasing insulation can lead to potential summer overheating issues.

Another area of interest is museums because they require strict thermal-hygrometric control for artwork conservation and visitor comfort. Given the constant operation of air-conditioning systems, energy-saving techniques that maintain microclimatic control are essential. A study examined strategies to reduce energy needs for HVAC systems in a museum exhibition room using Relative Humidity (RH) control [53]. Adjusting the indoor RH range from 50 $\pm$ 2% to 50 $\pm$ 10% yielded 40% energy savings. Despite the primary focus on energy efficiency, an intriguing aspect of their study was the payback analysis, which uniquely factored in the value of the artwork. This approach underscores the intricate complexities and nuances involved in designing and implementing such systems. This point, although somewhat divergent from the main theme, is crucial and merits special attention, emphasizing the multifaceted considerations in museum HVAC system evaluations.

In 2017 a study was carried out for the Natural History Museum in Heraklion Crete, which increased the energy efficiency from D to A+ [54]. Passive measures, such as insulating the building's envelope, introducing new windows and doors, constructing a green roof, and planting in the outdoor space, were implemented. Active systems, including rooftop wind turbines and photovoltaics, geothermal heat pumps utilizing seawater, and advanced lighting managed by a central system, were also introduced, along with reactive power compensation. These combined interventions led to a significant reduction in energy consumption, with savings ranging from 40% to 93%. Specifically, the building's active and reactive electricity consumption for air conditioning decreased by 91%, and lighting energy needs were reduced by 41%. Additionally, passive measures contributed to a 64.77% and 59.46% reduction in heating and cooling loads, respectively. The overall primary energy consumption plummeted from 273.65 kWh/m^2 to just 18.36 kWh/m^2, marking a 93.29% reduction. This comprehensive upgrade also resulted in a remarkable 93% reduction in the building's CO_2 emissions.

3. Energy in the Building Sector

3.1. Energy Usage Patterns in Buildings

Table 4 presents an estimated the energy usage patterns of different public buildings based on a compilation of data from the Commercial Buildings Energy Consumption Survey (CBECS) [55–57], Building Performance Institute Europe (BPIE) [58], IEA [59], DOE's Building Performance Database (BPD) [60]. A striking observation from the table is the pronounced energy demand for heating and cooling in all building categories, significantly overshadowing other energy needs.

Table 4. Estimated energy usage patterns of different public buildings.

Energy Need/Public Building	Schools	Sports Centers	Swimming Pools	Hospitals	Government Offices
Heating & Cooling	40–50%	45–55%	55–65%	35–45%	30–40%
Lighting	20–30%	15–25%	10–20%	20–30%	25–35%
Water Heating	8–12%	8–12%	8–12%	8–12%	8–12%
Appliances & Equipment	4–6%	4–6%	4–6%	8–12%	8–12%
Plug Loads	4–6%	4–6%	4–6%	4–6%	4–6%
Ventilation	4–6%	4–6%	2–4%	4–6%	4–6%
Elevators & Escalators	4–6%	4–6%	1–3%	4–6%	4–6%

In schools, heating and cooling account for a substantial 40–50% of energy usage, indicating the critical role temperature regulation plays in creating conducive learning environments. Similarly, sports centers, often vast in size and requiring constant temperature maintenance for both players and spectators, report an even higher 45–55% energy allocation to these services. Swimming pools, given their intrinsic need to maintain water temperature, unsurprisingly register the highest demand in this category, consuming 55–65% of their energy for heating and cooling purposes.

Hospitals, despite their multitude of energy-intensive equipment and operations, still allocate 35–45% of their energy consumption to thermal comfort, underscoring the importance of patient comfort and care environments. Lastly, government offices, places that see regular footfall and need to maintain a standardized work environment, spend 30–40% of their energy on heating and cooling.

In stark contrast, other energy needs such as lighting, water heating, appliances and equipment, plug loads, ventilation, and elevator operations command a much smaller percentage of the total energy usage. For instance, lighting, essential for any building's operation, ranges only between 10–30% across all establishments. Appliances, plug loads, ventilation, and elevator services each fall in the narrow range of 1–12%.

In summation, this data underscores the overarching importance of heating and cooling systems in public buildings. Regardless of a building's primary function, whether it's education, recreation, healthcare, or administration, maintaining thermal comfort remains paramount, often demanding about half of the total energy resources. This analysis underscores the potential value of innovations and efficiencies in HVAC systems, given their substantial energy footprint in public infrastructure.

3.2. Energy Usage Type in Buildings

Table 5 offers a comparison of the reported thermal and electrical energy usage across various building types. Drawing predominantly from the 2018 CBECS with additional data from ECON78 and CIBSE reports for specific building categories, the table provides a clear view of the energy intensity of different facilities.

Table 5. Comparison of Reported Thermal and Electrical Energy usage for different buildings.

Building Type	Thermal Energy (kWh/m^2)	Electricity (kWh/m^2)	Year	Source (CBECS)
Education	180–230	50–70	2018	CBECS [57]
Healthcare	240–320	80–100	2018	CBECS [57]
Industrial	100–170	40–60	2018	CBECS [57]
Office	190–250	70–80	2018	CBECS [57]
Residential	120–170	30–50	2018	CBECS [57]
Retail	300–390	100–190	2018	CBECS [57]
Sports Centers	343	105	2001	ECON78 [31]
Sports Center	330	95	2008	CIBSE [30]
Swimming pool	1321	258	2001	ECON78 [31]
Swimming pool	1130	245	2008	CIBSE [30]

Undeniably, swimming pools stand out as the most energy-intensive structures, with their thermal energy consumption dwarfing that of other establishments. For instance, the 2001 ECON78 [31] report indicates that swimming pools required a staggering 1321 kWh/m^2 for thermal energy and 258 kWh/m^2 for electricity. A subsequent 2008 CIBSE report cites marginally lower but still impressive figures of 1130 kWh/m^2 and 245 kWh/m^2, respectively. These figures highlight the unique energy demands of maintaining large volumes of water at consistent temperatures, especially when compared to other building types.

In contrast, most other buildings—from educational institutions to retail spaces—display a closer range of energy consumption figures. Educational buildings, for instance, use between 180–230 kWh/m^2 thermally and 50–70 kWh/m^2 electrically, while healthcare facilities report a slightly higher 240–320 kWh/m^2 and 80–100 kWh/m^2, respectively. Industrial spaces, offices, and residential buildings all fall within a similar ballpark, with their thermal energy consumption ranging from 100–250 kWh/m^2 and electricity between 30–80 kWh/m^2.

Retail spaces and sports centers also present comparable figures, though retail spaces appear to have a broader range for electrical energy, possibly due to varied lighting, cooling, and electronic equipment needs depending on the nature of the retail establishment. Interestingly, sports centers' data from two distinct sources (ECON78 and CIBSE) and years (2001 and 2008) show only a slight decrease in energy usage over seven years, with thermal usage dropping from 343 to 330 kWh/m^2 and electricity from 105 to 95 kWh/m^2.

It is worth noting the consistency in data across the years. While Table 5 predominantly references the 2018 CBECS data, previous CBECS reports from 2003 and 2012 have shown similar energy consumption patterns for these building types, suggesting a stable trend in energy usage over the years. This consistency underscores the importance of focusing on sectors such as swimming pools that remain consistently high in energy demand, offering a potential area for energy conservation and efficiency improvements.

