A SYSTEMATIC REVIEW OF ENERGY RETROFIT MEASURES IN THE BUILDING SECTOR: COST, CARBON AND POLICY PERPECTIVES UNDER EU FRAMEWORKS

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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Keywords: Deep Retrofitting, Building Energy Efficiency, Retrofit Cost, Carbon Reduction.

A systematic literature review regarding energy retrofit measures in the building sector, financial modelling of retrofit measures, the most used types of energy retrofit measures, and knowledge gaps that could inform future studies. This study used PRISMA methods to rigorously screened literature published between 2014 to 2025, ultimately selecting 42 high-quality publications including peer-reviewed articles, technical reports, conference papers, and academic thesis from an initial 55 sources. Quantitative trend analysis completed in Excel and SPSS, evaluated publishing dynamics and knowledge gaps of energy retrofit studies. Study found that the dominate studied category was "envelope retrofits" which had an energy performance increase between 10%-95% with an average payback of 13.4 years. Moreover, envelope and heating system retrofits produced most financially favourable outcomes with heating system retrofits yielding 40.9% energy savings, 46.7% CO_2 emissions reduction, and a payback of 9.2 years. Additionally, control systems were found to produce the best financial returns at 1.7 years while producing only moderate increases in efficiency. Because of the moderate efficiency gains, control systems are recommended for early-stage energy retrofit initiatives as part of a larger integrated energy retrofit package to achieve the best long-term reductions (about 70%) in energy usage and associated CO_2 emissions. Nearly Zero-Energy Building (NZEB) strategies produced 72% energy and 77.5% CO_2 emissions, but the costs were €600 - €1,050/m² and the associated paybacks are generally significant. The best approach for executing an energy retrofit for residential and commercial building is a sequential phase approach using the energy retrofit strategy of quick-wins, system upgrades, envelope improvement, and deep retrofit as the applicable best practice.

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SYMBOLS AND ABBREVIATIONS

Abbreviations

EED	Energy Efficiency Directive
EPBD	Energy Performance Buildings Directive
NZEB	Nearly Zero Energy Building
RBC	Rule Based Control
LCC	Life Cycle Cost
HVAC	Heating, Ventilation, and Air Conditioning
ASHP	Air-Source Heat Pump
GSHP	Ground-Source Heat Pump
EU	European Union
MPC	Model Predictive Control
PI	Proportional-Integral (Control)
VTT	Technical Research Centre of Finland
IEA	International Energy Agency
NPV	Net Present Value
kWh	Kilowatt hour
°C	Degree Celsius
%	Percentage
m^2	square meter
€	Euro (currency)
CO_2	Carbon Dioxide
Mt	Megatonne (million metric tonnes)

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DECLARATIONS

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The originality of this thesis has been reviewed with the Turnitin similarity checking service.

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1. Grammarly
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Responsibility

The author, Kaspia Rahman Tanima, takes full responsibility for the content of this thesis and has reviewed and edited the content generated by the possible use of AI tools.

1 Introduction

Energy drives the development of all modern societies, contributing to economic growth, social cohesion, and the viability of ecosystems. However, the built environment has become a major site of energy-related problems and potential solutions. Within the European Union, buildings account for a significant portion of energy consumption and almost one third of the carbon footprint European Environment Agency (2024). Annual reports, policy briefs, and public discourse emphasize the need for responding to energy challenges. This situation is particularly relevant to the Nordic region because of high winter operational energy demands created by extended periods of sub-zero temperatures.

1.1 Rationale of the Study

In Finland, the energy efficiency challenge is indeed significant. Pre-1990s residential buildings, where regulations on energy use and efficiency were less developed, still constitute a major part of the building stock. Numerous scholarly reviews outline how such buildings, particularly those constructed during decades of the 1970s and 1980s, contain systems that poorly insulate and inadequate electric, district or oil-based heating systems that contribute to high energy consumption and excessive operating costs. (Numminen et al., 2024; Olkkonen et al., 2021; Schroderus et al., 2025) High up-front costs and significant financial investment continue to slow the rate of deep retrofitting, even with the recent technological advances of heat pumps and smart heating controls Niemelä et al. (2017). For Finnish homeowners and housing associations, the renovation cost is a considerable investment of over €500 - €600 per square meter.

Buildings consume energy in the form of heating, cooling, ventilation, lighting, and for powering appliances, which is expressed in kilowatt-hours (kWh) per square meter per year. The total energy consumption of a building is directly related to its energy performance, which is the measure of how efficiently the building incorporates energy to maintain a comfortable environment in indoors. The building is said to be energy efficient when for every unit of energy it uses, it produces a significant useful output while lowering its operational costs and reducing its carbon footprint. The energy retrofit of a building

(envelope, insulation, windows, heating and ventilation systems) is aimed at improving this efficiency, which mostly done through deep interventions.

Retrofitting can involve altering a building's structure, thermal balance, and mechanical systems with the aim of improving energy performance and achieving direct energy and emissions reductions. In this case, energy efficiency involves obtaining additional comfort or productivity from a building or facility for the same energy expenditure, primarily through the use of advanced technologies (such as better insulation and heat pumps), along with changes in human behaviour and operational practices. A thorough cost assessment which comprises a detailed forecast of all the costs and savings for the entire duration of the retrofit project from an operations standpoint, and balances this against the initial outlay as well as long-term maintenance costs must form the basis of all planning and execution. The energy performance of a building or facility can be quantified and compared before and after a retrofit, thus allowing for performance gap analyses and accurate guidance on opportunities for subsequent refinements. Importantly, successful retrofits lead to a decreased energy load and a reduced carbon footprint. Several studies corroborate that deep retrofits can result in a 30–60% reduction in annual energy use, primarily because these retrofits include changes to the building envelope and modern heating systems. (Hirvonen et al., 2020; Simson et al., 2025) There are currently significant economic and environmental benefits to these strategies in achieving nearly zero-energy standards on Finnish buildings.

1.2 Key Insight from EU Energy Efficiency Directive

The EU Energy Efficiency Directive (Directive EU 2023/1791) is a cornerstone of EU's climate and energy policy. The Energy Efficiency Directive requires all Member States to respond to the EU policy aimed at improving the energy efficiency and fulfilling the ambitious goal of energy consumption reduction by 2030. The Directive emphasizes the "energy efficiency first" principle, which requires all countries to consider cost-effective energy savings in every stage of policy, investment, and renovation activities of buildings. For the construction sector, the Directive imposes legally binding energy demand reduction targets and requires the public sector to exemplarily lead with annual efficiency improvement tied to comprehensive monitoring and transparent reporting. The Directive promotes deep renovation of buildings and the transition to almost zero-energy standards to

reduce emissions and foster sustainable development in the EU. In all over europe, these requirements drive national strategies and investments in large-scale retrofit programs and align local efforts with the EU climate neutrality targets.

1.3 Problem Statement

Finland still faces uncertainty in effective retrofit measures, cost efficiency, and regulatory compliance even with advanced technology and new policy frameworks. Stakeholders still lack decision-support systems that incorporate scenario analysis, life cycle costing, and policy compliance that leaves building owners to face the intricate web of design, economic, and regulatory issues. Investor's assessment of risk, the gaps in their knowledge, and the challenges in anticipating long-term results still inhibit the adoption of necessary measures.

This thesis aims to conduct a systematic review, analysis, and synthesis of the literature on energy efficiency, and the cost analysis of energy efficiency, for retrofitting buildings per the EU Directive.

1.4 Research Questions

1. Which retrofit measures are most adopted, and what levels of energy savings do they achieve according to the literature?
2. How do current research findings reflect or support the goals of the EU Energy Efficiency Directive and Finland's national energy efficiency targets?
3. What limitations, research gaps, and future directions have been identified in existing studies on building retrofitting for energy efficiency and cost-effectiveness?

1.5 Objective of the thesis

1. To systematically review and synthesize existing studies on building retrofit energy efficiency and cost analysis in Finland and the EU context.
2. To identify the most adopted retrofit measures and their reported energy savings.
3. To identify knowledge gaps and suggest directions for future research.

2 Literature Review of Building Retrofit Energy Efficiency

A thorough review of approximately 250 scholarly publication was conducted through both direct and indirect search strategies and from this extensive pool an initial set of 55 research papers identified during the systematic review process. However, 42 research were selected for in-depth analysis, as these works exhibited relevance to the topic of building retrofit energy efficiency and cost effectiveness.

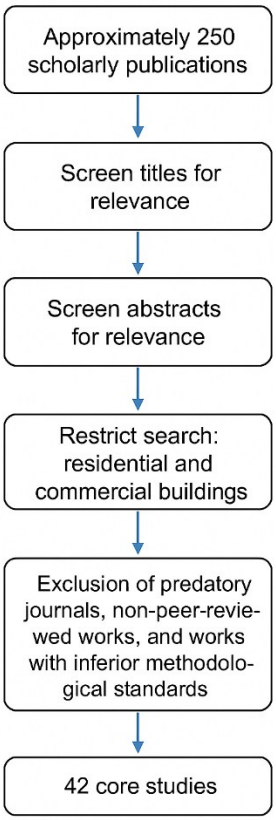

Figure 1: Primary Systematic Literature Review Process

A systematic literature review was undertaken within the framework of major publication sites and academic databases. Articles were first screened by title to assess relevance to retrofit energy efficiency and cost-effectiveness in the built environment. This was followed by a review of the abstracts, during which irrelevant studies were dismissed based on the thesis parameter or if the content did not align with the intended scope of the study.

The search was further refined by restricting the scope to studies pertaining to residential and commercial buildings, which were to the exclusion of studies on industrial infrastructure. This exclusion was deliberate to maintain thematic consistency. Further, the review excluded works published in predatory journals, lacking peer review, or characterized by inferior methodological standards.

The review adhered to the PRISMA guidelines to guarantee a transparent and systematic approach to the study selection. Successively imposed study selection limits title, abstract, building type, publication type, and relevance to research vision reduced the initial pool to a final 42 core studies. This approach, considering the abundance of related literature available, was imperative to ensure that only the most focused, credible, and quality publications were analyzed. This database was then segregated into 6 different for the literature review.

2.1 Peer Reviewed Journals

Among these 42 studies, most of the publications (32) were peer reviewed journal articles, ensuring a high degree of academic rigor and methodological consistency within the literature. This selection highlights a research landscape predominantly shaped by scholarly contributions which provides a robust foundation for synthesizing key findings and identifying prevailing trends in retrofit practices.

2.1.1 Most Adopted Retrofit & Energy Savings Measures

Tushar et al. (2022) showed a detail cost benefit analysis which is focusing on retrofitting building façade and considering the energy star rating improvements on a life cycle financial analysis. The research implemented dynamic energy simulation and Monte Carlo risk analysis on different combinations of insulation and window glazing and assessed them over 20, 40, and 60-year periods. The research work shows how insulation improvements, especially ceiling and wall insulation, along with window glazing, provide substantial energy savings and return on additional cost. Upgrading mandatory star ratings from 6-star to 8-star has proven to be very cost effective across a wide range of climates and the time horizons analysed. The research work proven the optimal retrofit levels by demonstrating rapidly

diminishing returns on further insulation beyond certain thresholds. This research also highlighted the international and policy implications related to their work by encouraging life cycle costing on energy renovations to Australian standards, which the authors argue are too lenient compared to Europe. The authors noted the lack of empirical evidence on which to base their suggestions for stronger regulations for stakeholder cooperation.

Liu and Ren (2020) examined the energy efficiency design strategies of Xi'an's and Shaanxi cold climate zone's Chinese university buildings, particularly the green performance of libraries and dormitories. Using on-site studies, thermal environment assessments, and architectural simulations, they pinpointed causes of inefficiencies which included inadequate thermal insulation, a lack of airtightness, overly large glazing components, and poorly controlled operation of the HVAC, lighting, and water systems. Their five-layered planning and design strategy model that encompasses system operational management, administrative control, energy awareness measures, and established technical systems. It is based on the assertion that energy retrofits of building envelopes could improve energy performance by 47.4%, yet resulting performance would remain above the country's energy standards. Study proposed that energy efficient approaches can be integrated at the initial stages of construction rather than integrating them afterward as a patchwork solution. In addition to this, the study considered inadequate oversight at the managerial levels and siloed policies as the most significant impediments to advancement. The study promoted the adoption of all-inclusive green retrofits, integrated campus management systems, and an enhanced culture of energy saving and conservation as the means to improve the implementation of sustainable practices in the Chinese higher education sector.

Ramesh et al. (2024) performs a comparative analysis of the energy flexibility, cost savings, and occupant comfort on the heating-control strategies in Finnish residential buildings and evaluate the impact by focusing on two case studies in Helsinki, a conventional 1970s apartment block and a cutting-edge positive energy building (PEB) built in 2023. Therefore, study simulated the performance assessments of Proportional-Integral (PI) feedback control, Rule-Based Control (RBC), and Model Predictive Control (MPC) were conducted using white-box simulations (IDA ICE and algorithms in Python) in extreme winter conditions and with different electricity cost scenarios. The study found that the MPC not only saves the most cost during aextreme conditions but also saves most cost relative to all the other control strategies during conditions with fluctuating grid pricing, with saves of 29.9% and

14.8% in the oldest and in the PEB, respectively, compared to PI control. Moreover, RBC control offered lower savings, and compared to other strategies, was quite stagnant. The smart control retrofits for the Finland building stock have large potential. Advanced Model Predictive Control can increase energy efficiency and comfort, while dynamically adjusting to the weather and market. The study also pointed out that intelligent heating control system exists and are essential for retrofits and new builds in cold Nordic climatic zones, aligning with the EU policy energy for energy resilient building.

Hirvonen et al. (2022) addressed the socio-economic and environmental effects of large-scale deep energy retrofit on Finnish apartment buildings through scenario modelling to the year 2050. Their work was framed considering the Renovation Wave of the European Union and the Finnish target of achieving carbon neutrality by 2035. By employing building stock modelling and simulation-based multi-objective optimization across four building archetypes based on the construction codes of various periods, the authors aimed to assess both low-impact, cost-neutral and high-impact, non-profitable retrofitting strategies across different time periods. Furthermore, the research demonstrated that deep retrofitting techniques applied before 2050 would allow for 30% more CO_2 emissions reduction compared to the baseline scenario of retrofitting, evaluable to the time of the no-retrofit, with most of the reductions being achievable through early interventions. Moreover, the study foresees that each million euro invested in retrofitting translates to the creation of 15–17 jobs but also spells out the main fiscal paradox of the research. The author defended that economically and active local economy combined with lower imported fossil fuels is counter-balanced by economically efficient retrofitting, which paradoxically generates a net negative government energy tax stream. Along with that the author emphasised that resolving this paradox and economically maximizing the gains obtainable through retrofitting while decreasing emissions require urgent coordinated large-scale retrofitting. The study highlights the fiscal paradox in which dependence on imported fossil fuels and advancing a cleaner economy ultimately decreases government revenue form energy tax stream.