4. Retrofitting Measures

4.1. Overview Retrofitting Measures

There are also several methodologies and computation tools that assist in the modelling of thermal comfort and design of buildings during the planning stage, to achieve a bioclimatic energy efficient design [38,61–63]. However, the primary focus of this study is on large-scale retrofitting interventions, distinguishing it from new installations. A multitude of analytical approaches for energy retrofits can be sourced from existing literature [7,64–69]. In the context of large-scale retrofitting, Swan, Ismet, and Ugursal delved into techniques for modeling end-use energy consumption specifically in the residential sector [70]. Balaras et al. [71] have previously explored retrofitting within the Greek building sector. Furthermore, Pittarello et al. introduced an artificial neural network (ANN) methodology designed to optimize zero-energy building projects from their initial design phases [72].

Genetic algorithms and other optimization methods have been used to solve Building Energy Efficiency Retrofit (BEER) problems with multiple non-linear objectives and constraints for a single building [73–79]. He et al. [80] diverged from traditional research that predominantly centered on single-building retrofit decisions, and proposed an innovative approach that amalgamated particle swarm optimization with genetic algorithms in the context of retrofitting within a budgetary constraint. This hybrid method aimed to judiciously select buildings for retrofitting and pinpoint the most effective measures to adopt, striking a balance between economic returns and environmental benefits. The framework's practicality was validated through its application to 27 distinct buildings located in Delaware, USA. Such advancements in retrofit decision-making methodologies underscore the growing emphasis on sustainability, within budgetary confines.

Contokosta [14] delved into the decision-making processes of building owners and asset managers concerning energy efficiency retrofits, particularly in the commercial office sector. Using a comprehensive survey of 763 office buildings across nineteen cities from the CBRE, Inc. portfolio, the research scrutinized the influence of ownership type, tenant demand, and local real estate market on retrofit choices. The findings underscored that ownership type and local market conditions significantly swayed retrofit decisions. While the direct impact of tenant demand remains ambiguous, the study emphasized the pivotal role of understanding varied motivations across different ownership types. The research also advocates for tailored energy efficiency incentives and policies, emphasizing the significance of local regulations, market conditions, and building ownership. The study also suggests distinct approaches for energy efficiency in small- to mid-sized office buildings compared to larger commercial structures.

Finally, methodologies for assessing the economic effect have been proposed [81,82].

4.2. Passive Retrofitting Measures

In the realm of building design and energy conservation, passive technologies have long been recognized for their efficacy [83]. These techniques, with origins dating back to ancient cave dwellings, have been modernized and are now integral to contemporary energy-efficient building applications [10,84].

Table 6 provides a comprehensive overview of passive retrofitting measures for buildings, as highlighted in various case studies. The table is organized into three columns: the type of passive energy-saving action, the references where these actions were proposed or implemented, and any additional comments related to the action. A notable observation from the table is that a larger number of references suggest a significant research interest or opportunity in energy savings, indicating the growing emphasis on passive measures in the realm of building efficiency. This layout offers insights into the prevalence of each measure and considerations in different case studies, emphasizing the importance of passive retrofitting in the pursuit of sustainable building practices.

Table 6. Passive Retrofitting in case studies.

Type of Action	Proposed/Implemented in	Considered but Not implemented
Insulation	[12,18,19,26,27,35,39,45,47,50,52,54,85–87]	[44]
Replacement of old openings	[12,17,18,26,35,45,50,54,85]	
Fenestration	[12,18,19,26,27,39,40,50,86,88]	[44]
Roof insulation	[44,54]	
Shading of windows	[26,39]	
Natural Ventilation strategies	[18,39]	
Outdoor tree planting	[54]	
Phase Change materials	[19]	
Zoning areas	[45]	

Thermal insulation is a cornerstone in energy-efficient building design and should be among the initial elements to be assessed. Its significance has been underscored over the years, with the recommended insulation thickness in northern Europe doubling between the 1970s and 2010s [85,86,89]. This is primarily because the energy required for thermal regulation, encompassing both cooling and heating, represents a substantial chunk of a building’s total energy usage, often nearing half. Proper insulation of walls, roofs, and floors acts as a barrier, reducing heat transfer and ensuring consistent indoor temperatures. This not only conserves energy but also enhances the comfort of building occupants [50,61,85]. A study focused on the Cyprus climate considered dynamic insulation methods to achieve the near Zero-Energy Building specification [87]. Recent technological development and research support the use of variable insulation systems and switchable insulation technologies [85]. However, it is the authors’ view that shares technical and behavioral intervention characteristics, while their optimal benefits are only achieved with active resident participation.

While insulation is instrumental in reducing heating demands, especially in colder climates, it is essential to strike a balance. Over-insulating can inadvertently lead to increased cooling requirements during warmer months, particularly in northern regions. Thus, while insulation is pivotal for energy conservation and comfort, it is crucial to ensure it is optimized to avoid unintended consequences on cooling needs [18].

Optimizing the building's thermal mass is another pivotal passive technique. By employing materials such as concrete or brick, which can absorb, store, and release heat, buildings can naturally regulate temperature fluctuations. The innovative integration of phase change materials further enhances this process, providing a dynamic solution to managing thermal loads [50,89,90].

Sun shading techniques, whether through external fixtures, vegetation, or architectural design, can significantly reduce the need for cooling, especially in regions with intense sunlight [61]. A study conducted on a passive sports hall in Słomniki emphasized the role of sun shading, which reduced sunlight access by up to 30% [91].

The design and quality of building openings, or fenestration, are paramount in energy conservation [12,61,84,86,88]. Modern advancements in materials, such as aerogel and vacuum glazing, offer exceptional insulation [89,90,92]. Moreover, strategically placing and designing windows can optimize natural light while minimizing heat gain or loss [32], while some researchers have proposed movable insulation systems for windows [85]. Additionally, there are different types of energy-efficient walls (such as Trombe walls, ventilated walls, and glazed walls) [89,90].

Roofing techniques can drastically reduce a building's energy consumption, because roofs are directly exposed to sunlight, which presents unique challenges and opportunities. Green roofs offer insulation and absorb sunlight, photovoltaic installations harness solar energy, and radiant-transmitted barriers reflect excessive heat [50,89,90]. Buonomano et al. [44] reported that in taller buildings, roof insulation leads to minor reductions in heating and cooling.

Designing spaces to promote the natural flow of air can significantly reduce the reliance on mechanical ventilation. By allowing fresh air to circulate, natural ventilation not only conserves energy but also enhances indoor air quality, promoting a healthier living environment.

4.3. Active Retrofitting Measures

Table 7 provides a comprehensive overview of various active retrofitting interventions tailored to enhance energy performance in buildings from the literature review. The range of measures presented in the table underscores the multi-dimensional approach researchers and practitioners are taking to improve the energy efficiency and sustainability of our built environment.

Among the retrofitting interventions, the use of Heating and cooling systems, incorporating a variety of technologies such as condensing boilers, heat pumps, solar-combi systems etc., stands out prominently in the literature review. Their frequent occurrence suggests their pivotal role in enhancing thermal comfort while optimizing energy use across both thermal and electrical domains.

Another prominent intervention is the installation of a PV station, with references spanning multiple studies. The prevalence of this measure in the literature underscores its importance and effectiveness in harnessing solar energy for electrical needs and the effect on the building's overall energy efficiency improvement. Similarly, energy-efficient lighting devices are another measure with significant representation, being investigated or implemented in numerous studies. This highlights the pivot towards energy-saving lighting solutions that not only reduce power consumption but also enhance occupant comfort.

While other measures such as geothermal stations, biomass, and ventilation systems have multiple references, some interventions such as wind turbines, air purifiers, and hydrogen technologies are less frequent in the cited literature. This could indicate either niche applications or emerging areas of research and implementation.

Table 7. Table of active retrofitting interventions.

Type of Action	Investiged/Implemented in	Energy Type	Comments
Heating/cooling systems	[12,17,19,26,29,35,36,39,44,46], Solar-combi [34,37,47]	Thermal/Electrical	Condensing boilers, Heat pumps And Upgrades
Photovoltaic station	[12,17,19,23,28,35–37,42,50,52]	Electrical	
Ventilation systems	[12,19,26,27,39,44,45]	Electrical	
Energy efficient lighting devices	[7,12,17,35,46,50,54]	Electrical	
Geothermal station (close or open)	[17,37,51,54]	Thermal	
Biomass	[34,35,61]	Thermal	
Heat Recovery Systems	[26]	Thermal	
Reactive power coefficient compensation	[46,54]	Electrical	
Wind turbines	[54]	Electrical	
Air purifiers	[27]	Electrical	
Relative Humidity Control	[53]	Thermal	
Hydrogen Technologies	[42]	Electrical	

It is worth noting that several measures focus on specialized energy aspects, such as reactive power coefficient compensation and relative humidity control, indicating a nuanced approach to retrofitting where even specific electrical and thermal parameters are fine-tuned for optimization.

In the following subsection, further information is provided on water heating, the integration of renewable energy sources and also on district heating and cooling systems.

4.3.1. Water Heating Technologies

Water heating technologies play a pivotal role in the energy dynamics of buildings, not just because of the direct consumption of hot water for daily activities, but also due to its integral function as a medium for heat transfer in both heating and cooling processes. The dual nature of water's role—as both a consumable resource and a conduit for thermal energy—underscores the importance of optimizing water heating systems. Efficient water heating not only ensures that occupants have access to hot water when needed but also contributes significantly to the overall energy savings in a building. Given its multifaceted impact on a building's energy profile, it is essential to delve deeper into water heating technologies, understanding their potential and challenges in the broader context of building energy efficiency.

Various techniques are used to improve the energy efficiency [83]. Heat pumps and boilers have been developed for over a century and recent improvements have increased their efficiency [93]. Heat pumps saw another record year in 2022 with 11% growth in sales which is close to the 15% average compound annual growth needed to fully align with the Net Zero Scenario [94].

Solar thermal technology, which harnesses solar radiation to generate hot water as opposed to photovoltaic systems that produce electricity, is a prevalent form of renewable energy [95]. According to an International Energy Agency (IEA) report, the global market in operation for Solar Heating and Cooling at the end of 2019, was estimated to be 479 GWth worldwide [96]. Fadzlin et al. [95] explored the obstacles associated with building-integrated Solar Water Heating and found that only a marginal proportion of the deployed systems serve purposes other than domestic hot water generation. Studies have indicated that evacuated solar thermal collectors offer more favorable payback periods compared to alternative solar thermal collection technologies [97].

Radiant heating and cooling RHC systems are becoming more common, mainly because they give the same thermal comfort levels with lower energy use [98]. The efficiency of RHC systems is due to their ability for high-temperature cooling and low-temperature heating, however, they are still dependent on heat pumps/boilers [83].

Katsaprakakis investigated different passive and active heating systems for swimming pool facilities and reported that (a) passive solar systems reduce the swimming pool's heating loads by more than 90%, and that Geothermal Heat Exchangers (GHE) and Geothermal Heat Pumps (GHP) can be used to supplement the water heating in energy production [17,99].

A study considered the efficacy of a Water Solar Assisted Heat Pump (W-SAHP) paired with unglazed flat solar collectors, contrasting its performance with a conventional gas-boiler plant [100]. Under Italian climatic conditions, the W-SAHP demonstrated energy savings ranging from 35% to 50%. Interestingly, the power savings displayed an almost linear relationship with the Degree Days of the location. In a separate study, Chow et al. [101] explored a solar-assisted heat pump system designed for indoor swimming pool water heating. Their findings indicated that the system's Coefficient of Performance (COP) could achieve 4.5, and the energy savings fraction was a substantial 79% when compared to traditional energy systems.

Additionally, Combined Heat and Power (CHP) systems derived from Phosphoric Acid Fuel Cells were mathematically modeled, revealing a promising potential to enhance the fuel cell's utilization efficiency [32]. Biomass-fueled CHP systems have also been suggested for applications such as water heating in swimming pools [102] and healthcare [48] and other non-residential processes [103]. These systems have showcased both technical and economic viability. However, it is worth noting that the current adoption of these systems is limited due to their associated high costs.

Waste heat from an ice rink's chiller unit in Gaziantep, Turkey, has been successfully utilized to heat a swimming pool [104]. Specifically, an ice rink measuring 475 m^2 is optimally suited to heat a semi-Olympic swimming pool of 625 m^2. Liebersbach et al. [105] reported on the potential of greywater heat recovery in indoor swimming pools, noting a reduction in energy demand ranging from 34% to 67%.

Substantial reductions have also been documented through the optimization of swimming pool operations. The Pool Efficiency Program report highlighted that by retrofitting pool pump speed controllers, the energy consumption of the pool pump can be curtailed by as much as 71% [106]. Furthermore, by reducing flow rates by up to 75%, typical solar collectors can achieve electrical energy savings of over 80%, with only a minor decrease in collector efficiency of about 10~15% [107].

4.3.2. Electricity Generation and Renewables

Integrating renewable energy sources, such as solar photovoltaic panels, and wind turbines, in retrofitting projects is pivotal for enhancing energy efficiency in buildings. These candidates not only provide sustainable electricity generation but also drive sustainable development, reduce carbon footprints, and align with global environmental goals.

Alshuraiaan et al. [108] aimed to identify the most pertinent renewable energy technologies for buildings in Kuwait and evaluate their long-term effectiveness. The research utilized methods of analogies and comparisons to highlight energy efficiency features based on the technologies examined. The findings reveal that solar energy systems have been the predominant choice for harnessing solar energy in Kuwait over the past three years. Solar collectors equipped with booster reflectors exhibit an increased level of energy efficiency, coupled with a reduction in the notional cost of enhancing energy savings. The study's proposed model for gauging energy-saving levels offers an economic rationale for integrating renewable energy technologies into buildings. In essence, the research underscores the potential of solar energy systems, especially solar collectors with booster reflectors, in advancing energy efficiency and savings in Kuwait's buildings.

4.4. Retrofitting Intervention and Buidling Type

Table 8 delineates the types of retrofitting interventions, organized by the category of action in the rows and the classification of building structures in the columns. Each cell contains citations for articles that have investigated the corresponding intervention within a specific type of building.

Table 8. Matrix of retrofitting interventions categorized by building type.

Type of Action	Schools	Swimming Pools	Sport Centers	Hospitals	Museums/ Heritage Bldgs
Insulation	[12,26,27]	[35]	[39]	[45,47] Not: [44]	[18,19,50,52,54]
Replacement of old openings	[12,26]		[17,35]	[45]	[18,45,50,54]
Fenestration	[12,26,27]	[40]	[39,40]	Not: [44]	[18,19,50]
Roof insulation				[44]	[54]
Shading of windows	[26]		[39]		
Natural Ventilation strategies			[39]		[18]
Outdoor tree planting					[54]
Phase Change materials					[19]
Zoning areas				[45]	
Heating/cooling systems	[12,26,29]	[34–37]	[17,39]	[44,46,47]	[19]
Photovoltaic station	[12,23,28]	[35–37]	[17]	[42]	[19,50,52]
Ventilation systems	[12,26,27]		[39]	[44,45]	[19]
Energy efficient lighting devices	[12]	[17,35]	[17]	[7,46]	[50,54]
Geothermal station (close or open)		[37]	[17]		[51,54]
Biomass		[34,35]			
Heat Recovery Systems	[26]				
Reactive power coefficient compensation				[46]	[54]
Wind turbines					[54]
Air purifiers	[27]				
Relative Humidity Control	[53]				
Hydrogen Technologies	[42]				

Table 8 serves two primary functions. Firstly, it highlights the interventions with the highest benefit-to-cost ratios in each building type, based on the frequency of their occurrence in the literature. Secondly, it identifies underexplored areas in retrofitting interventions, providing a roadmap for future research.