Niemelä et al. (2017) focused on 1960s Finnish brick apartment buildings, carrying out an extensive simulation-based optimization study investigating potential cost-efficient retrofitting and primary energy use and lifecycle cost reduction tactics. The research modelled more than 2 billion combinations of retrofits. Furthermore, the study emulated

deep retrofitting scenarios involving external walls and roofs insulation, replacement of glazing, ventilation system enhancement, various heat pump systems adoption, and solar PV or solar thermal systems integration. After that these scenarios then compared under different heating configuration. The result indicated that retrofitting with ground source heat pumps combine with solar PV was able to achieve energy performance approaching the NZEB standards for new Finnish apartments, while GSHP Air-to-water and exhaust-air heat pumps were also competitive for buildings where GSHP installation is not feasible. Although envelope and ventilation improvements deliver significant energy savings, the study found they are optimally cost effective at higher energy performance targets, or when subsidized. The author further showed that package-based renovations where holistically implementation and scheduled apartment maintenance can simultaneously economically viable and environmentally viable.

Popovski et al. (2023) analysed how deep retrofits of the urban building stock and modernization of the district heating (DH) systems can work together to implement the "Efficiency First Principle" in the European Union. The research shows that considering ambitious building retrofits, in the dense urban areas of the five largest cities in Europe to the year 2050, building networks can be optimally served by cost-effective and low-emission renewable district heat (DH) systems. The author states that as retrofits are implemented, the peak heating demand supplied by district heating (DH) systems decreases. This reduction enables DH networks to operate more efficiently and the use of EU compliant decarbonized renewable heat and excess grid heat to be integrated. While the systems unit costs increase with increasing retrofits penetration, comprehensive retrofits in low-density urban areas help to minimize the overall urban heating costs borne by DH system. The author emphasizes that the coordination and balancing both retrofit and DH systems strategies is essential to enable district heating to be decarbonized in a cost-effective manner.

Hirvonen et al. (2019) examined possible low-cost pathways for decreasing greenhouse gas emissions from detached houses in Finland in order to fit the targets of the EU's climate goals for 2050. Taking dynamic simulation and a multi-objective optimization approach for each age class of houses and different heating systems, the authors identified ground-source heat pumps (GSHP) as the most significant retrofitting option, achieving reductions of 79-92% on emissions, especially those from oil and wood boilers. In most cases, combining air-to-air heat pumps for supplementary heating and planned envelope improvements for a 55%

emission reduction in the overall detached house stock (74% when considering unrestricted investment) was the best cost-effective option. Moreover, the authors acknowledged that deeper retrofits including mechanical ventilation, photovoltaics, or solar thermal systems would result in greater savings but to establish those systems, subsidize and policies amendments are required. The authors advised to prioritizing information campaigns, along with low-interest loans programmes, to facilitate the adoption of ground-source heat pumps (GSHP) and key building envelope improvements. They further emphasize that more comprehensive energy retrofits in the residential sector would require policy frameworks designed to be economically attractive and accessible to all homeowners.

Rose et al. (2019) studied outcomes related to deep energy renovation of Danish multi-story apartment buildings. The authors case studied building envelope insulation, triple glazed windows, heat recovery ventilation systems, upgraded heating systems, and integrated PV systems and found that primary energy use dropped by 48-54% during the heating season, although retrofits did not achieve modeled expectations due to uninsulated thermal losses, and uninsulated pipes. Deep retrofits financed during economically optimal periods, coinciding with routine maintenance cycles, highlights the importance of synchronizing energy renovation measures with routine building cross-section maintenance. Importantly, the study showed that comfort and health, asset value and maintenance load, emissions, and job creation associated with deep retrofitting not only increase comfort, health and asset value but also reduces maintenance demands, lowers emissions and stimulates job creation, thereby generating socio- economic benefit that surpass the value of energy savings alone. These findings advocate for integrating the mitigation of performance gaps and socio-economic externalities with the technical dimensions of retrofitting to reach near zero energy renovation levels and respond to the EU Policy framework.

Gustafsson et al. (2016) performed a techno-economic analysis of energy renovations for multi-family district-heated buildings located in the Stockholm region of Sweden. The authors evaluated the upgrades to the building envelope including facade, roof insulation, triple glazing, as well as water-saving taps and various HVAC configurations that included mechanical ventilation with heat recovery (MVHR) systems and exhaust air heat pumps (EAHP). The study found that the best renovation packages combined envelope insulation with water-saving measure and used EAHP for space heating and domestic hot water. This approach reduced life cycle cost by 24%, primary energy use by 58%, and CO_2 emissions

by 65% compared to reference renovations. Adding low-temperature radiators further improved heat pump performance. However, insulation alone was economically beneficial with other planned renovations, even though it provided clear environmental benefits. The authors also concluded that in the context of Swedish and other Nordic countries' multi-family buildings, EAHP are the best economical and energy efficient and that MVHR systems economically fail. Sensitivity analyses confirmed these core results.

2.1.2 Alignment with EU Directive & Finland's National Targets

Li and Shui (2015) provided a thorough review and critical analysis of China's building energy efficiency (BEE) policies, focusing on the evolution in the context urban expansion and raising living standards and climate challenges. The review traced the development BEE policies from the early research and pilot initiatives to the establishment and refinement of national regulatory frameworks covering both residential and public structures throughout the country's various climate zones. The key areas of focus include improvement on envelope insulation, equipment standards, and integrated building design. The study pointed out notable achievements, such as the creation of robust regulatory and monitoring system, strong compliance in new urban developments and the rapid escalation of retrofitting initiatives especially in the energy-intensive northern heating regions. They further highlighted the influence of changes in building envelops, adoption of energy metering and integration of renewable energy, and economic measures like tax incentives and subsidize. However, the authors pointed out persistent policy gaps especially in impact rural and existing built environment. Command and control policies dominates often undermining economic incentives, effective retrofitting, transparent data collection, and retrofitting. The study also noted that the lack of cost-effectiveness and sustainability considerations in technical standards has hindered the development of refined data systems and better inter-agency collaboration. To address these challenges, Li and Shui recommended more frequent updates of cross-agency codes. They further suggested the expansion of the BEE goals to incorporate the social and the economic dimensions, aiming for aspirational goals like near-zero-energy and zero-carbon structures. Finally the advocates for a shift to economically inclusive, sustainable, and market-oriented policies concerning the building industry in China.

Hirvonen et al. (2020) conducted a quantitative analysis not only evaluating the emission reduction potential and the cost-effectiveness of energy retrofits across six major building types in Finland including detached houses, apartment buildings, elderly care facilities, offices, schools, and commercial buildings. The study combined simulation results from multi-objective optimization models. They assessed the impact of envelope retrofits along with heat pump systems, solar PV and thermal installations, ventilation improvements with controls, and other integrated retrofits over the 25-year life cycle considering emissions from the Finnish grid and district heating. The research showed that switching single-family houses from oil or wood boilers to ground-source heat pumps offers the most significant emission reductions (up to 95%) while reductions of 60–85% can be achieved on apartment buildings, offices, schools, and elderly care facilities by heating system upgradation or with the addition of heat pumps. Most cost-neutral retrofits were also significant, with emission reductions of 20–70% and an investment cost of €100–400/m². The abatement costs were also lower in service buildings, which were occupied continuously, and solar retrofits improved performance in commercial buildings. The overall abatement cost ranged from €132 to €578 per tonne of emissions avoided. Furthermore, the research stated that among all system upgrades, heating system upgrades have the greatest impact, specifically heat pumps, outperforming district heating due to Finland's lower grid carbon intensity. They also concluded that to fully realize retrofit-driven climate gains across the entire building stock of the country, stricter renovation standards and specific financial incentives are needed.

2.1.3 Limitations, Gaps, and Future Research Directions

Liu et al. (2018) developed one of the first cost-benefit frameworks for evaluating energy efficiency retrofits to existing residential buildings using a detailed case study of Huixin Western Street from Beijing. This research combined a lifecycle cost-benefit approach with measured pre-energy and post-energy retrofits data to analyse the economic and energy efficiency performances of interventions that included external insulation, efficient windows, HVAC improvements, and upgrade to heating pipe network and ventilation system. The author noted that while theoretical savings could reach 50%, actual post-retrofit savings were more realistically between 25% and 35%. The most economically efficient

measures were the upgrades on the heat source and heating pipe network with payback periods of 1.7 years and high internal rates of return. In contrast, although envelope insulation and retrofits were only marginally efficient due to low energy prices in the region. Cost-effective window retrofits perform better than wall insulation, particularly with economically accessible materials like plastic-steel. The study's sensitivity analysis also showed the appeal of retrofits would only improve with significant increases in energy prices. Changes in user habits or cost had smaller impacts on the attractiveness of the retrofit to the investor.

Zhang et al. (2023) analysed energy efficiency's impact on residential property values across 54 major cities in China from 2007 to 2018 using DEA and productivity indices along with regression models. The research found that every 1% increase in energy efficiency results in a 0.58% increase in property value, with the strongest impact in cities that are economically developed, service-oriented, and have temperate climates. However, in the more northern cities with high heating demands, the effect becomes negative or largely insignificant, likely due to the prevalence of centralized coal-based heating, and the low value recognition of energy performance in these markets. The study argues that the economic development and strong service sector strengthens the positive impact of energy efficiency on property values and recommends more aggressive policies and subsidies for retrofitting in cities where private market incentives are lacking. Such findings supports the need for integrated policies that address the energy and housing markets, in order to promote retrofitting towards carbon neutrality and maximise the value gained from efficiency improvements in different city landscapes.

Olkkonen et al. (2021) evaluated the system-wide impact and cost-effectiveness of building energy efficiency measures on Finland's 2050decarbonization targets. In the research, scenario modelling was used to measure the impact of retrofits such as. insulation upgrades, window replacement, advanced ventilation, heat pumps, and solar energy installations on energy demand, emissions and energy systems. The study stated that the emissions retrofitted buildings impacts the most when the energy used is carbon rich. This indicates that aggressive building retrofits during the initial decarbonization implementation phases optimizes cumulative savings. As decarbonization progresses, building energy savings will reduce consumption of saved wood-biomass with a substitution effect becoming stronger when carbon land-use and forestry balance is considered. The scenario assumed vast impacts

and costs, primarily due to energy marginal costs showing dynamic land carbon, coupled with energy system transitions, determines high marginal net benefit of deep building retrofits. This study supports the hypothesis that coordinated building retrofits should be align with land and national carbon energy system. It highlights that optimum results are achieved when building energy system retrofits coordinated with national energy and biomass systems.

Zimunya and Mhlanga (2025) investigated the challenges and potential for enhancing the energy efficiency of older buildings which were constructed before the inception of green building policies in Mutare City, Zimbabwe, referencing international case studies for context. Their qualitative research involving expert interviews and participants observations, highlighted key challenges including retrofit costs, financial accessibility, insufficient regulations, lack of technical skills, and either ignorance or scepticism toward the benefits of retrofits. The authors underscored the contrast between Zimbabwe's lack of proactive green building practices toward international best practices. The author further proposed a several approaches, including activating policies to encourage retrofitting of older building, providing government financing, building of human resources, reforming legislative framework, mobilization community educational campaigns, and integrating intelligent and renewable energy systems. The authors also noted the importance of coordinated and targeted action from all stakeholders to unlock the extensive benefits of upgraded non-green buildings, including the deep sustainability gaps and improving health, wealth, and climate resilience.

Moeller and Bauer (2022) analysed the energy performance gap (EPG) in multi-apartment buildings near Leipzig, Germany and found that the expected reductions in energy use after envelope retrofits are often not fully achieved due to occupant comfort behaviours. Their mixed-methods study combined detailed energy consumption analysis with surveys of heating and ventilation habits among 34 households. The results showed that improved insulation and airtightness create a more stable indoor climate but simultaneously enable "energy-inefficient" practices such as higher heating setpoints and increased window ventilation. These adaptive behaviours varied significantly across households and reduced the potential energy savings, indicating that physical upgrades alone are insufficient. Furthermore, the research concluded that retrofit programs must engage with the complex social-technical interactions between building systems and user behaviour, moving beyond

informational campaigns to actively address feedback and control mechanisms, in order to close the EPG and achieve intended energy efficiency goals.

Zaunbrecher et al. (2021) described the impact intermediaries e.g. craftspeople, architects, and energy consultants who have the influence on the homeowners on energy efficiency retrofits in the Aachen region of Germany. Through a qualitative interview with 11 professionals, the author demonstrated how intermediaries act as gatekeepers determining which retrofitting options are selected and swhich are overlooked. Their decision are influenced by personal beliefs and experiences, as well as laws and regulations and prevailing market conditions. The authors found that homeowners tend to rely on the intermediaries' decision, and as a result, these professionals have disproportionate control on the scope and ambition of retrofits. Moreover, the researchers concluded that energy transition policies should specifically targets intermediaries by providing them training and incentives to them, as they hold the potential to facilitate or counter the implementation of energy-efficient measures at the residential level.

Lundqvist et al. (2020) examined the need to adjust heating systems after deep envelope retrofits in sub-Arctic climates. The study used two identical multi-family buildings in Kiruna and Sweden as case studies. After one building recieved extra wall insulation and new windows, comparative monitoring for four heating seasons showed that even though heating comfort improved (with indoor temperature raising about 2°C), heating energy use remained relatively unchanged. Following to that the heating system continued providing the same heat flow, simply resulting in higher indoor temperatures. Simulation results further showed that heating system controls to match occupant comfort standards could achieve a 13–14% reduction in heat supply and post-retrofit energy savings of 15% annually. This indicated an absence of system control on captured energy savings of 15% post envelope improvement. The study clearly highlights the critical need for control adjustments following envelope upgrades in clod climate.

2.1.4 Systematic Review Approaches

Yu et al. (2017) examined the impact of building energy efficiency policy in India through the case of the Energy Conservation Building Code (ECBC) in Gujarat. Using the Global Change Assessment Model (GCAM) at both the national and Gujarat state levels, the authors

projected trends in building stock, demographics growth, and the resulting energy and emissions outcome based on economy changes. Their research analysed energy demand and infrastructural implications across several scenarios, including no policy, ECBC policy with various compliance rates on commercial building under the ECBC, extension of building codes to residential buildings, and the aggressive adoption of green building initiatives. The study concluded that complete and strict implementation of the ECBC would reduce electricity demand in Gujarat by 20% by 2050, and by 30% if codes for residential buildings also included. Complete implementation would also reduce the need for investment in additional power generation infrastructure. The study also pointed out that the limited extent of green building programs means that mandatory codes will be more impactful on a system-wide basis. The authors recommended strengthening institutions, enforcement mechanisms, and adopting international best practices for building sector policies in India will give its rapid growth.

Gupta et al. (2023) assessed a wide range of energy-efficiency benchmarking approaches to address the lack of a unified national building benchmarking systems, particularly for residential buildings in Jaipur, India. The study used data from over 2,700 houses across different types and income levels and evaluated three energy-efficiency benchmarking methods e.g. two black-box methods (Multiple Linear Regression and Principal Component Analysis) & one grey-box method (Bayesian Ridge Regression). These methods utilized building characteristics, household appliances, energy bills, occupant behaviour, and energy consumption appliances (especially from air conditioners) to derive an Energy Performance Index (EPI). The research identified household items, especially air conditioners, were the primary energy consumers, while larger built-up spaces were associated with lower EPI values. All benchmarking techniques were efficient in classifying building performance, but there was difference in ranking distributions and sensitivity to data feature. Among these, Bayesian Ridge Regression showed the most consistency and predictive performance. The also found a substantial concentration of buildings in the highest and lowest tiers with standard EPI-based ratings, which suggests a practical limitation to this rating technique. Finally, the authors concluded that relative to the hybrid or combined benchmarking techniques, these techniques provide a more dependable energy efficiency rating and improvement strategy.