Specifically, the frequency of each intervention in the table serves as an indicator of its perceived value, implying a higher benefit-to-cost ratio. This can guide stakeholders in prioritizing interventions for each building type.

Concurrently, Table 8 uncovers research gaps, particularly in the exploration of technologies such as phase change materials and hydrogen technologies. These gaps stand in contrast to well-researched areas and building categories such as schools and cultural institutions. Thus, the table can be instrumental in directing future scholarly efforts.

4.5. The Relevance of District Heating and Cooling Systems

District heating and cooling systems have evolved over the decades, adapting to technological advancements and changing energy landscapes. The first generation, initiated in the late 1800s, relied on steam systems operating at high temperatures. The second generation, emerging in the 1930s, introduced pressurized hot water as the heat carrier. The third generation, prevalent from the 1970s, optimized systems with pre-insulated pipes and lower temperatures. The fourth generation, from the 2000s, emphasized sustainability, integrating renewable energy sources and further reducing temperatures (40 °C to 70 °C).

In this evolutionary trajectory, the emergence of Fifth Generation District Heating and Cooling (5GDHC) systems represents a revolutionary shift. These systems, operating at temperatures ranging from 5–35 °C, diverge significantly from their predecessors, offering enhanced efficiency through a variety of innovative features. By utilizing low operating temperatures, 5GDHC systems can harness a broad spectrum of renewable energy sources, including solar thermal, geothermal, and waste heat. This not only improves efficiency but also diminishes the reliance on fossil fuels, contributing to broader environmental and energy security goals [109].

5GDHC systems, with their decentralized design, offer enhanced resilience against energy supply disruptions. Their bidirectional energy flows and integrated thermal storage efficiently balance and manage thermal loads. Public buildings, given their prominence and societal role, are uniquely positioned to champion these systems. Their adoption in such infrastructures not only showcases the practicality and benefits of 5GDHC but also paves the way for broader societal advantages. These include not just energy savings but also environmental conservation, improved air quality, and economic stimulation.

One of the standout benefits of 5GDHC systems is their ability to significantly boost the energy efficiency of public buildings. By refining thermal performance, they set a gold standard for energy management practices. Their design inherently equips them to tackle climate change challenges, offering adaptability and resilience. As 5GDHC technology matures, its integration in public buildings promises to usher in a transformative phase in energy management, harmonizing efficiency, environmental care, economic benefits, and societal welfare.

5. Technological Intervention Adoption and Effectiveness

5.1. Introduction

In the preceding chapters, we delved into the complex world of energy patterns and energy usage types in public buildings, meticulously analyzing retrofitting measures, and their potential energy savings a benefits benefits. A consistent trend emerged, emphasizing the profound significance of thermal energy needs. It became evident that thermal energy often constitutes close to, if not more than, half of a building's total energy usage. This striking revelation steers our attention towards the crucial role of technological interventions in addressing thermal energy requirements. With the goal of understanding the real-world effectiveness of technological advancements, this chapter will assess thermal energy requirements per unit area. By focusing on average energy consumption per unit area, we aim to gauge the tangible impact of research advancements on a building's energy efficiency. After all, it is not uncommon for theoretical technological breakthroughs to falter when applied practically—a phenomenon that warrants thorough investigation.

5.2. Methodology

Our methodology in this section unfolds in many phases. It commences with an exploration of the regulatory landscape, spotlighting the mandatory maximum U values in Europe and the US. These values serve as an indirect metric, reflecting the progression of technological capabilities in building insulation and energy conservation. Using data from building surveys in the US and UK spanning from 2000 to 2020, we then examine the average thermal and electricity energy consumption per unit area. This granular analysis unveils distinct patterns and trends that have manifested over two decades. An integral facet of our methodology is the incorporation of climate effects, specifically through the metric of degree days. We will present this data, laying the foundation for a subsequent deep dive in our discussion. There, we will compare and contrast the observed thermal energy trends with the degree days to evaluate if climatic variations can be used as a compelling explanation for the energy consumption patterns observed. Concluding our methodology, we juxtapose the average energy consumption patterns of both thermal and electricity. This comparative approach not only highlights the differences but also strives to interpret the underlying reasons for the emerging patterns, emphasizing the practical effectiveness of technological advancements.

5.3. Historical Evolution of Insulation Maximum Transmittance (U-Values)

Figure 1 presents the evolution of external wall maximum permissible U-values over recent years [110,111], a metric that measures the rate of thermal transmittance in building materials, denoted in W/m^2 K The marked decline in U-values, evident from the plotted data points, signifies the architectural shift toward more energy-efficient building materials and practices.

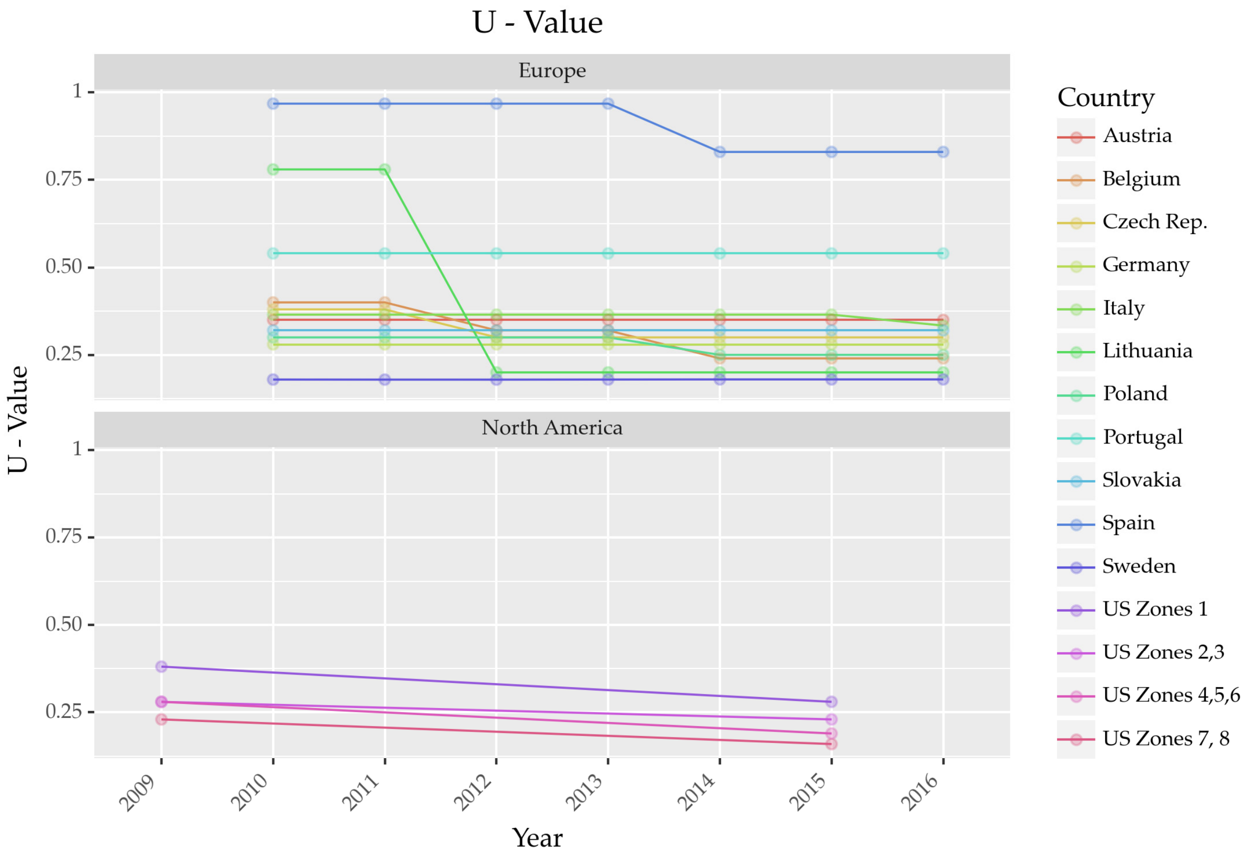

Figure 1. Evolution of the maximum permissible U-Value for external wall from 2009 to 2016 (sources: [30,31,57]).