Fang et al. (2024) conducted a literature review on EMS (energy management system) considering public EMS literature specifically and including studies on residential, commercial, zero energy and other buildings. In the period 2010-2024 and covering China, US, and Europe as well as other serrated regions, the study considered and screened 55 core studies and performed GIS (Geographic Information Systems) and bibliometric analysis studies to determine the typological, regional and methodological distribution and diversity. The study highlighted the progress of EMS in leveraging digital technologies, the rise of interdisciplinary EMS, and the combination of passive and behavioural strategies to enhance energy eco-efficiency. The research described the importance flexibility in standards, the complexity of data EMS systems, and role of adaptive contextual benchmarking for the success of EMS. The author also emphasized the challenges such as complexity of assessments, fragmentation and comparability of data and the theoretical and practical gaps in benchmarking and validation. The study outlined the use of AI and machine learning for intelligent EMS control as well as the harmonization of standards and integration passive strategies as primary findings and recommendations. The review of the literature also contains suggestion for deploying incentives around zero and low carbon goals and best practice energy management.

Maaouane et al. (2023) conducted a top-down and bottom-up sequential optimization estimations paired with Building Information Modelling (BIM) techniques to identify cost-effective measures for improving energy efficiency for different North Africa buildings with an amazing case study focus on Morocco. They analysed interventions such as envelope insulation, windows, HVAC systems, lighting, and building orientation across six climate zones and 9 building types. The study found that individually tailored retrofit packages could achieve energy consumption reductions in the range of 31–56%, with optimal packages reaching 56% and suboptimal ones 31% depending on building types and climatic zones. The suboptimal packages differ by more than three energy efficiency measures. For Morocco, the nationwide potential impact of these results could be a 24% reduction in energy demand by 2050. Moreover, adoption of the retrofit measures and further electrification of building energy, hot water, and cooking (for example, by removing LPG subsidies) would drive the demand reduction. The study emphasized that the energy enhancements and cost savings relates to net zero energy goals from strategic sizing of PV, controlling efficient heating and cooling, improved lighting, and sizing windows for net zero energy goals. To

gain the full benefit from energy efficiency measures across the North Africa building stock, the research concluded that it is necessary to implement regionally adaptive energy codes with compensatory systems across the region.

Son and Kim (2018) study introduced the use of evolutionary many objective optimization to simultaneously optimizing the energy efficiency, CO_2 emissions, cost, and thermal comfort in buildings. They conducted a case study on a 1960s university building in Seoul and evaluated multiple optimization techniques, including NSGA-III, the latest and most developed method for "many-objective" problem optimization, and realistic retrofit interventions (insulation, windows, and HVAC systems). The study estimated that NSGA-III improved outcomes compared to older techniques (NSGA-II, MOPSO, MOEAD) because it delivered retrofit plans that approached theoretical optimum on all objectives and provided a greater solution diversity. This diversity increases the decision maker's available trade-off range. The authors stated that the developed many-objective optimization techniques improved retrofit planning transparency and efficiency, which, they stated, is relevant to the EU public building performance directives and zero energy targets. The authors estimated many-objective optimization techniques improved retrofit planning in transparency and efficiency and stated that it is relevant to the EU public building performance directives and zero energy targets.

Nita et al. (2023) analysed the diverse influences affecting the implementation and outcomes of energy efficiency (EE) projects in Indonesia's public sector buildings. The author conducted intensive interviews with decision-makers in government, education, finance, and the construction sector, and utilized the grounded theory approach with content analysis. Furthermore, the authors identified 32 interrelated factors determining the projects outcomes. While the economic viability and financing are crucial, the finding also highlights the equal importance of organizational dedication, supportive political frameworks, and robust technical and informational systems. Additional barriers regulatory stagnation, lack of coherent system integration, and various technical and institutional challenges within system networks. The author emphasizes the need for policy improvements and better delivery methods specially in system financing and regulatory reforms, and integration of collaborative interfaces with multiple stakeholders. The work thus provides the consideration factor for stakeholder-oriented framework for the acceleration of EE in public sector buildings.

Wu et al. (2017) developed a multi-objective optimization framework to determine optimal retrofit and energy system upgrades for residential areas in terms of cost and GHG emissions. The authors used the energy hub model with mixed-integer linear programming and dynamic simulations in EnergyPlus software. The authors further considered the age, size, and diversify of the heating system in buildings in the Swiss village of Zernez. The study simulated a wide range of retrofit depths from targeted roof, window, and facade upgrades to full economic overhauls. Supply-side measures included options such as heat pumps, oil and biomass boilers, and PV panels. The study shows trade-off situations for instance, comprehensive retrofits with GHG minimizing enhancements like heat pumps tend to have high costs, while moderate retrofits with system upgrades achieve notable emissions savings at more moderate cost. Finally, the study's flexible approach in modelling offers a useful framework for urban planners in designing cost-effective emissions retrofitting strategies for both buildings and residential areas.

Krarti and Dubey (2018) assessed the economic and environmental consequences of energy efficiency retrofitting in United Arab Emirates (UAE) alongside electricity consumption and relevant governmental policies and regulations standards. Through buildings simulations and case studies, the authors showed that all kinds of refurbishment, whether superficial or extensive, consistently leads to drastic reductions in energy consumption, peak demand of electricity, and carbon emissions. The study also found that residential buildings in particular are very profitable, yielding short payback periods. The study highlighted the cost-effectiveness and job creation potential of efficiency programs at the scale described, attributing this strength to performance contracting and government sponsored initiatives (e.g. Etihad ESC). Programs such as energy rating systems and mandatory standards (like BREAM, Green Building Regulations), and other regulated energy performance enjoyed the benefits of synergistic actions. The author emphasized benefits such as economic growth, power plant investment needs, and emission reductions that were previously unacknowledged and described their work as guiding steps to increasing the sustainable retrofitting of buildings in the UAE.

Lops et al. (2025) developed a dynamic simulation framework to assess potential improvements in energy efficiency and climate resilience of existing buildings in Popoli, Central Italy, which represents the Mediterranean climates. The research incorporated high-resolution climate projections extending to 2070 and coupled advanced climate building

energy modelling with validated Energy Performance Certificates for three typical residential buildings e.g. a historic masonry palace, a 1900s masonry row house, and a modern concrete home. After that they assessed these buildings both in existing state and after envelope retrofits (such as insulation improvements, triple or low-E glazing) aimed at energy improvements. Furthermore, the research found that envelope retrofits, especially for the older masonry buildings, achieved a substantial total energy saving of 44%. Moreover, under future climate conditions, building load profiles shifted dramatically, and there was a significant decrease in building heating, while there was an increase in building cooling. The research articulated the need custom retrofit solutions to be designed and that balance type and age of the building, along with its climatic vulnerability. The authors proposed the scalable simulation framework for planners supporting climate mitigation and adaptation for a resilient and sustainable built environment.

2.1.5 International & Comparative Insights

Thonipara et al. (2019) examined energy consumption patterns in residential buildings and associated efficiency from 2000 to 2015 in some selected European Union countries and highlighted the differences in the consumption patterns. They used panel data regression and qualitative expert interviews to assess the impact of climate, energy prices, income, housing characteristics, and policy measures on household energy use. The study notably pointed out the substantial energy savings in Sweden and Finland which were the result of the combination of strict building regulations and strong carbon taxation (especially Sweden's €120/ton CO_2 tax) and renewable-powered district heating systems. The authors observed that regulatory driven construction activity takes time to deliver results as seen in Latvia, Hungary, and Ireland, where more recent tightening of policies has resulted in significant energy reductions. The research also pointed out that the energy efficiency policy's effectiveness depends on its range, structure, and implementation and asserted that within the European context, the combination of strict standards, financial incentives, and integrated district heating systems produces the greatest efficiency gains.

Jia et al. (2024) showed a comprehensive optimization framework for retrofitting residential apartment buildings incorporating several envelope upgrades (windows, wall, and roof insulation), rooftop PV installations, and a maintenance plan. The evaluation was performed

using Marine Predators Optimization Algorithm (MPOA). This model considers not only immediate energy and environmental effects, but also PV panels operational deterioration and time-spanning financial cycles for more sophisticated life-cycle estimations. The study was conducted on a 65-unit apartment block in Maseru, Lesotho, and the results showed that combined tailored envelope improvements and PV systems offer 44% of energy savings. Economic paybacks were contingent on the investment and priorities set for the project. The research also emphasized that most optimizing flexibility is greatest when envelope improvements are prioritized, demonstrating the critical importance of envelope upgrades in achieving targeted efficiencies. Furthermore, the author highlighted that with PV integration, envelope refinements supply most of the building's required energy and offer most flexibility in optimization. The study underlined the value of supporting stakeholders and decision-makers in custom-retrofitting, recommending the use of strategic weighting to balance saving, cost or energy goals.

2.1.6 Additional Relevance to Context, Technologies, or Methods

Lazariev and Sukhodub (2025) conducted a comprehensive review on international and Ukrainian literature analysing forty studies and case applications on the role of Phase Change Materials (PCMs) in energy efficiency. The research emphasized the thermal energy storage optimization in buildings and detailed the impact of PCMs in energy retention and building envelopes. The study explored the use of organic (paraffin) and eutectic PCMs in building envelopes (walls, ceilings, and floors), as well as heating and hot water systems, describing practical methods such as microencapsulation, microencapsulation, and stabilized shapes. The study cited substantial improvement in energy, indoor comfort, and policy outcome offering quantitative results, explaining PCM incorporation can reduce peak heat fluxes, (flatten up to 41%) reduce peak indoor temperature by 7–8°C, and decrease cooling load by 39%. The study also highlighted the critical importance of a well-defined selection of transition temperatures for building integration of PCMs as well as their positioning and integration methods (external elements are best for passive cooling) within buildings. The PCM-enhanced research highlighted the challenges of material stability, leakage, and low thermal conductivity, while commendably pushing for the PCM-enhancing incorporation of metal inclusions, fins, heat pipes, and composite matrices. In the end, the study proposed

that more research into PCM composites to develop climate and application-specific solutions that are tailored to the particular environment and recommended more practical field studies particularly those integrating renewables and advanced building technologies such as photovoltaics and heat pumps.

Asghari et al. (2024) studied energy efficiency by incorporating phase-change materials (PCMs) and thermal insulation layers (TILs) into building envelopes of residential prototypes in the mixed climate zone of Kansas City. Using parametric simulations with DesignBuilder and EnergyPlus, the authors analysed the retrofits where TILs, PCMs, and a hybrid approach were applied individually. The research's findings showed that PCMs positioned in target locations and tuned to appropriate phase change temperatures achieved energy savings of 33-55% for heating and cooling with inner wall applications proving most effective. TILs alone resulted annual energy savings of 16%, while PCM combined savings were 38%, primarily benefiting the cooling demand. The authors further emphasized climate-specific material optimization to demonstrate the impact of envelope retrofits on building energy efficiency in mixed climate regions even though the study does not include direct economic or policy impact considerations.

Lachheb et al. (2024) provided an extensive overview of the state of the art in the implementing phase change material (PCM) technologies into brick walls, aimed at improving the energy efficiency and thermal comfort of buildings worldwide. The review integrated experimental, simulation, and field data across a spectrum of climates and buildings, systematically reporting on the three PCM categories (organic, inorganic, and eutectic) and various implementation strategies (encapsulation, positioning in brick cavities, and matrix stabilization). The most significant conclusions concerned both the quantity type, and positioning of bricks containing PCM, which affect thermal regulation, peak load demand reductions, energy/CO_2 emissions reductions, and overall PCM stratification. The PCM-brick technologies consistently improved indoor comfort and energy efficiency, but the review also pointed out challenges, such as making the technology cost effective, easy mechanization, fire safety, and expanding the scope to the entire building. The review concluded that using active PCM bricks help to decarbonizing the building stock globally. The authors finally proposed improvements on climate-specific design and life-cycle economic assessments as the most urgent research priorities.

Stasi et al. (2025) investigate the use of new modular solar exoskeleton (en-SLEX) for deep energy retrofitting to target NetPlus (net positive) energy performance. The research proposed a self-supporting solar exoskeleton that cam be added to the outside existing multi-family buildings. This study combined solar thermal panels, solar PV (photovoltaic) panels, and modular green walls using 25% high-efficiency solar technologies. These exoskeletons can be quickly installed with minimal disruption in dense urban environments. The researchers tested their idea on a dynamic model of a 1970s apartment block Bari, Italy. The exoskeleton alone lowered heating needs 33% and cooling needs by 25% and with heat pump upgrades, these values increased to 80% and 60%, respectively. The study also shows that the annual building electric demand can be met by integrating PV system and modular solar exoskeleton structures, with a surplus of over 150%. Although the payback period is long, under strong state incentives, it can be within 13-18 years, making it more competitive. The authors believe that modular retrofitting solutions like en-SLEX are key to transforming older, energy-consuming buildings into NetPlus energy producers and helping cities meet climate and decarbonization goal.

2.2 Thesis, Books and Reports

Among this 42 research documents a small segment was found in thesis, book and report format. While numerically limited to 3 but still these contributed insight on implementation of energy efficiency measures and related cost direction.

2.2.1 Most Adopted Retrofit & Energy Savings Measures

Dubina (2014) conducted a detailed analysis of sustainable retrofit strategies across several countries for large panel concrete (LPC) buildings several countries. The primary focus of the analysis was Eastern Europe, particularly Romania, with comparisons to Finland, Switzerland, and Denmark. The study focused on many aspects of retrofit strategies, at not just technical and economic aspects but also policies, embodied energy, business models, case and demonstration project studies. Key findings demonstrate that post-socialist countries face major challenges, where building management is more systematic. In contrast most of the LPC building stock in Eastern Europe was built quickly poor construction quality

and social management. The authors promoted retrofitting strategies that focuses on energy efficiency, lifecycle analysis, and careful retrofit design. The study highlighted how Knowledge transfer from Finland underscored the importance of 'administrative quality' and 'policy tools' for planning renovations. These tools help set strong, comprehensive policies for improving old LPC stock in Eastern Europe. The volume reinforced that real transformation requires adaptive approaches, financing mechanisms, and institutional and human resource development for the sustainable building upgrades both internationally and at the and EU regional level.

2.2.2 Limitations, Gaps, and Future Research Directions

Arapi (2021) examined the optimal energy-retrofit strategies for 1960s concrete-panel apartment buildings, which are among the least efficient and one of the most common types of residential apartments in Finland across the EU. Using simulation modelling of a typical apartment block under both current and future climate scenarios, the study analysed how different retrofitting strategies affected energy efficiency, carbon emission, and thermal comfort. The study also estimated that using radical measures such as maximum envelope insulation, triple-glazed windows, increased airtightness and heat pump could keep the indoor temperature comfortable for decades, while reducing annual energy use by 86% and carbon emission by 76%. The study also noted that hybrid retrofits which involves a mix of insulation and systems while varying the facade and solar exposure, can nearly match the performance of uniform retrofit but with less construction risk and greater flexibility. Additionally solar PV and advance heating, ventilation, and air conditioning systems helps the buildings to meet EU's nearly-zero energy building (NZEB) standards. Overall, the study demonstrated that adaptive and hybrid systems are effective way to optimize energy and emission performance in Finland's apartment buildings.

2.2.3 Additional Relevant to Context, Technologies, or Methods

Sofronievska et al. (2024) studied the integration of Building Information Modelling (BIM) and principles of the circular economy to incorporate sustainable energy renovations of existing buildings. Their studied a landmark case involved the Skopje Hydrometeorological

Service, an important example of brutalist architecture. The study examined the building's poor energy use and significant thermal inefficiency of caused by the absence of an insulated thermal envelope. Furthermore, they proposed renovation solutions that preserved both the technological and aesthetical features of the building by applying external silica aerogel-based nanomaterial plaster. Moreover, the empirical result showed that the 68% of heating energy consumption during the cold season, 40% of active heating energy consumption during the cold season and 50% CO2 emissions could be reduced by modernizing the building envelope and adding aerogel during the renovation. The comfort and durability of the renovation are improved significantly with only minimal impact on the historical facade. BIM played a key role by allowing simulation of renovations approach which supported sustainability. The study concluded with a fact that incorporating digital modelling with new advanced insulation technologies enables deep energy savings and emission reductions in heritage buildings, providing a replicable approach for sustainable refurbishments in various global contexts.

2.3 Proceedings

Among these 42 research documents, an additional small segment of seven study was found in proceedings format. Each of this contributed to discourse on building retrofit strategies by presenting emerging findings.

2.3.1 Most Adopted Retrofit & Energy Savings Measures

Simson et al. (2025) presented a meticulously detailed comparative study of Nearly Zero-Energy Building (NZEB) requirements in Denmark, Finland, and Estonia. The authors compared and evaluated each of the country's standards against the European Commission's recommendations for residential and office buildings, using dynamic simulation and harmonized EU datasets. The study found that current Estonian NZEB standards are the closest to the EC Nordic standards. Denmark, with its milder climate, has somewhat less demanding NZEB standards and Finland's NZEB requirements are the least stringent among three countries. The author noted differences between primary energy factors (PEFs) and various systematic measurement approaches such as granularity of simulation, energy use

scope inclusion which leads to greater variation in benchmark results than the building envelope or upgrades. The author also disclosed that whereas in Denmark and Estonia most office buildings will still need to have efficiency improvements and additional PV for compliance with EC standards, in Finland, buildings more than often exceed national NZEB standards, but under harmonized calculation they fail to meet EC standards. Furthermore, the authors demonstrated that cross country assessments face 10-15 percent discrepancies purely due to differences in calculation approaches and policy design. These findings are directly relevant for the ongoing harmonization of national NZEB standards with evolving EU policies. They also highlight the regulatory and technical barriers to the obstacles to unified performance, and respond directly to the issues of stringency, compliance, and prospective code development in Finland and the Nordic region in general.

2.3.2 Limitations, Gaps, and Future Research Directions

Satriopratomo et al. (2025) used simulation modelling to perform a cost-benefit evaluation of various energy efficiency retrofitting approaches, such as switching to non-tinted window films, insulated paint application, skylight installations, and natural daylight expansion via additional windows of a multi-tier hotel located in Yogyakarta, Indonesia. Furthermore, the authors analysed a combination of retrofitting insulated walls and selective window corridors to achieve a hybrid approach which was found to be the most successful as it resulted in a 12% decrease in annual energy consumption and cost savings of 272 million IDR. This scenario of optimal retrofitting had a 5.5-year payback period, a net present value of IDR 1.92 billion, and economic IRR of 13.6%. Although other alternatives involving small window and paint upgrades resulted in reasonable savings, layout rearrangements or room count reductions were unsustainable economically despite being technically feasible due to the income loss it would present to the hotel. The authors emphasized that in similar hotel setting, incremental and specifically targeted energy retrofits provide the most practical benefit.

Olli et al. (2020) demonstrated commissioning by monitoring (MBCx) as a leading strategy for achieving and maintaining high building performance and quality, especially in renovations and new constructions in Finland. Using examples from Oulu and Helsinki and

some national level references, the authors claimed that remote monitoring with continuous evaluation and smart sensors is essential for energy consumption and for addressing persistent issues to indoor air quality and moisture in the older building stock. The authors also described Finnish regulatory and commissioning support tools such as city quality cards and technical guidelines as beneficial for the commissioning process. Nonetheless, challenges remain, including fragmented practices, inconsistent data quality and uncoordinated reporting, calibration, and altered values. The authors recommended developing advanced normative and technical standards for municipal integration of building management system, unified municipal commissioning procedures, and comprehensive reporting to track building performance. Moreover, they also suggested possible future developments through building smart readiness indicators and closer alignment to advanced EU measures.

2.3.3 Systematic Review Approaches

Sameer (2025) conducted a comprehensive literature review on energy efficiency retrofits for existing buildings by integrating a multitude of academic and industry studies. This review analysed both passive upgrades, such as insulation, improved glazing, optimal orientation, and active measures e. g. high-efficiency HVAC systems, automation controls, and particularly the lighting retrofits using LEDs, daylighting strategies, and smart sensors. The research used case studies from California, including commercial buildings like 435 Indio Way and Stater Bros. In the study showed that Supermarket control systems designed for upgraded lighting contribute to a 50% reduction in energy cost, with paybacks of less than five years. This paper also discussed the main reasons for unsuccessful retrofitting, upfront investments, the legacy structure's technical constraints, regulations, and people. The author found that focusing on high baseline inefficiency settings and engaging active occupants enhance retrofit measures. Although the review did not focus on the EU or Finnish regulations, it synthesized global best practices and suggested future direction involving building automation (including AI, IoT), renewable energy, building incentives programs, and building codes. The review illustrated how energy efficient building retrofits and effective regulations can drive best practices and sector innovation.

2.3.4 Additional Relevant to Context, Technologies, or Methods

Patrick (2024) conducted a comprehensive review on policies, technologies, and global approaches to improve energy efficiency value of retrofitting and upgrading existing infrastructures. The research findings showed that enhancements to HVAC systems, building retrofitting, modernizing of industrial automation, and electrification of urban transportation are crucial for achieving significant reductions in energy use and emissions. Therefore, the study emphasized the importance of behavioural change and systems thinking, noting that upgraded energy systems would result in the energy efficiency of buildings achieving one-third of the global emissions reductions to fulfil the targets of the Paris Agreement. In addition, the study conducted quantitative analysis and interviews in each of the economic sectors and identified the absence of technological, regulatory, and financial resources in developing regions as major challenges while underscoring the enabling role of policy change, tax breaks, and direct grants. The study demonstrated that modern retrofitting of buildings and HVAC systems can provide energy savings of 30-50%, whereas modernizations in the industrial and transportation sectors provide savings of 20-30%. The study concluded by emphasizing the highest value on the policy development, technology, and behavioural changes in energy efficiency interventions for improving the value of the global energy efficiency investments.

Nan et al. (2018) developed a comprehensive model to assess the energy efficiency of buildings using air-source heat pumps (ASHP) with user comfort integrated as a key design element. The authors used mathematical modelling and Simulink-based simulations to study how system components interact with building heat balance and different indoor temperature set points. They developed a new efficiency index based on fossil fuel equivalence. Their results showed that maintaining a 21°C indoor temperature is an effective compromise between energy use, heating demand and occupant comfort, due to the building thermal inertia. The model was validated by accurately replicating real-world temperature patterns, including operational details like defrost cycles, and the effects of solar heating and thermal control. Furthermore, the author emphasized that the adjusting temperature control and operational strategies of ASHP systems can significantly improve both energy efficiency and comfort. This finding enhances the case for the electrification and intelligent control in retrofitting buildings. The authors also suggested future studies should focus on integration

of system-level strategies with time-of-use pricing and behavioural guidance to further optimize performance.

3 Methodology

This thesis adopts a systematic review methodology to ensure a rigorous and transparent evaluation of selected literature on energy retrofitting buildings. A systematic review system is the cornerstone of rigorous academic research, providing a transparent and reproducible framework for gathering, screening, selecting, and synthesizing evidence across a complex landscape of scholarly outputs Page et al. (2021). In addition to that building retrofitting for energy efficiency in EU examined using both bibliometric analysis and structured review protocols such as PRISMA. This method ensures that evaluations are both thorough and analytically robust.

Bibliometrics examines publication patterns, citation counts, journal rankings, cooperation networks, and field-specific impact factors. This approach helps scholars identify leading journals, key authors, prominent institutions, and emerging research trends (Aria and Cuccurullo, 2017a ; Donthu et al. 2021). The power of bibliometrics lies in turning the vast, sometimes overwhelming landscape of scholarly communication into actionable, interpretable patterns, making it indispensable for identifying gaps, guiding future research policy, and benchmarking the efficacy of scientific inquiry across geographical and temporal boundaries Perianes-Rodriguez et al. (2016)

3.1 Significance of the Review System

The importance of the review system is in ensuring transparency, objectivity, and repeatability, key elements required for evidence-based decision-making in applied fields like building energy renovation policy Page et al. (2021). For this field, where findings directly inform EU wide renovation target, financial incentives programming and technical standard, a structured review system safeguard both academic validity and practical impact. A structured review system guards against bias by prespecifying inclusion criteria, documenting every decision from initial search to final synthesis, and enabling both internal and external audits of the review process (Donthu et al., 2021; Moher et al., 2009). This is particularly vital when the findings are intended to inform national or EU-wide targets, financial incentive programming, or technical standard revisions.

3.2 Definition of PRISMA Model

The PRISMA model (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) provides a gold-standard, stepwise methodology for every stage of the literature review. Following PRISMA, the process began with the definition of review questions and precise eligibility/exclusion criteria, followed by systematic literature searches across multiple global platforms. Citations were exported and managed in Excel and reference software. Furthermore, the title and abstracts were screened first for relevance to retrofit energy efficiency and cost effectiveness in the built environment, based on the predefined inclusion rules and research objective. Moreover, studies passing this filter were then subjected to a comprehensive full-text assessment with data sought or clarified as needed to maximize the validity and completeness for the final study pool. (Aria and Cuccurullo, 2017a; Moher et al., 2009) This approach enabled and explicit audit trail of all inclusion and exclusion decisions and ensure reproducibility and transparency. Page et al. (2021)

3.3 Searching Keywords for Research

Keywords for the search were developed from both policy and technical lexicons around energy efficient retrofits. These included energy efficiency, existing building retrofitting, building energy retrofit in Finland, EU cost-optimal renovation measures, thermal comfort of retrofit, EC recommendation, building envelope. These keywords set was iteratively refined to reflect emerging policy language, technical taxonomies, and consultation with subject matter experts. Aria and Cuccurullo (2017b) This ensure the database search was sensitive and focused to the aspect of this research work.

3.4 Sources of Retrieved Documents

An exhaustive search was conducted using a suite of internationally recognized bibliographic databases and digital libraries including Elsevier (ScienceDirect), Springer Link, Web of Science (WoS), Scopus, Research Gate, Wiley Online Library, MDPI, LUT primo, JSTOR, and Google Scholar. A total number of 20 journal site including MDPI

sources were included in this review following Beall's list of Potential Predatory Journals and Publishers.

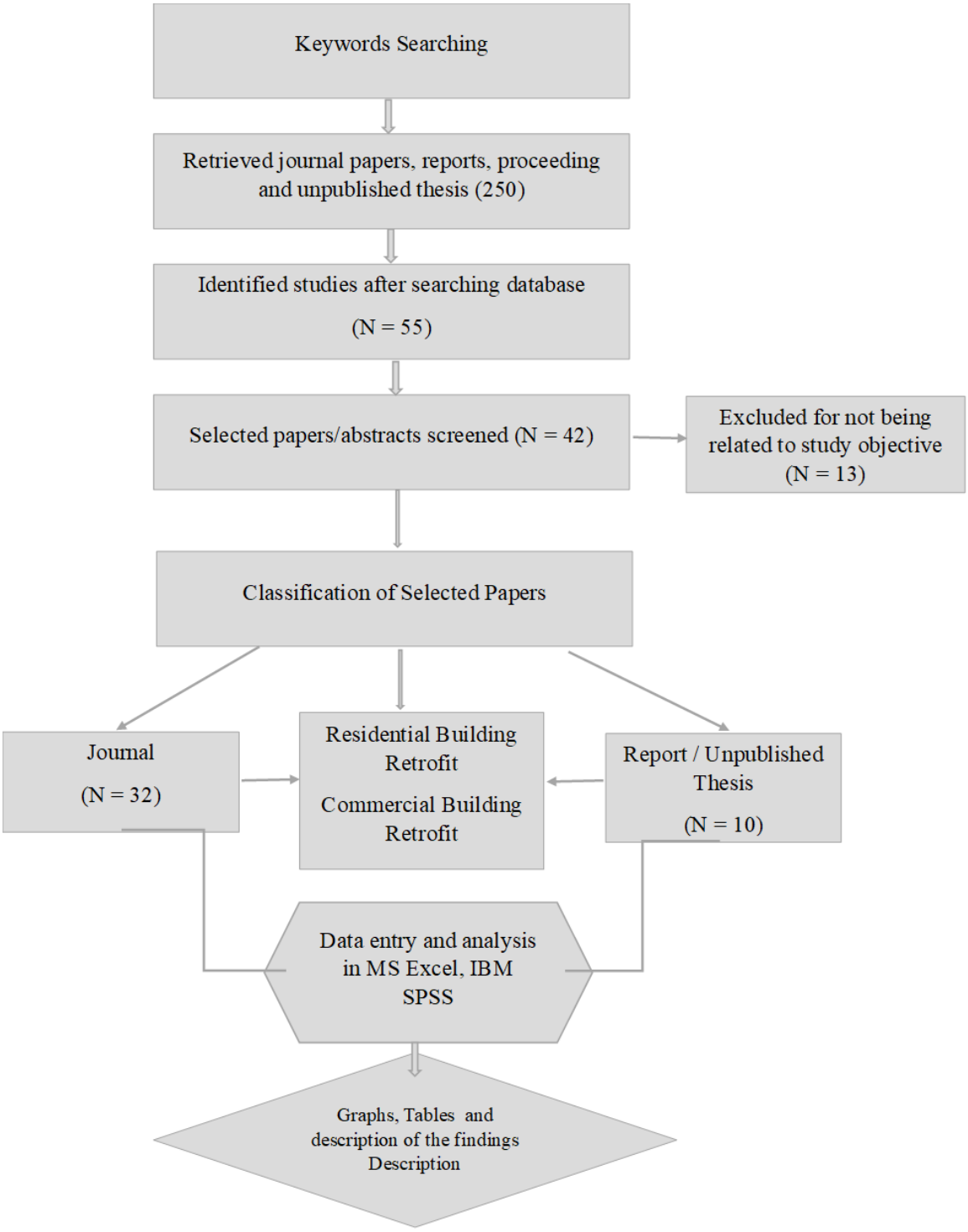

Figure 2: *PRISMA Flow Diagram* (Hossain et al., 2019)

For grey literature and practitioner reports, institutional and governmental repositories such as VTT Technical Research Centre of Finland and European Commission were covered.