European countries emerge prominently in this trend, with nations such as Austria, Belgium, and Spain showcasing significant reductions in their U-values, underscoring their commitment to sustainable building practices. However, this drive towards energy efficiency is not confined to Europe and the US alone. In essence, Figure 1 encapsulates a global movement towards energy-efficient buildings and sustainable construction—a testament to the collective commitment to creating buildings that are both functional and environmentally responsible.

An examination of the 2015 Swedish GRIPEN database [40] demonstrated a link between the year sports halls were constructed and their subsequent average energy efficiency. Sports halls constructed prior to 1979 consumed an average of 191 kWh/m^2. This consumption notably declined to 148 kWh/m^2 for those built between 1980 and 2009. Remarkably, for sports halls established post-2010, energy use plummeted even further to 104 kWh/m^2, underscoring the positive impact of evolving technological innovations.

5.4. Evolution of Average Thermal Energy Consumption per Unit Area

Figure 2 delves into the intricacies of thermal energy consumption across a diverse range of building types over the years. Measured in kWh/m^{2}K, this metric offers insights into the heating and cooling patterns integral to each structure's functionality. Figure 2 complements the insights from Figure 1, presenting the thermal energy consumption patterns across diverse building types over the years. While Figure 1 showcased a decline in U-values, indicating enhanced insulation properties and potentially reduced thermal energy needs, the trends in Figure 2 provide a more complex narrative.

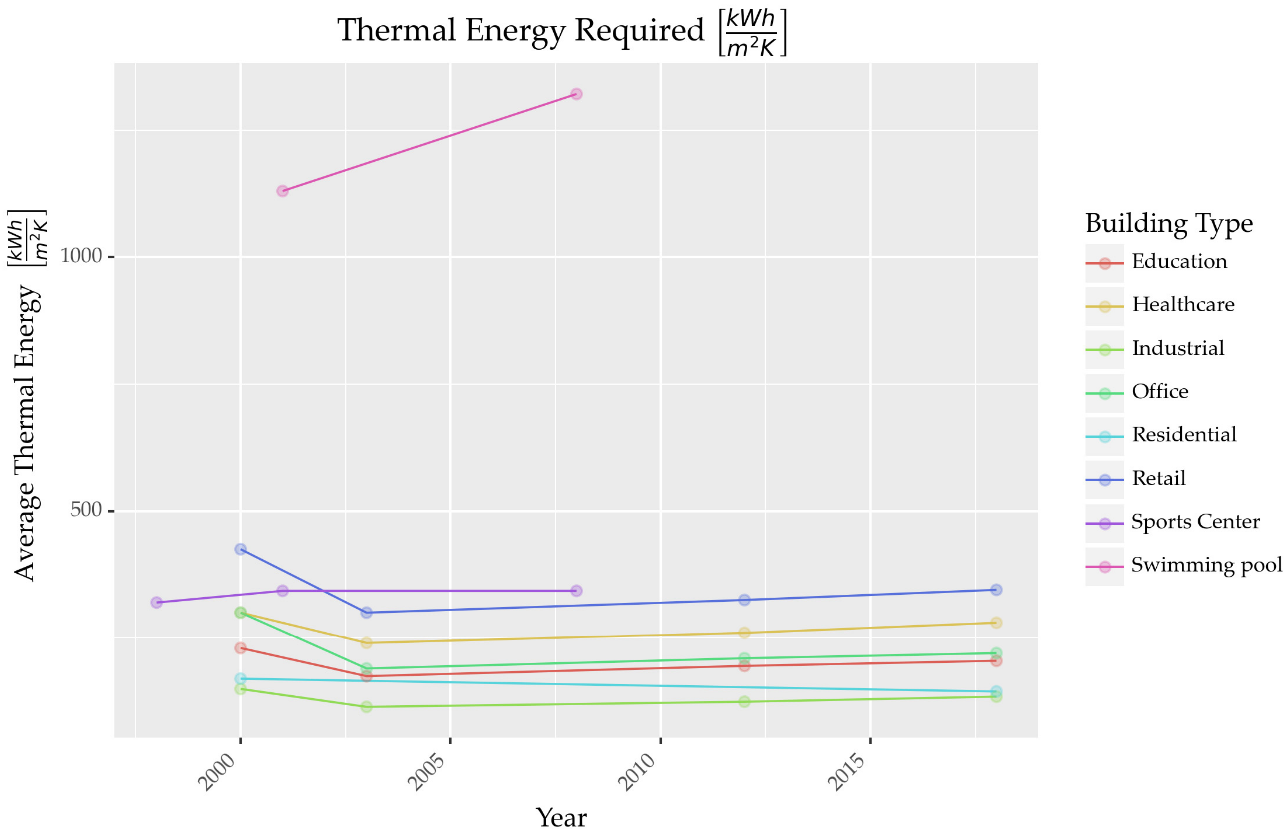

Figure 2. Evolution of average thermal energy requirements between 2000 to 2018, based on data from Table 5 (data sources: [30,31,55–57]).

Educational buildings, for example, saw a dip in consumption in 2003 but rose again by 2018. Healthcare facilities consistently increased their thermal energy use from 2000 to 2018. Industrial and office spaces displayed varied trends, with the former seeing a rise by 2020 and the latter fluctuating until 2018. Residential areas moved towards energy conservation, while retail spaces increased consumption. Sports centers remained stable, but swimming pools, with their unique energy demands, saw a surge from 2001 to 2008.

However, the expected reduction in thermal energy due to lower U-values is not immediately evident. Several factors can explain this:

- The transition to buildings with lower U-values is gradual. As structures upgrade or are replaced over time, the benefits of improved insulation become more apparent.
- Behavioral aspects play a crucial role. The operation of buildings and the attitudes of their operators can lead to sub-optimal energy usage, counteracting the potential benefits of better insulation.

5.5. Evolution of Average Electrical Energy Consumption per Unit Area

Figure 3 delves into the intricacies of electrical energy consumption measured in kWh/m^2, across various building types reported in US and UK studies between the years 1998 and 2018. A closer examination of the data points, especially in the latter years, reveals the transformative impact of LED lighting technology on energy utilization and the stark contrast with Figure 2 that presents the evolution of thermal energy consumption. This is in accordance with the Tracking Clean Energy Progress 2023 [94], which states that the Lighting in the Building is on track to achieve the desired targets.