Each step of the literature identification, screening, and selection process is depicted in the PRISMA flowchart, visually communicating the rigorous funnel from over 55 initial hits down to the 42 eligible studies included in this review. After data collection, 42 key sources comprising peer-reviewed research articles, meta-analyses, field monitoring reports, and technical guidance documents were selected for review. These sources represent the most authoritative voices in the field, spanning journals such as Energy and Buildings, Building and Environment, Buildings, Energy, Renewable & Sustainable Energy Reviews, Solar Energy, Journal of Cleaner Production, Energy Policy, Technologies and Engineering, BIO Web of Conference, International Conference of Energy Internet, Smart Energy, Energy Research & Social Science, E3S Web of Conferences 172, and in-depth technical reports from VTT, IEA, the European Commission, and various European research consortia.

3.5 Application of the PRISMA Method in this Study

Systematic review development under PRISMA included:

1. Multistage keyword-driven search across all above platforms and repositories
2. Comprehensive, criteria-based title/abstract/full-text screening for policy, technical, economic, and behavioural relevance
3. Extraction of bibliometric, methodological and thematic data into Excel and reference management systems
4. Quantitative and qualitative synthesis using both Excel and SPSS where needed for advanced trend and spatial analyses.

From initial 55 studies reviewed, 42 were chosen for detailed qualitative and quantitative analysis and grouped into journal publications and other forms of research, including reports, unpublished theses, and conference proceedings categories. Categorization by document type (peer-reviewed, reports and white papers) and sectoral (residential and commercial) allowed detailed and context specific findings. This meticulous methodology upholds the standards of both systematic review and bibliometric science, producing a review that is transparent and exhaustive for energy efficiency retrofits. The combined approach enables

identification of high-impact findings, multidisciplinary trends, and persistent policy/tech gaps within EU retrofit practice.

3.6 Synthesis, Categorization and Data Extraction

The categorization stage of the selected literature commences after the multistage extraction and screening process. At this stage, literature is categorised systematically creating categories that enable further detailed review and comparative analysis. The 42 eligible studies are classified according to document type as peer-reviewed journals, reports and white papers enabling a distinction between theoretical/empirical research and practice-based or policy-oriented perspectives.

At the next stage of the flow chart, these studies were evaluated, and further categorised based upon their primary focus/application. Sources were separated into residential, commercial, or (in some reviews) sector-agnostic categories, so that findings and recommendations could be specifically tailored to the issues, technologies, and barriers to implementation that exist in these different building types.

Following to that a careful synthesis was performed:

- Firstly, extraction of information related to retrofit measures, energy savings attained, cost analyses, and policy impacts as they relate to each of the specified categories, allowing for trends to emerge that are sector-specific (e.g., envelope upgrades dominate residential retrofits, whereas integrated control systems are more prevalent in commercial buildings).
- Secondly Information regarding practitioners and other reports included additional level of depth to the recommendations, including constraints present in the real world, challenges occurring during operations, and examples of success that would not be represented in purely academic research.
- The final stage of the research effort involved developing recommendations and conclusions based on theoretical and practical sources of information. In regard to theoretical information, the recommendations and conclusions were based on a combination of theoretical evidence and lessons learned from both academia and

practical experience. While practical information provides the most significant emphasis (and need) in terms of identifying gaps in knowledge, there are also practical implications for future research required by policy and building owners.

Throughout the research process, all extracted data was maintained in a structured format using Microsoft Excel and SPSS. This allows for advanced thematic coding, bibliometric trend analyses and policy focus across the Finnish/EU landscape. It ensures that each stage's outputs are traceable, transparent, and ready for further analysis, visualization, or reporting hallmarks of best practice in systematic review methodology.

In conclusion, this flow from initial wide-angle search and abstract screening, through sectoral and document-type categorization, to full synthesis ensures that the resulting evidence base is robust, representative, and fully responsive to the strategic needs of building retrofit research for Finland and the EU.

4 Result and Discussion

The reviewed documents are organized into nine main categories based on technological approach and implementation methodology. Building Envelope category consists of 19 scenarios on thermal insulation, window replacement, and passive design strategies (Arapi, 2021; Gustafsson et al., 2016; Hirvonen et al., 2020; Wu et al., 2017). Heating System category consists of 7 scenarios on ground-source heat pump conversion, district heating networks, consumption-based billing systems, and heat pump technology (Hirvonen et al., 2022, 2020; Popovski et al., 2023). Active Systems and Controls encompass 2 scenarios involving heating, ventilation, and air conditioning (HVAC) system upgrades combined with heat recovery ventilation and light-emitting diode (LED) lighting retrofits (Maaouane et al., 2023; Nita et al., 2023). Control Systems category accounts for 3 scenarios on PI baseline controls, rule-based controls RBC, and advanced MPC heating optimization strategy Ramesh et al. (2024). Renewable Energy integration includes 1 scenario addressing solar thermal and photovoltaic panel integration, whereas for advance materials, 1 scenario documenting phase change material (PCM) is installed (Gustafsson et al., 2016; Lachheb et al., 2024; Lazariev and Sukhodub, 2025; Maaouane et al., 2023). Nearly Zero-Energy Buildings cover 3 scenarios of complete deep retrofit implementations on single family houses, apartment buildings and office buildings Simson et al. (2025), Integrated Retrofit Programs category presents 6 scenarios that represent multi-level national and regional retrofit initiatives Simson et al. (2025). Integrated Retrofit Programs category presents 6 scenarios that represent multi-level national and regional retrofit initiatives (Krarti and Dubey, 2018; Olkkonen et al., 2021). Building Rating Standards consist of 5 scenarios based on the Australian star rating system Tushar et al. (2022).

4.1 Carbon Dioxide Reduction Performance

The study shows a distinct hierarchy by retrofit category in CO_2 reduction performance. The Nearly Zero Energy Buildings s have the highest average CO_2 reduction of 77.5% and are direct implementations of the requirements of the European Union Energy Efficiency Directive 2018/844 for new building construction and major renovation projects (Simson et

al. (2025). Building Rating Standards retrofits, under the Australian performance classification system, had an average CO2 reduction of 61.0%, which was considered to be achieved through incremental envelope improvements with market incentives. Integrated Programs had an average CO2 reduction of 49.3% through structured multi-level national retrofit initiatives Tushar et al. (2022). These include the United States retrofit levels, which achieve 4.6 to 28.6 Gt annually, and Finland's energy efficiency scenarios, which achieve 11 to 113 Mt cumulatively by 2050 (Krarti and Dubey, 2018; Olkkonen et al., 2021). Heating System retrofits had an average CO2 reduction of 46.7%, reflecting the importance of operational heating energy to building energy consumption, especially in cold climates where space heating dominates energy balance (Hirvonen et al., 2020; Popovski et al., 2023)(Hirvonen et al., 2020; Popovski et al., 2023).

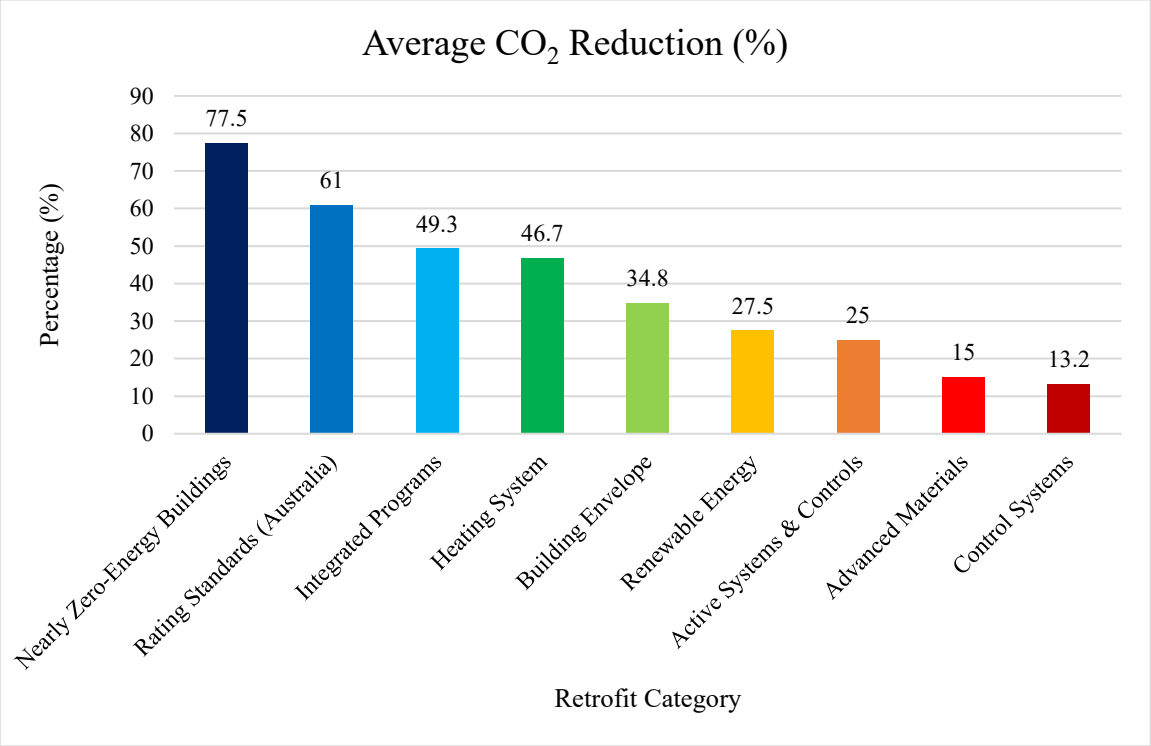

Figure 3: Average carbon dioxide reduction percentages

A building envelope retrofit reduces carbon dioxide emissions by an average of 34.8%. This is considered the most effective way for buildings to meet state energy codes and improve energy efficiency over time. Renewable energy systems produce an average 27.5% reduction in carbon dioxide emissions and renewable energy sources work best when combined with

other energy-efficient measures (Gustafsson et al., 2016; Maaouane et al., 2023). Active systems and controls can reduce carbon dioxide emissions by an average of 25% through more efficient use of HVAC systems and advanced lighting control systems (Nita et al. (2023). Advanced materials and phase change materials have achieved an average reduction of 15.0% through various use cases, but additional field study will be necessary before these types of materials reach their full potential for thermal comfort, building efficiency, and long-term energy cost savings Lachheb et al. (2024). Control systems have the lowest potential for carbon dioxide reduction at 13.2%, since they optimize infrastructure rather than replace existing systems, yet this also creates a very quick return on investment compared to other types of retrofits Ramesh et al. (2024).

4.2 Energy Reduction Performance and Category Comparison

Energy reduction performance varies significantly between retrofit categories, thus providing important insights to developing effective retrofit strategies. The largest improvement is demonstrated by Nearly Zero- Energy Buildings, showing a reduction of 72% in energy consumption. This retrofit category belongs to comprehensive retrofits that incorporate envelope upgrades, heating system conversions, advanced control systems, and the integration of renewable energy Simson et al. (2025). Close to rating standards retrofits come in with an average energy reduction of 68% achieved by systematically improving the building envelope performance. These are closely aligned with the improvements in the Australian star rating system, starting from the five-star minimum standard to eight-star and higher classification Tushar et al. (2022). Integrated Programs have a mean saving of 46.1 % by using policy- driven, multi-level retrofit frameworks. In these programs, basic retrofits save approximately 26.2% energy reduction in just 0.4 years, while the deep retrofits achieve about 75.2 % within approximately 2.3 years Krarti and Dubey (2018).

Retrofits of Heating System yield an average energy reduction of 40.9% through the replacement of fossil fuel-based systems with better efficient alternatives. Ground source heat pumps largely contribute to the decrease in energy requirement within the range of 30-80%, while district heating networks usually achieve a reduction within a range of 20 to 60% (Hirvonen et al., 2020; Popovski et al., 2023).

Building envelope retrofits achieve a mean energy reduction of about 39.1% largely due to better insulation. Wall insulation alone cuts energy use by 45 to 50%, passive design strategies have reached up to 70%, while roof insulation provides reductions from 10 to 30 percent (Arapi, 2021; Wu et al., 2017).Retrofits with the main emphasis on Active Systems and Controls results in an average reduction of 32.5%, due to the efficiency in HVAC and additions of heat recovery ventilation systems (Maaouane et al., 2023; Nita et al., 2023). In the retrofit buildings it is seen that advance material contributes a 25% decrease, while renewable energy integration contributes for 20% reduction in energy use. Lastly, control systems alone can deliver a 13.2% reduction through intelligent control strategies that optimize heating performance without the need for costly replacements of equipment Ramesh et al. (2024).

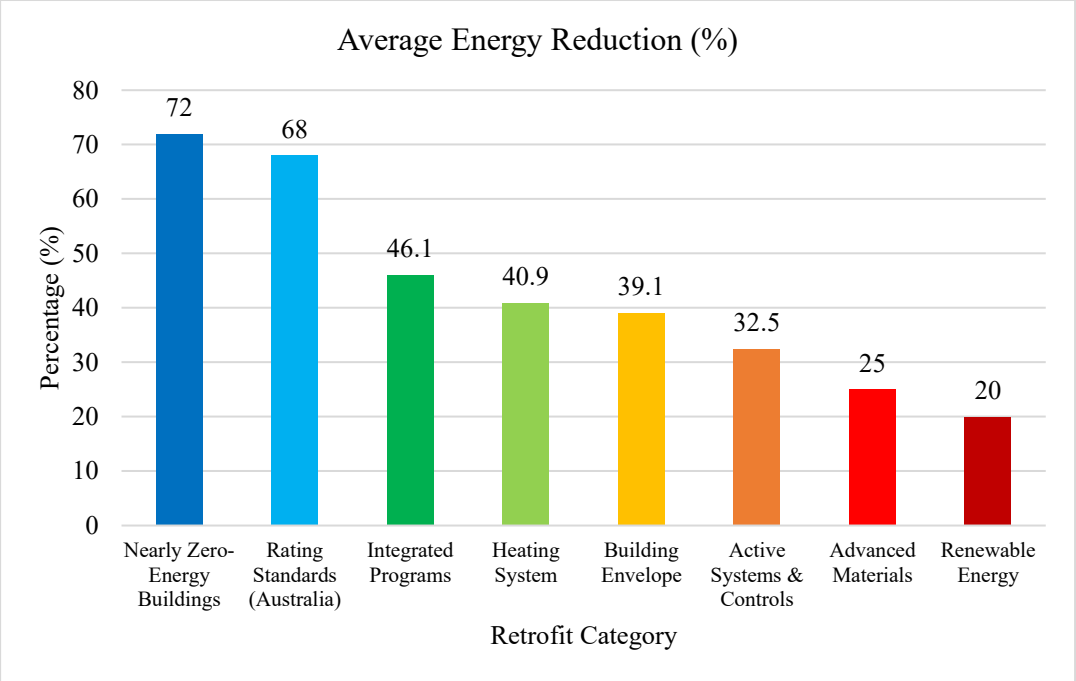

Figure 4: Average Energy Reduction Percentage

4.3 Comparative Analysis of CO2 and Energy Reduction

The comparative analysis also presents evidence that the energy savings associated with the retrofits of the four categories of retrofits (Nearly Zero-Energy Buildings, Integrated Programs, Heating Systems, and Renewable Energy) exceed the energy savings associated

with the retrofits of their respective categories, (i.e., retrofit of heating systems will produce emissions reductions greater than 7.5 percent compared to their associated energy savings). The analysis further demonstrates that these four categories of retrofits generally require the replacement of fossil fuel burning equipment with electric equipment or renewable energy sources, resulting in greater emissions reductions achieved by retrofitting buildings with renewable energy systems. The carbon intensity of electric generation compared to that of burning fossil fuels indicates that the use of renewable energy generates disproportionate amounts of CO2 emissions reductions relative to the operational energy savings that each Retrofit Strategy Category has produced (Gustafsson et al., 2016; Maaouane et al., 2023).

Table 1: Comparative Analysis of CO2 Reduction versus Energy Reduction by Retrofit Category

Retrofit Category	CO2 Reduction (%)	Energy Reduction (%)	Difference (CO2 - Energy) %	Classification
Nearly Zero-Energy Buildings	77.5	72.0	+5.5	CO2 > Energy
Rating Standards	61.0	68.0	-7.0	Energy > CO2
Integrated Programs	49.3	46.1	+3.2	CO2 > Energy
Heating System	46.7	40.9	+5.8	CO2 > Energy
Building Envelope	34.8	39.1	-4.3	Energy > CO2
Active Systems & Controls	25.0	32.5	-7.5	Energy > CO2
Renewable Energy	27.5	20.0	+7.5	CO2 > Energy
Advanced Materials	15.0	25.0	-10.0	Energy > CO2
Control Systems	13.2	13.2	0.0	Equal

In contrast, there are four retrofit categories that reduce energy more than CO2: Rating Standards (-7.0% difference), Building Envelope (-4.3% difference), Active Systems & Controls (-7.5% difference), and Advanced Materials (-10.0% difference). These categories reduce energy used in building operations by increasing the efficiency of buildings, however, the amount of CO2 savings achieved will rely on the decarbonization of the electricity grid and the fuel sources used to supply heat. A 10.0% difference in the category of Advanced

Materials suggests that simply reducing energy does not mean equal proportional reduction of CO2 emissions when the primary energy source remains unchanged(Lachheb et al., 2024; Lazariev and Sukhodub, 2025). Control Systems show a perfect correlation of energy cost savings (0.0%) directly corresponding to operational energy reductions.

The analysis of retrofits indicates that both energy consumption and emissions objectives should be addressed when selecting a retrofit strategy. Retrofits that are focused on reducing energy consumption, such as building envelope improvements and control systems, will result in long-term operational cost savings however, the amount of energy savings for these types of retrofits will depend on whether the utility provides a decarbonized electric supply in the future. On the other hand, retrofitting existing heating systems and integrating renewable energy resources into existing systems will produce immediate benefits in emissions reductions as the energy source is replaced with les carbon intensive option. An optimal strategy for achieving both energy and emissions reductions during the transition to climate neutrality for EU Member States is to concurrently convert existing heating systems to renewable energy systems (within the near term) while planning for improvements to building envelope systems (within the longer term).

4.4 Cost Analysis of Building Retrofits in Finland and Eu Context

According to the study, a large discrepancy was uncovered in costs for retrofitting buildings. Estimates ranged from €50/m² (basic roof insulation) to €2,183/m² (complete deep-energy retrofitting), a difference of 43-fold cost in retrofit scope and building stock characteristics. This discrepancy is primarily due to the magnitude difference in the types of retrofitting being done and the type of existing structures being retrofitted. The typical cost of retrofitting reported to date for buildings based in Finland is €402/m², retrofitting costs for different age groups (which fall within the same category for buildings built in colder climates) show little difference in costs per square meter (€445 to €501). However, GSHP systems require a significant capital outlay, but offer significant energy-savings potential (up to 80% energy-savings) depending upon the scale of building, with documented costs associated with GSHP systems ranging from €200 to €500/m² for installations and 4 to 8 years for typical installation paybacks Hirvonen et al. (2020). Control systems present the most economical means of retrofitting buildings and cost of implementing Model Predictive Control (MPC)

is on average, €115/m² (with a range of projections between €80 and €150/m²) and achieves energy savings of 22.3% to 29.9%, with average paybacks of 1 to 3 years (Ramesh et al. 2025). Across the EU, average costs of retrofitting are approximately €522/m², with a significant variance attributable to uneven levels of retrofitting, i.e., basic envelope improvements costing €50 to €150/m² versus total deep-energy retrofitting costing €1700 to €2666/ m².

Table 2: Cost Analysis of Building Retrofits

Category	Average Cost	Range
Control Systems	€85/m²	€30-150/m²
Heating Systems	€277/m²	€60-500/m²
Building Envelope	€276/m²	€40-501/m²
NZEB Retrofit	€800/m²	€600-1,050/m²
Deep Energy Renovation	€2,183/m²	€1,700-2,666/m²

The Several Nordic Nations demonstrate consistent price points for energy efficient building retrofits like Denmark with €725/m², Estonia with €800/m² and Finland with €875/m² Simson et al. (2025). This consistency persists despite significant differences in each country's primary energy requirements due to climate conditions (Denmark: 36.1 kWh/m² per year, Estonia: 100-120 kWh/m² per year, Finland: 90-109 kWh/m² per year). Cost performance analyses reveal that retrofitting with control systems is the lowest cost method of achieving an energy reduction of €3.85 to €5.10 per percent energy use reduction, which supports the use of sequential retrofitting systems that provide early returns on initial renovations that can be used to support future deep retrofit projects. Amongst the limitations of the literature on the cost data associated with the Regional Market Specificity of the Member States (limited transferability across Member States), temporal snapshot characteristics of data (i.e. 2015-2025 with no future projections for the decline in cost over time), the exclusion of soft costs and occupant adaptation costs, and the limited inclusion of long-term operation and maintenance cost of construction.

4.5 Payback Period by Retrofit Main Category

The nine categories of retrofitting are ranked according to their average payback periods in Figure 4.3, indicating that there is a significant amount of difference in the economic feasibility of these nine categories. As an example, the fastest payback period was for Control Systems with an average period of 1.7 years, while Model Predictive Control had an average of 1-3 years and Rule-Based Controls had an average of 2-4 years Ramesh et al. (2024). These high levels of economic performance are due to the low capital investment required for advanced Controls (€80-150/m2) and the immediate operational cost savings that can be implemented by these strategies. Advanced Materials had an average payback of 4.5 years, and therefore is a feasible option for newer experimental technologies. Lastly, Active Systems and Controls had an average payback of 8.3 years, due to their moderate capital investment as well as the consistency of performance of HVAC systems being optimized.

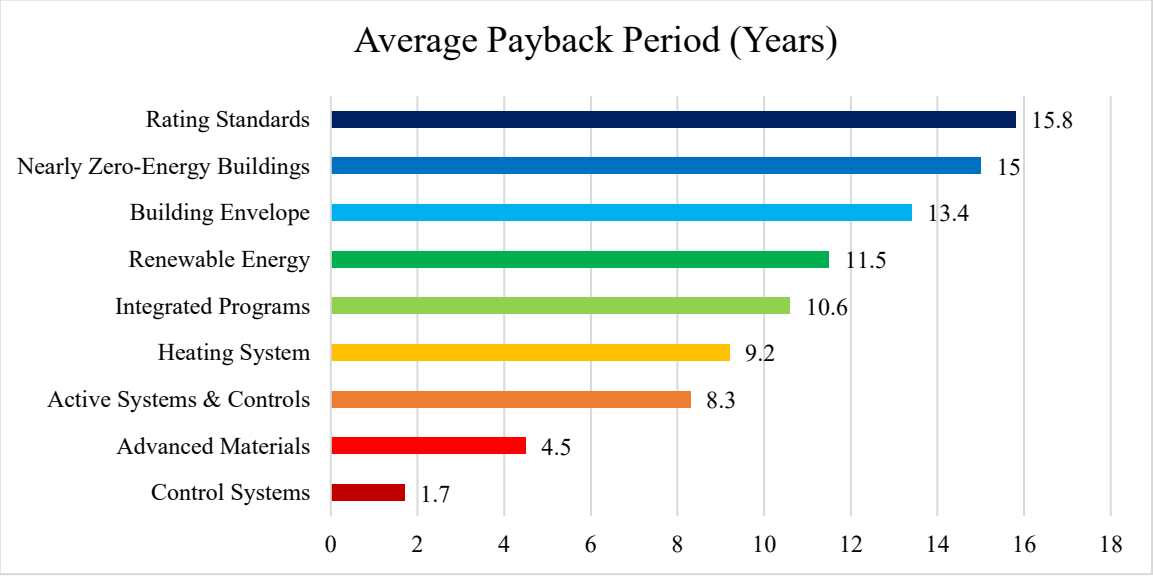

Figure 5: Average Payback Period by Retrofit Main Category

The average payback period for Heating System Retrofits is 9.2 years, although there is a considerable variation between Heat Metering Systems (2-5 years) and Comprehensive Heat Pump Conversion (4 - 20 years) dependent upon local electric prices and heating fuel costs (Hirvonen et al., 2020; Popovski et al., 2023). Renewable Energy Integration averages 11.5

years, which reflects the decreasing price curve on Photovoltaic Systems, but still holds price points where it would take 8 to 15 years to recover financially. Integrated Programs average 10.6 years through multiple level approaches combining quickly paid basic measures with comprehensive Retrofits that take longer to pay back. The average of 13.5 years payback period is required for Building Envelope Retrofits, which represent the longest payback of the medium performance categories, resulting in a financial barrier without policy incentives. Retrofits for Nearly Zero Energy Buildings (NZEB) and Rating Standards both average 15 years of payback period, although a few may take 20 years or longer.

Across all Retrofit Categories the average payback period is 10.0 years, indicating that the majority of building Retrofits require at least a decade or longer to achieve Simple Financial Recovery. For Member States where Discount Rates are in excess of 10 percent per annum, Long Payback Retrofits may show negative Net Present Value calculation results (NPV) even though there is significant Energy and Carbon Dioxide Savings associated with them. The Economic Reality indicates that Policy Support is necessary through Capital Subsidies, Tax Incentives, or Favorable Financing Mechanisms to overcome the Financial Barriers for Retrofit Deployment, especially for Envelope Improvements and NZEBs. (Hirvonen et al., 2020; Popovski et al., 2023).

4.6 Energy Reduction versus Payback Period (Cost-Effectiveness Analysis)

The scatter plot in Figure 4.3 illustrates the relationship between energy reduction performance (y-axis) and payback period (x-axis) for 25 individual retrofit measures, revealing critical trade-offs between environmental performance and economic viability. The optimal quadrant for retrofit investment contains measures with high energy reduction and short payback periods. Notable optimal measures include the Level-3 Deep Retrofit from the United States integrated programs (75.2 percent energy reduction in 2.3 years), Level-2 Moderate Retrofit (54.2 percent in 2.7 years), Level-1 Basic Retrofit (26.6 percent in 0.4 years), and Model Predictive Control systems (26.1 percent in 2.0 years) (Krarti and Dubey, 2018; Ramesh et al., 2024). These exceptional measures enable rapid capital recovery that can fund subsequent retrofit phases.

Scatter plot (Figure 4.3) shows the relationship between energy reductions (y-axis) and payback periods (x-axis) for 25 retrofit measures and highlights the trade-off between the environmental performance and economic viability. The most advantageous place to invest in a retrofit is in the optimal quadrant, which contains a high percentage of energy reduction along with a short payback period. Some of the most advantageous retrofit measures are: the Level 3 Deep Retrofit from the integrated US programs, which has an energy use reduction of 75.2% in 2.3 years, the Level 2 Moderate Retrofit at 54.2% in 2.7 years, the Level 1 Basic Retrofit at 26.6% in 0.4 years and Model Predictive Control systems at 26.1% in 2 years (Krarti and Dubey, 2018; Ramesh et al., 2024), all of which will allow a quick return on capital and help to finance future retrofit phases.

The upper left quadrant is consists of high-performance retrofit measures that have the longest payback period. Nearly Zero-Energy Building (NZEB) retrofits have an energy reduction of 70-75%, but the payback period is 14-16 years and financing to support these NZEB retrofits will likely require some type of grant, subsidized loan or favorable tax treatment, thus necessitating policy support Simson et al. (2025). Finally, the lower right quadrant contains the low-performance measures that have a long payback period, which should be deprioritized and considered only as required by building codes or energy efficiency regulations, for example, Basic insulation (20%/16 years) and over 8-star rated (92%/20 years) are in this unfavorable position.

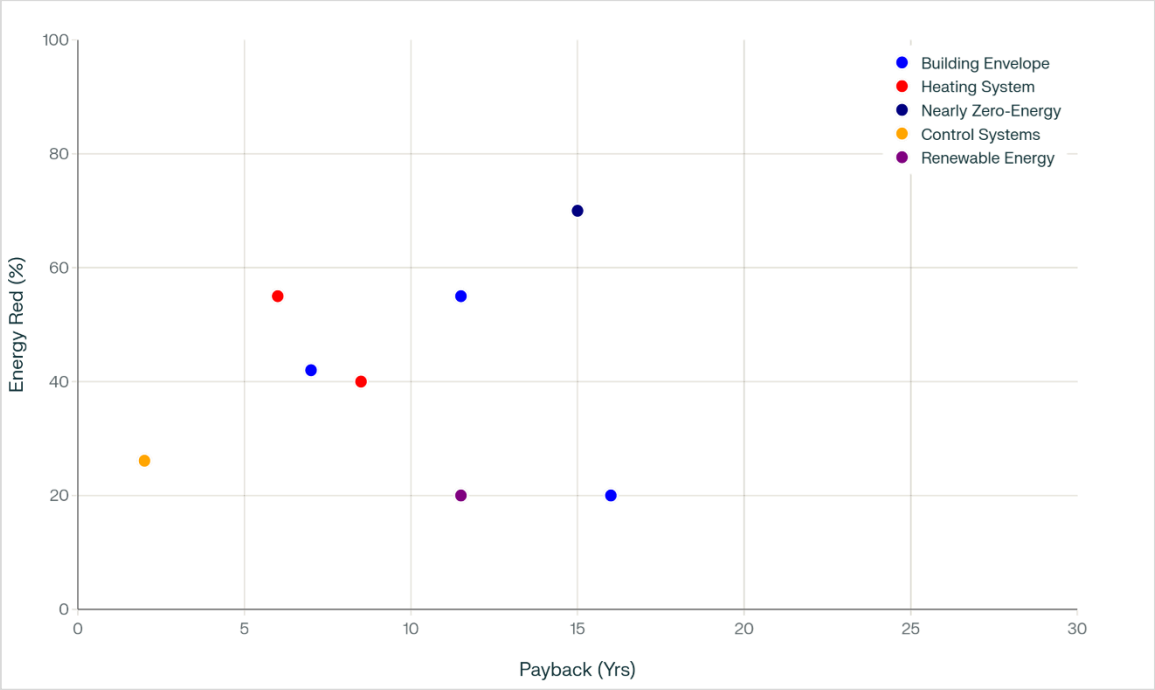

Figure 6: Relationship between energy reduction performance.