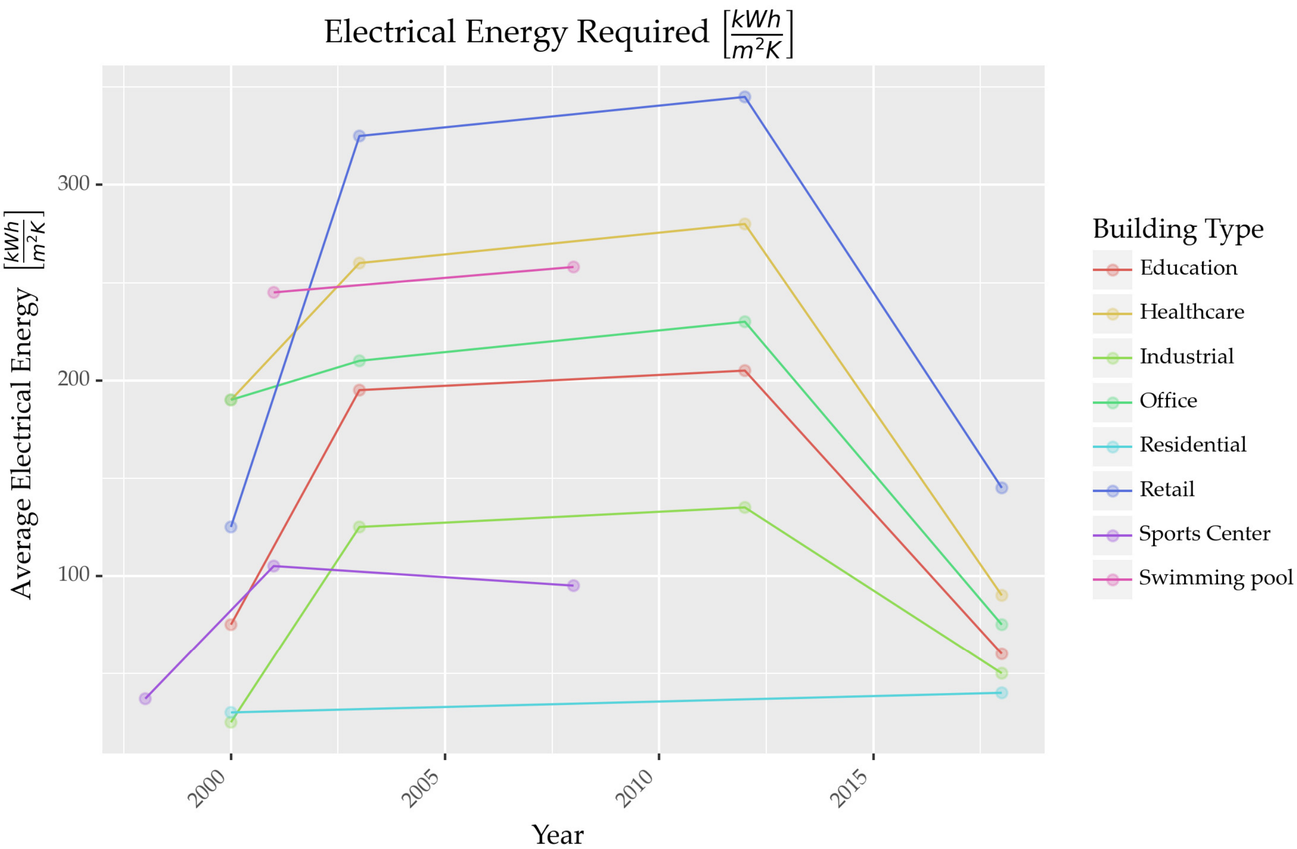

Figure 3. Evolution of average electrical energy requirements between 2000 to 2018, based on data from Table 5 (data sources: [30,31,55–57]).

From the onset of the 21st century, there has been a global push towards sustainable and energy-efficient solutions, and LED technology has been at the forefront of this movement. Its penetration in the market can be correlated with some of the changes observed in our data.

For instance, educational buildings showed a significant surge in electrical consumption, reaching 205 kWh/m^2 by 2012. However, there was a sharp decline to 60 kWh/m^2 by 2018. This reduction can be attributed to the transition from traditional lighting systems to LEDs. The initial high consumption could be due to the integration of various electronic devices in educational settings. However, the subsequent drop signals the energy savings from LED adoption.

Similar trends can be observed in healthcare and office spaces. While there was an evident rise in electrical consumption in the early 2000s, indicative of increased electronic usage and traditional lighting, the notable decreases in later years, such as the drop in healthcare establishments from 270 kWh/m^2 in 2015 to 90 kWh/m^2 in 2018 and office spaces from 220 kWh/m^2 to 75 kWh/m^2, underscore the energy-conserving capabilities of LED lights.

Retail spaces present an interesting narrative. The remarkable growth from 125 kWh/m^2 in 2000 to 345 kWh/m^2 by 2012 can be attributed to the enhanced lighting required to create appealing spaces for customers. However, the significant reduction in 2018 hints at the shift to LEDs, which provide the same brightness but at a fraction of the energy cost.

In essence, Figure 3 not only charts the ebb and flow of electrical energy consumption across different architectural spaces but also narrates the silent revolution brought about by LED technology. As LEDs continue to dominate and innovate, it is anticipated that future trends will further highlight the decline in electrical consumption, paving the way for a more sustainable architectural future.

5.6. Climate Effect

The growing emphasis on energy efficiency in buildings is further underscored by the observed and projected changes in cooling and heating degree days across the globe. The findings by Spinoni et al. [112] accentuate the complexity of energy-saving interventions in buildings in the context of global warming. Several studies [112–114] investigated whether energy demand for cooling and heating buildings is likely to increase or decrease under climate change.

The last few decades have witnessed the apparent effects of global warming in Europe, impacting various sectors, including energy consumption in buildings. Through the evaluation of heating degree-days (HDD) and cooling degree-days (CDD) using high-resolution, bias-adjusted EURO-CORDEX simulations, the researchers forecast a notable decline in HDD, most prominently over Scandinavia and European Russia, alongside a rise in CDD, with the most significant increases observed in the Mediterranean region and the Balkans [112,113,115]. A country-level demand in cooling degree days using the IEA database is reported [114].

Such findings carry considerable implications for the global energy landscape. Under a static population model, the decline in HDD is anticipated to offset the rise in CDD across the majority of Europe, culminating in a net reduction in energy demand as represented by Energy Degree-days (EDD). Conversely, when factoring in projected population growth, EDD is projected to escalate across various European regions, resulting in an overall uptick in Europe's EDD, despite ongoing warming trends [113].

Figures 4–6 present the Cooling and Heating Degree Days for Greece, France and Norway, respectively, from 1980 to 2022, and notable shifts in energy demands across different climate zones become apparent. The data is obtained from Eurostat.

Figure 4, representing Greece, showcases a steady decline in HDD with an average drop of approximately 3.48 DD per year from 1979 to 2022. This suggests a diminishing need for heating over time. In contrast, CDD for the same period have been on an ascent, rising by an average of 4.73 units annually, indicating an increasing demand for cooling interventions.

France, presented in Figure 5, echoes a similar trend but with more pronounced variations. The country's HDD has experienced a significant reduction, with an average annual decrement of about 16.58 DD per year. Concurrently, the CDD has observed a moderate increase at a rate of 2.49 DD each year, signifying a gradual uptick in cooling necessities.