The scatter plot analysis suggests a practical, step by step retrofit strategy. It starts with introducing control systems and heat metering, which offer the quickest returns with payback periods (1–4-year payback), followed by heating system upgrades (2-12 years), then building envelop improvements (7-20 years) and finally a comprehensive NZEB retrofits (12-20 years). This order ensures continuous positive cashflow and builds momentum for deeper energy efficiency improvements as retrofit experience accumulates and technology becomes for affordable. (Krarti and Dubey, 2018; Ramesh et al., 2024). Cost Benefit Analysis

The cost-benefit analysis underscores the substantial variation in retrofit economics across regions and technologies. Finnish retrofit costs, averaging €285/m², are lower than EU averages (€522/m²), reflecting differences in building stock, climate challenges, and technology costs.

Table 3: Cost Benefit Analysis

Key Metric	Range / Value	Note
Average Cost (€ per m²)	€285 (Finland), €522 (EU)	Reflects broad economic differences and retrofit depth
Median Cost (€ per m²)	€445 (Finland), €180 (EU)	Central tendency varies significantly due to outliers in deep retrofits
Cost per % Energy Reduction (€)	€1.50 (Wall Insulation) to €75.28 (Deep Renovation)	Shows efficiency of measures; simple measures outperform expensive deep renovations per benefit
Average Payback Period (years)	10.9 years	Typical financial return period across multiple measures
Fastest Payback (years)	0.4 years (USA, national programs)	Rapid energy savings measures, ideal for quick investments
Slowest Payback (years)	20 years (Deep Renovation)	Deep retrofit measures require long-term planning
Cost-Effectiveness Rating	Very High to Low	Ranges from quick return, low-cost measures to long-term deep renovations
Regional Highlights	Finland: €285/%; EU: €8.14/%; USA: rapid payback; Denmark/Estonia: €10-11/%	Variability driven by climate, market, and policy contexts

The median costs further reveal that while some measures like basic wall insulation are highly cost-effective (€1.50 per % energy reduction), efforts like deep energy renovations are significantly more expensive (€75.28 per %), emphasizing the importance of staged retrofit strategies. The analysis indicates an average payback period of approximately 11

years, with rapid returns (~0.4 years) achievable through measures like national-scale programs in the USA, which often prioritize fast payback, whereas comprehensive deep retrofits may extend to 20 years.

Cost-effectiveness ratings span from "Very High" for simple, low-cost measures that maximize short-term benefits, to "Low" for large-scale deep renovations requiring long-term commitment and policy support. Regionally, the USA demonstrates exceptional financial returns due to large-scale program implementation, while Nordic countries like Finland and Estonia show moderate costs aligned with climate constraints and existing infrastructure. This summary encapsulates the critical trade-offs and strategic considerations necessary for efficient retrofit deployment at regional and national levels. The details cost benefit mapping in Appendix 3

4.7 Correlation Analysis

The correlation heatmap reveals important interrelationships among key retrofit performance variables. There is a strong positive correlation between energy reduction and CO_2 reduction, indicating that measures yielding higher energy savings also tend to achieve greater carbon emissions reductions. This alignment supports using either metric as indicators of retrofit effectiveness. Meanwhile, cost and payback period are moderately positively correlated, reflecting that more expensive retrofits generally require longer times to recover their investment through energy savings. A moderate positive correlation between cost and energy reduction shows that achieving higher savings often entails higher initial investment. Additionally, a slight negative correlation between energy reduction and payback suggests that some energy-efficient technologies can deliver faster financial returns. These relationships highlight the inherent trade-offs decision-makers face between upfront costs, financial viability, and environmental benefits. This quantitative synthesis supports phased retrofit strategies that begin with cost-effective, high return measures and

progressively advance to deeper, costlier retrofits to optimize overall building performance and investment value.

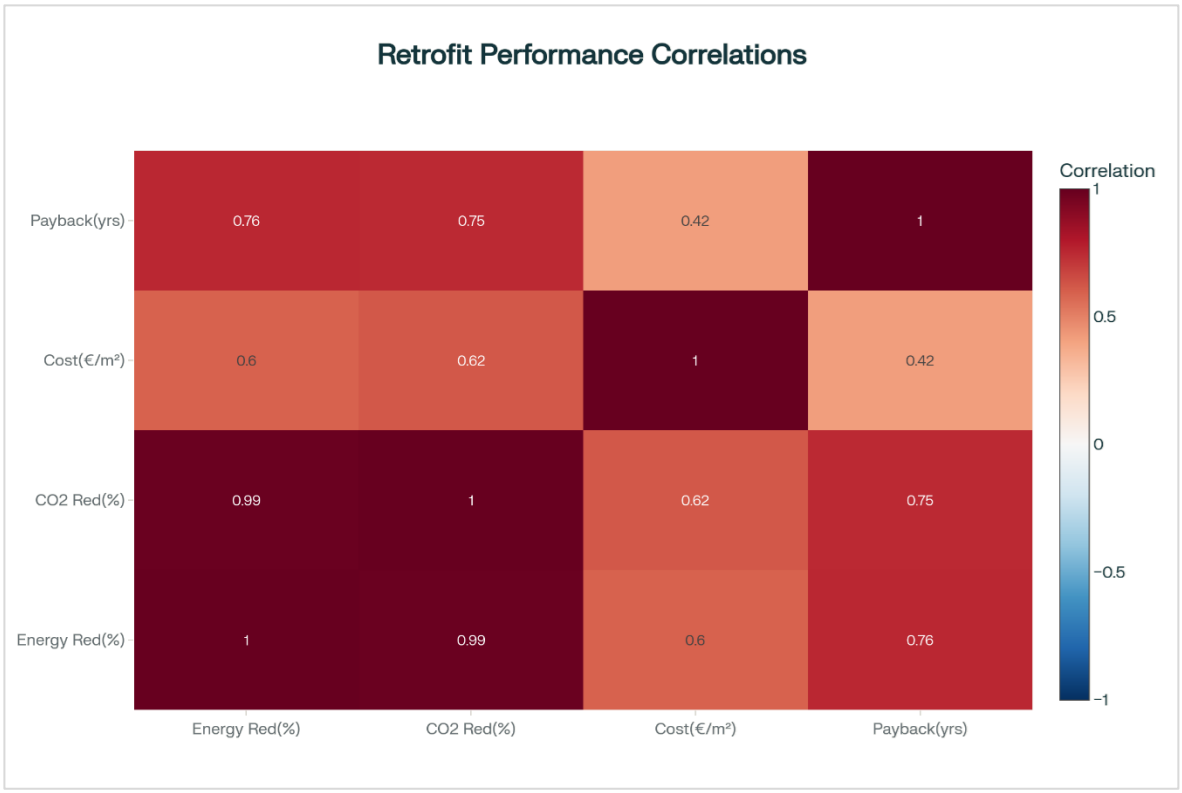

Figure 7: Correlation Heatmap

This interpretation aligns with academic analyses of building retrofit economics demonstrating similar correlations and reinforcing the importance of balancing multiple performance criteria for sustainable retrofit investment decisions (Hirvonen et al., 2019; Walter & Sohn, 2016; Han, 2021).

4.8 Policy impact

The Policy Impact Network Map in Figure 6 provides a visual overview of how various European and national policy frameworks interact with different building retrofit measures. On the left side, the graph shows key policy drivers such as the Energy Performance of Buildings Directive (EPBD), the Energy Efficiency Directive (EED), the Renewable Energy Directive (RED II), REPowerEU, and Horizon Europe, along with the EU Taxonomy and National Strategies. (*Directive (EU) on promotion of energy from renewable sources, and repealing Council Directive*, 2023) These frameworks collectively form the foundation of the European Union's climate and energy transition agenda. The right side of the diagram represents major retrofit measure categories, including envelope improvements, HVAC systems, renewable energy integration, advanced materials, control systems, behavioural interventions, deep retrofits, optimization models, and institutional frameworks.

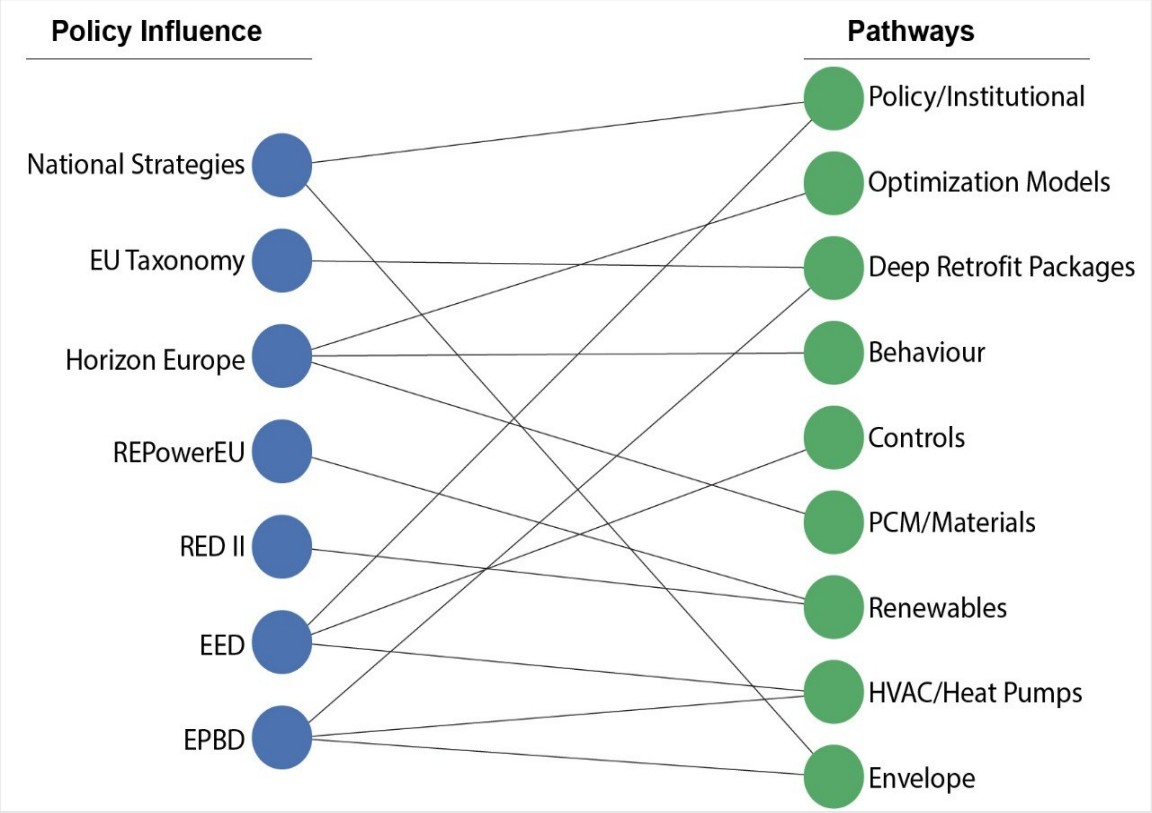

Figure 8: Policy Impact Network Map

The directional connections (arrows) between the nodes demonstrate the policy influence and alignment pathways. The EPBD shows the broadest influence, linking to multiple retrofit measures such as envelope, HVAC, and deep retrofit packages indicating its central role in setting mandatory energy performance standards for buildings. Similarly, the EED connects to HVAC systems, controls, and policy/institutional factors, reflecting its focus on efficiency improvements and system-level optimization. The RED II and REPowerEU policies are specifically tied to renewable retrofits, underscoring their role in promoting solar and distributed energy systems.

Horizon Europe exhibits a distinctive connection to emerging innovation areas, including advanced envelope materials, optimization models, and behavioural research, highlighting the importance of research and technological development in overcoming retrofit limitations. The EU Taxonomy targets financial alignment by linking primarily to deep retrofit packages, where investment classification and sustainable finance play a key role. Meanwhile, National Strategies bridge both technical (Envelope) and institutional (Policy/Institutional) categories, showing how member states adapt EU-level directives to local contexts through funding programs and regulatory adjustments.

4.9 Barriers and key research gaps

This table 6 provides an integrated overview of critical barriers and research needs across all major retrofit categories. It demonstrates that while technical innovations such as advanced materials, renewable systems, and control solutions hold substantial promise, their adoption remains constrained primarily by economic and institutional challenges. High costs, both for envelope upgrades and HVAC/heat pump systems, are universally recognized deterrents, compounded by renovation disruption, fragmented building ownership, and often low occupant awareness. These challenges highlight the necessity for lifecycle and cost-benefit analyses (LCA/LCC) to be systematically embedded in retrofit planning, ensuring investments are both strategically timed and economically justified.

Table 4: Main Barriers and Research Gap in Retrofit Strategies

Retrofit Category	Main Barriers	Key Research Gaps / Future Focus
Envelope	• High cost • Renovation disruption • Fragmented ownership	• Integrate LCA/LCC into decision frameworks • Develop timing and staged renovation models
HVAC / Heat Pumps	• High investment cost • Space and technical constraints • Low user awareness	• Validate real COP/SPF performance in field conditions • Model hybrid and grid-integrated systems
Renewables (PV, Solar Thermal)	• High upfront cost • Limited roof area • Unstable tariff policies	• Advance techno-economic optimization of PV/solar under different incentive schemes
PCM / Advanced Materials	• High material cost • Lack of large-scale demonstration projects	• Conduct pilot studies to assess durability and scalability • Validate cost–benefit ratios under real conditions
Controls / Commissioning	• Limited data standards • Operator skill gaps	• Develop AI-based diagnostic tools • Standardize commissioning protocols for buildings
Behavioural Factors	• Rebound effects post-retrofit • Low occupant engagement	• Integrate behavioural science into retrofit design • Use feedback-driven control strategies to close the performance gap
Deep Retrofit Packages	• High capital cost • Coordination and management barriers	• Develop innovative business models for financing • Quantify multi-benefit valuation (energy, comfort, health)
Optimization Models	• Computational complexity • Lack of real-world validation	• Empirical validation of model outputs • Integrate optimization results into decision-support systems
Policy / Institutional	• Governance gaps • Funding limitations and fragmented coordination	• Foster governance innovation and cross-sector coordination • Strengthen intermediary institutions for policy and finance integration

Moreover, research gaps extend to real-world performance and validation, especially for emerging technologies like phase change materials (PCM) and hybrid renewables, where

there is a lack of large-scale demonstration data. Efforts to develop and standardize commissioning protocols supported by AI-enabled diagnostics are also crucial for ensuring long-term operational efficiency and for upskilling building operators. Behavioural aspects, such as post-retrofit rebound effects and low occupant engagement, further complicate the realization of projected energy savings. Integrating feedback-driven control strategies and behavioural science into retrofit design will help close these performance gaps.