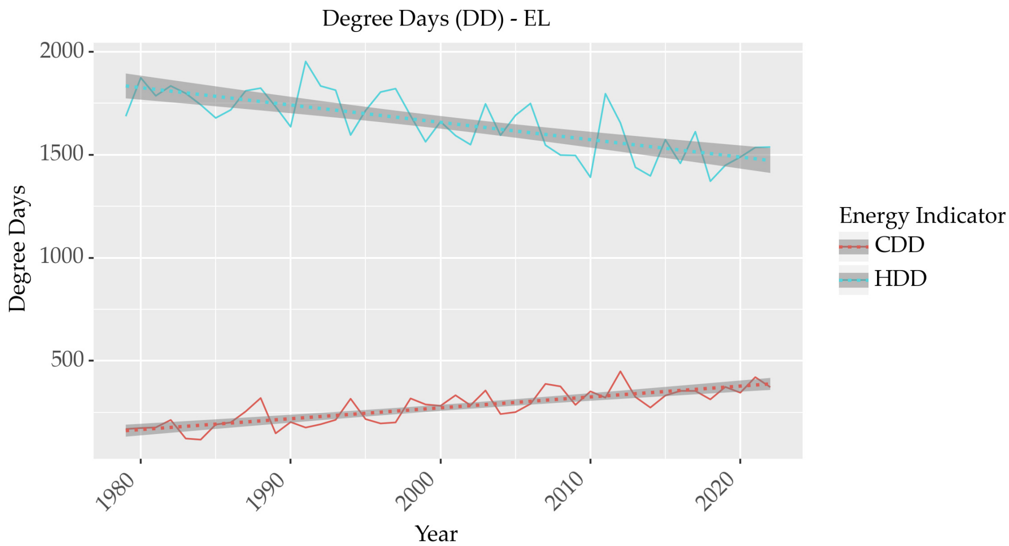

Figure 4. Heating and cooling days in Greece (EL) from 1980 to 2022.

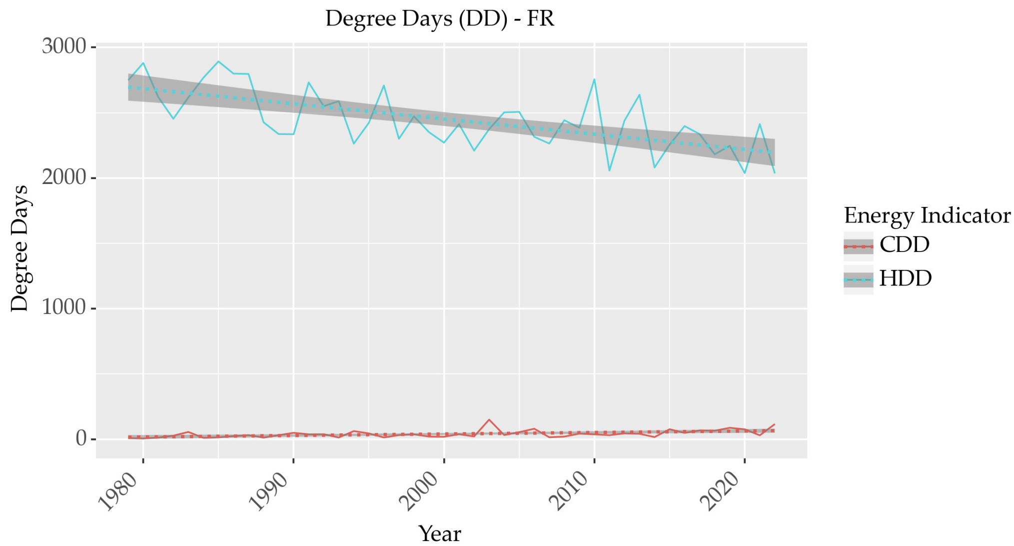

Figure 5. Heating and cooling days in France (FR) from 1980 to 2022.

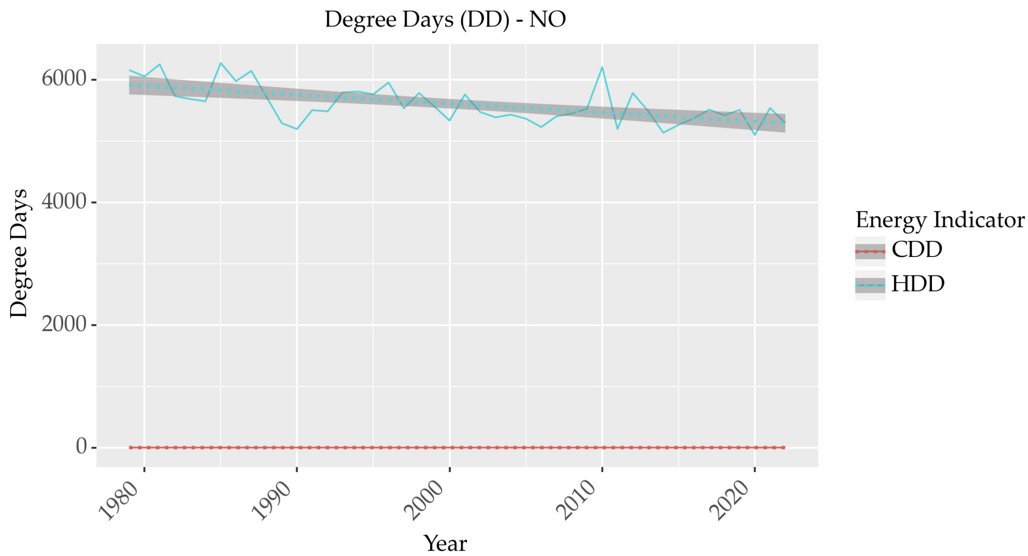

Figure 6. Heating and cooling days in Norway (NO) from 1980 to 2022.

Norway's patterns, as illustrated in Figure 6, are particularly intriguing. The country has witnessed a substantial decline in HDD, averaging an annual decrease of 20.09 HDD. However, its CDD has remained almost static, with a negligible yearly increase of 0.007 CDD, suggesting that while heating requirements have dramatically shifted, cooling needs have remained nearly constant.

The unmistakable decrease in HDD across all three nations suggests a diminishing requirement for heating. This trend aligns with findings from numerous climate change research studies, which predict a rise in global temperatures and a consequent reduction in colder periods. This shift in HDD underscores a significant change in the energy landscape. On the flip side, the increase in CDD is a testament to the growing demand for cooling solutions. It's essential to note that while the magnitude of this increase varies based on the climate zone, the upward trajectory of CDD is almost universal. Thus, while regions may experience the effects of climate change differently, the overarching trend leans towards a decreased need for heating and an enhanced reliance on cooling.

5.7. Discussion

Public buildings stand as pillars of strength and resilience within communities. Historically crafted with traditional materials and methods, many of these edifices accrue cultural and historical significance over time. Their stature often elevates them to landmark status, accompanied by limitations on structural modifications. Consequently, numerous public buildings fall short in terms of contemporary energy efficiency standards, as corroborated by studies [18,19,50].

This scenario, however, unfurls a dual-edged narrative. While the constraints impede certain structural enhancements, they pave the way for innovative energy-saving retrofitting measures. Implementing modern energy solutions in these structures not only upholds their historical essence but also steers them toward sustainability and long-term cost efficiency. The retrofitting interventions we reviewed in this work achieved energy savings close to or exceeding 50%, even attaining near Zero-Energy Building (nZEB) status. Considering the preponderance of thermal energy in a building's overall consumption, insulation emerges as a pivotal energy efficiency measure. Yet, the quest for optimal insulation, especially in colder climates, necessitates a judicious approach to counter excessive cooling demands. Despite advancements in insulation technologies and the implementation of stringent energy-efficient building codes (as depicted in Figure 1), tangible reductions in average thermal energy consumption per unit area remain elusive as depicted in Figure 2.

Conversely, electrical energy consumption per area has showcased a significant decline, as illustrated in Figure 3. This is noteworthy, given the increasing prevalence of electrical gadgets and the gradual transition from fossil-fuel-based heating systems to electrical heat pumps.

Furthermore, even as we observe improvements in insulation (Figure 1) and witness a decrease in climate requirements in the recent decade (Figures 4–6), the average thermal energy consumption remains steadfast Figure 2. This constancy, in the face of both technological and climatic shifts, implies that climate cannot solely account for the observed patterns in thermal energy consumption. Other factors, perhaps rooted in operational behaviors or system inefficiencies, might be at play, underscoring the complexities inherent in the energy consumption landscape of buildings.

The contrasting and seemingly counterintuitive trajectories in thermal and electrical energy consumption invite closer scrutiny. Several factors contribute to this observed disparity. One pertains to the technological lifespan of system components. Breakthroughs in insulation predominantly affect buildings, entities with lifespans spanning several decades. Even retrofitting measures, usually spaced out over ten-year intervals, introduce a system "inertia". This inertia implies that the full integration of cutting-edge insulation technologies into the existing building fabric is a time-intensive process. Conversely, advancements in electrical domains, particularly in areas such as lighting, have a more immediate and discernible impact. Such interventions, being less capital-intensive and having shorter lifespans, seamlessly blend into existing infrastructures, facilitating tangible benefits.

The true efficacy of technological interventions is deeply intertwined with user behavior. While installations such as insulation and LEDs might be perceived as inherently passive once set up, their effectiveness in real-world scenarios can differ significantly. For example, insulation is designed to assist HVAC systems, but it does not directly provide thermal comfort. It is the operational habits of users that play a pivotal role in determining the system's efficiency. While practices such as leaving lights on during daylight might lead to some energy wastage, the misuse of thermal comfort systems can be considerably more detrimental. Acts such as operating air conditioning with open windows or setting temperatures exceedingly low can gravely compromise energy efficiency, markedly undermining potential energy savings. As such, to harness the full potential of technological advancements, they must be paired with informed and judicious behavioral practices.

6. Conclusions

This research provided a comprehensive analysis of energy efficiency within non-residential public buildings, emphasizing their distinct energy profiles. When considering engineering decisions for such buildings, multiple variables come into play. KPIs, while beneficial, often have inherent limitations due to their inconsistency across varying domains, making direct comparisons or certain numerical calculations problematic.

From the literature review, a discernible energy consumption pattern emerged. Swimming pools, for instance, stood out as exceedingly energy-intensive structures. Hospitals, on the other hand, presented a myriad of energy challenges, given their round-the-clock operations and the encompassing nature of their energy-intensive activities. Notably, smaller facilities, although possibly more costly to retrofit, demonstrated a higher potential for energy savings per unit area.

A pivotal finding was the prominent role of heating and cooling systems in energy consumption. They accounted for a significant portion, 40–65%, of the total energy usage across numerous public facilities. This consistent trend over time accentuates the critical need for targeted energy-saving interventions, with swimming pools as a primary focus due to their elevated energy demands.

Delving into retrofitting, the study offered a two-pronged approach. Passive retrofitting stresses the indispensable role of insulation, given that thermal energy for heating and cooling dominates a building's energy footprint. Active retrofitting measures, meanwhile, presented a broad spectrum—from state-of-the-art heating/cooling systems to the integration of renewable energy sources. The insights into retrofitting unveiled a critical balance—achieving energy efficiency while remaining economically viable remains a challenge for many stakeholders.

In our exploration of Technological Intervention Adoption and Effectiveness, several salient findings have emerged. Foremost, thermal energy remains a dominant factor in the energy landscape of public buildings, consistently contributing to over half of a structure's overall energy requirements. Despite considerable technological advancements and the promise they hold, tangible reductions in the average thermal energy consumption per unit area have remained elusive.

This complexity is further nuanced when considering the retrofitting of historically and culturally significant public buildings. While these edifices often face constraints regarding structural modifications, they simultaneously present a unique opportunity. Innovative retrofitting measures have showcased their potential, with some interventions yielding remarkable energy savings, even approaching the coveted nZEB status.

Yet, as we delved deeper into energy consumption patterns, a contrasting trend became evident. Electrical energy consumption has seen a commendable decline, especially in lighting, largely attributed to transformative technologies such as LEDs. However, the thermal energy landscape tells a different story. Despite advancements in insulation and the promise of reduced U-values, the anticipated diminution in thermal energy consumption has not materialized. This disparity can be attributed to a combination of factors, including the gradual nature of building transitions and, crucially, the behavioral aspects of building operators and inhabitants.

Furthermore, the role of climate in shaping energy consumption patterns has been brought to the fore. While there is an undeniable decrease in the climatic requirements for heating, as illustrated by the decline in Heating Degree Days, thermal energy consumption remains steadfast. This stability, even in the face of changing climatic demands, suggests that climate alone cannot account for these energy consumption patterns, highlighting the multifaceted challenges inherent in the building's energy landscape.

Perhaps most crucially, our findings underscore that the true potency of technological interventions in the real world hinges heavily on user behavior. While technologies can be designed for optimal performance, their efficacy can be severely compromised by operational habits. Thus, for the world of tomorrow, it is not just about championing technological advancements but ensuring they are complemented by informed and judicious behavioral practices.

7. Future Work

While the advantages of district heating and cooling systems are well-documented, their application in public buildings remains underexplored. Additionally, a deeper investigation into behavioral interventions is essential to harness the full potential of technological advancements in energy efficiency, especially emphasizing thermal comfort.

Given the considerable impact of user behavior on energy consumption patterns, as evidenced by our findings, it is imperative for future research to intensify its focus on understanding the behavioral facets of both building operators and inhabitants. Employing methods such as surveys, interviews, and field observations can furnish invaluable insights into the prevailing habits and practices that either impede or facilitate energy-saving interventions. The inclusion of these behavioral aspects would bring an additional layer of comprehensiveness to the optimization strategies for energy efficiency in public buildings.

Table 8 highlighted unexplored areas in retrofitting interventions,(e.g., limited research on phase change materials and hydrogen technologies) across diverse building types. These gaps present opportunities for future research on the specific types of buildings.

Finally, in future research, it will be valuable to focus on the relationship between climate change and energy consumption patterns in public buildings. Employing predictive modeling techniques based on climate projections can provide essential insights for policymakers and building operators. This approach will not only help prepare for changing energy requirements but also offer guidelines for new constructions and extensive retrofitting projects and further enrich our understanding of sustainable energy interventions in public buildings.

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Abbreviations

ANN	Artificial Neural Network
AHU	Air Handling Unit
BEER	Building Energy Efficiency Retrofit
BEMS	Building Energy Management Systems
BREEAM	Building Research Establishment Environmental Assessment Method
CDD	Cooling Degree Days
DD	Degree Days
EEI	Energy Efficiency Initiatives
ESE	Energy Source Efficiency
EUI	Energy Use Intensity
EU	European Union
GHE	Geothermal Heat Exchangers
GHG	Greenhouse Gas
HDD	Heating Degree Days
HVAC	Heating, Ventilation, and Air Conditioning.
IAQ	Internal Air Quality
IEA	International Energy Agency
KPIs	Key Performance Indicators
LCOE	Levelized Cost Of Energy

LEED	Leadership in Energy and Environmental Design
PM	Particulate Matter
PV	Photovoltaic
ROI	Return on Investmen
nZEB	near Zero-Energy Building
UN	United Nations
VOC	Volatile Organic Compounds
WUE	Water Use Efficiency
ZEB	Zero-Energy Building

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