Financial, coordination, and governance issues loom especially large for deep retrofit packages and policy/institutional pathways. Innovative business models and financing mechanisms are needed to overcome high upfront investment barriers for comprehensive renovations. Concurrently, achieving effective policy impact demands strengthening intermediary institutions, fostering cross-sector governance, and ensuring smooth integration between policy instruments and financial support schemes. Ultimately, empirical validation, real-world pilot studies, and a holistic approach encompassing both technology and human factors are required to translate retrofit potential into large-scale, cost-effective climate and energy benefits.

4.10 Recommended Retrofit Sequencing for Optimal Outcomes

This research demonstrates a proper sequencing of retrofit work in four phases can be used to maximize both the environmental impact of retrofitting and long-term financial sustainability. In Phase One (Years 1-2), focuses on implementing Quick-Win Measures that include deploying a Control System (13.2% energy reduction with 1.7-year payback) and implementing Heat Metering systems with Consumption-Based Billing (15-25% energy reduction with a 3.5-year payback). Altogether, Phase One is expected to deliver cumulative reduction in energy bill of 15-25% can be achieved within 1.7-3.5 years. These early investments ensure a rapid return on invested capital and serve as a financial source for Phase Two activities.

Phase Two (Years 2-5) focused on implementing the Core System Upgrades which include retrofitting Well Heating Systems that can achieve a 40.9% reduction in energy use Hirvonen et al. (2020) and implementing Active Systems and Controls which provides a 32.5% energy reduction Nita et al. (2023). By combining these two retrofits' measures, a cumulative

energy expected reduction of 40-50% can be achieved over a 5–10-year period. It is anticipated that Phase Two costs range from approximately €20 to 500 per square meter, with a payback period of 2-9 years. Overall, with substantial improvements in performance, Phase Two represents the most cost-effective option in terms of initial investment Hirvonen et al. (2019).

The phase three (Years 5 to 15) consists of implementing a deep envelope retrofit approach by making improvements to the building envelope, resulting in an aggregate average energy savings 39.1% (Arapi, 2021; Wu et al., 2017). As part of the retrofit process, the roof insulation (10-30% reduction) is applied, followed by wall insulation (45-50% reduction) and the window replacements (10-20% reduction). When the benefits of these retrofit three phases combine, the expected total energy savings is between 60% to 70% after 10-15 years and between €30 and €2666 per square meter investment, returning with a payback period averaging 13.4 years Wu et al. (2017). Due to the length of the payback period, it requires long term financing choices or policy subsidies to facilitate the phase three retrofit.

Phase Four (Years 15+) involves a Comprehensive Deep Retrofit implementation with a specific focus on Nearly Zero Energy Building Retrofitting methods with 72.0% energy savings and between 46% & 75.0% energy savings from Integrated Program deep-level retrofit Simson et al. (2025). The combined energy savings of the phase four retrofit is expected to be between 70% and 95% after 20 years, for investments of between €600 and €1050 per square meter, and payback periods of between 2.3 years and 15 years, depending on which retrofit pathway is employed. The phased approach allows for continuous improvements and keeps a positive cash flow and building on the momentum for greater energy transformation (Krarti and Dubey, 2018; Ramesh et al., 2024; Simson et al., 2025).

5 Conclusions

The comprehensive retrofit analysis reveals several critical findings relevant to research questions and thesis objectives. First, building envelope retrofits represent the most extensively researched category (40 percent of scenarios) with widely adopted implementation practices achieving 10 to 95 percent performance range but requiring 13.4 year average payback. Heating system retrofits demonstrate superior economic performance (9.2 year average payback) with 46.7 percent CO2 reduction and 40.9 percent energy reduction, positioning this category as optimal for mid-term retrofit investment. Control systems achieve exceptional economic performance (1.7 year average payback) despite modest 13.2 percent performance, making this category essential for retrofit market initiation and funding subsequent phases.

Second, achieving 70+ percent energy reduction requires integrated multi-measure approaches combining envelope, heating, active systems, and control measures rather than single-technology deployment. Nearly Zero-Energy Buildings achieve 72 percent energy reduction and 77.5 percent CO2 reduction but require 15 year average payback and €600-1,050 per square meter investment, necessitating policy support through capital subsidies or favorable financing mechanisms. The research indicates that sequential retrofit deployment following the four-phase strategy (quick-wins, systems, envelope, comprehensive) optimizes both environmental performance and financial sustainability while generating capital from early-phase investment recovery to fund long-payback deep retrofits.

Third, retrofit adoption patterns reveal that 44.7 percent of documented measures remain in emerging deployment phase not due to technical immaturity but due to capital cost barriers constraining market penetration without policy support. Policy-driven programs in the United States and Finland demonstrate substantial market acceleration potential, achieving cumulative 28.6 billion tons annual CO2 reduction (USA) and 42 to 113 megatons cumulative reduction by 2050 (Finland) through coordinated policy frameworks combining regulatory requirements, financial incentives, and technical support. The research indicates that existing retrofit technologies suffice for achieving European Union climate targets; the limiting factor is market acceleration through innovative financing mechanisms and coordinated policy frameworks.

Fourth, substantial geographic variation in retrofit economics reflects diverse climate conditions, building stock characteristics, electricity grid decarbonization status, and Primary Energy Factor specifications across Member States. Finland's low electricity PEF (1.2 versus 1.9-2.0 in Denmark and Estonia) creates differential incentives for heat pump deployment, while district heating infrastructure availability in Nordic regions makes DH retrofits cost-optimal in some contexts but infeasible in others. Retrofit policy harmonization across European Union Member States requires standardized Primary Energy Factor calculations, coordinated financing mechanisms, and climate-appropriate technology selection frameworks recognizing regional context diversity.

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Appendix 1: Revied Literature Statistics

Annual Growth of Publications from 2014 to 2025

The figure 9 illustrate the volume of research on energy efficiency in buildings and building retrofits. Over the period from 2014 to 2023 the rate of publication increased very slowly and remained on a steady low level with only minimal increases in the number of studies published annually and a very sharp increase occurs in 2025. This significant increase may be the result of heightened interest from both the scholarly and the business community on the energy efficiency of buildings and the retrofitting of building energy systems, perhaps motivated by the new regulations, optimization of energy retrofitting, and improvements in energy retrofitting technologies. The figure suggests a significant increase in scholarly attention to the problem in the past year, indicating the likely impact on the discourse to be framed with new empirical research and innovative methods.

Figure 9: Trend of research on building energy efficiency and retrofits in this review

Analysis of Publication Types Retrieved from 2014 to 2025

The figure 10 illustrate the research types among the studies collected between the years 2014 to 2025, this figure shows clear dominance of primary studies, which comprise nearly

half the total count of publications. 19 primary studies testify to the significant concentration of empirical and field data primary research being conducted in the discipline. Findings further denoted that approximately 21% of the literature encompasses both primary and secondary studies, and review studies account for approximately 13%, which suggests that review papers comprise a considerable volume of the literature. In further contrast, titles that fit classifying as secondary and review are few and secondary studies are of the lowest volume. Among 42 studies, the emphasis in the hands-on research aspect correlates negatively to the methodological variety in the work, evidenced by substantial integrative and review contributions. The literature thus comprises a significant balance of primary data collection and critical evaluation, together with secondary literature review on the phenomena of air pollution and general contextual frameworks. The robust research underscores the importance of data collection in the field.

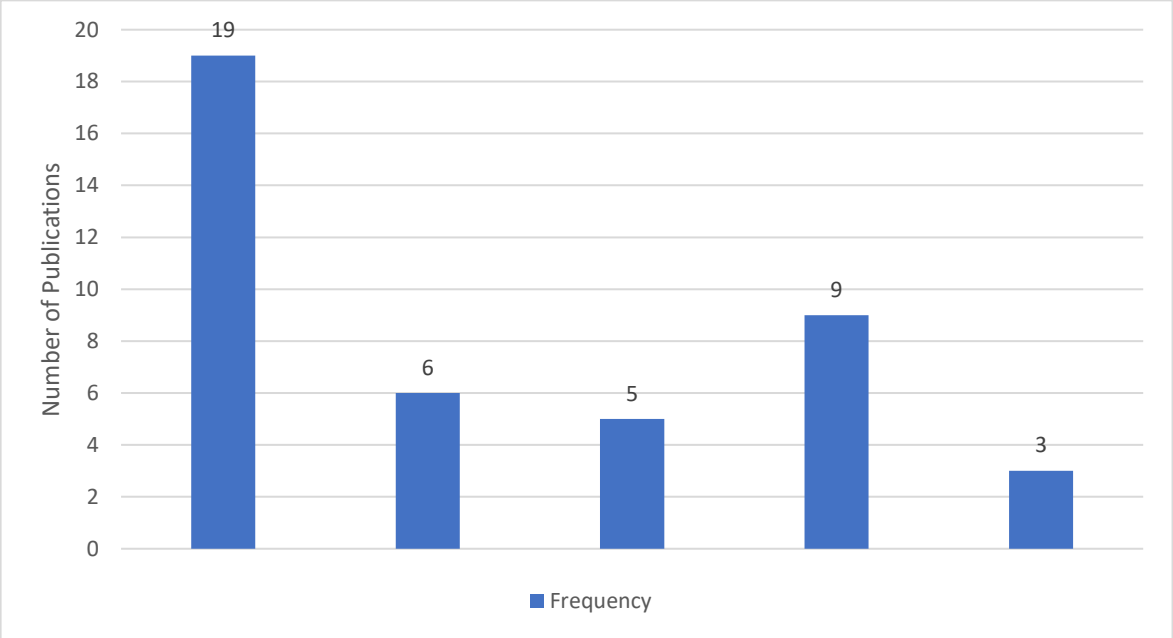

Figure 10: Study types of retrieved publication from 2014 to 2025 in this review

Classification of Retrieved Publications from 2014 to 2025

The figure 11 outlines the distribution of types of publications pertaining to research on building energy efficiency and retrofits, covering the years 2014-2025. Most of the research output, 32 of the 42 publications (about 81%), was recorded in peer-reviewed journals. Therefore, the distribution of research output showed that most of the research in this field was communicated through channels of considerable academic rigor. Other publications, including reports, books, unpublished theses, and conference proceedings, accounted for smaller but still significant contributions at about 9.5% publications. Such contributions, particularly conference proceedings, provide a useful diversity of perspectives and methodologies to the formal scholarly literature base for energy efficiency and retrofit research. The predominance of journal literature reflects the scientific and contextual certainty in energy performance, policy analysis, and technologic interventions research in the built environment, as well as the emphasis on methodological rigor and peer research validation associated with this body of knowledge.

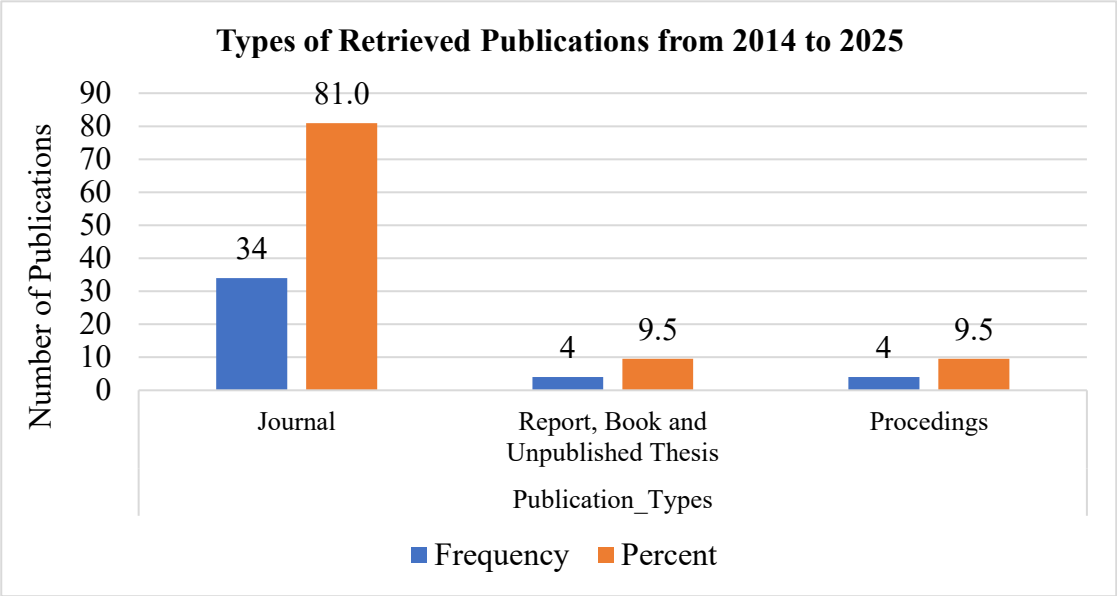

Figure 11: Types of retrieved publications from 2014 to 2025

Table 5: Top 10 Cited Papers among the 42 Retrieved Publications (2014-2025)

S. N.	Journal Name	Number of Citation
1.	Enhancing Energy Efficiency in Existing Infrastructure	929
2.	Multi objective optimisation of energy systems and building envelope retrofit in a residential community	270
3.	Cost-benefit analysis for Energy Efficiency Retrofit of existing buildings: A case study in China	213
4.	A comprehensive analysis of building energy efficiency policies in China: status quo and development perspective	189
5.	Cost-effectiveness of energy performance renovation measures in Finnish brick apartment buildings	141
6.	Improving building energy efficiency in India: State-level analysis of building energy efficiency policies	125
7.	Review analysis of economic and environmental benefits of improving energy efficiency for UAE building stock	114
8.	Energy efficiency of residential buildings in the European Union: An exploratory analysis of cross-country consumption patterns	103
9.	Research on the building energy efficiency design strategy of Chinese universities based on green performance analysis	101
10.	Enhancing building energy efficiency and thermal performance with PCM-Integrated brick walls: A comprehensive review	79

The table 1 highlights that the initial groundwork for building energy efficiency and retrofits was established by a few highly regarded studies. "Enhancing Energy Efficiency in Existing Infrastructure" has received the greatest number of citations and appears to be the most impactful of these studies, garnering 929 citations. It is followed by other influential studies on multi-objective optimization, cost-benefit analyses in China, policy evaluation, and energy renovations of Finnish buildings The citation counts show the impact and

sustainability of each piece in building subsequent research. In summary, the table demonstrates research methodology diversity and geographic diversity with respect to research on energy efficiency and retrofits. The studies incorporated and evaluated energy efficiency research and retrofits at the level of policy infrastructure, residential communities, and inter-country comparisons.

Distribution of Retrieved Publications by Journal and Source (2014-2025)

The figure 5 highlights the six main journals which published articles concerning building energy efficiency and retrofitting research from 2014 and anticipated through 2025. The data shows a pronounced pre-eminence of the journal Energy and Buildings which published 11 articles and is the most important outlet in this area of research.

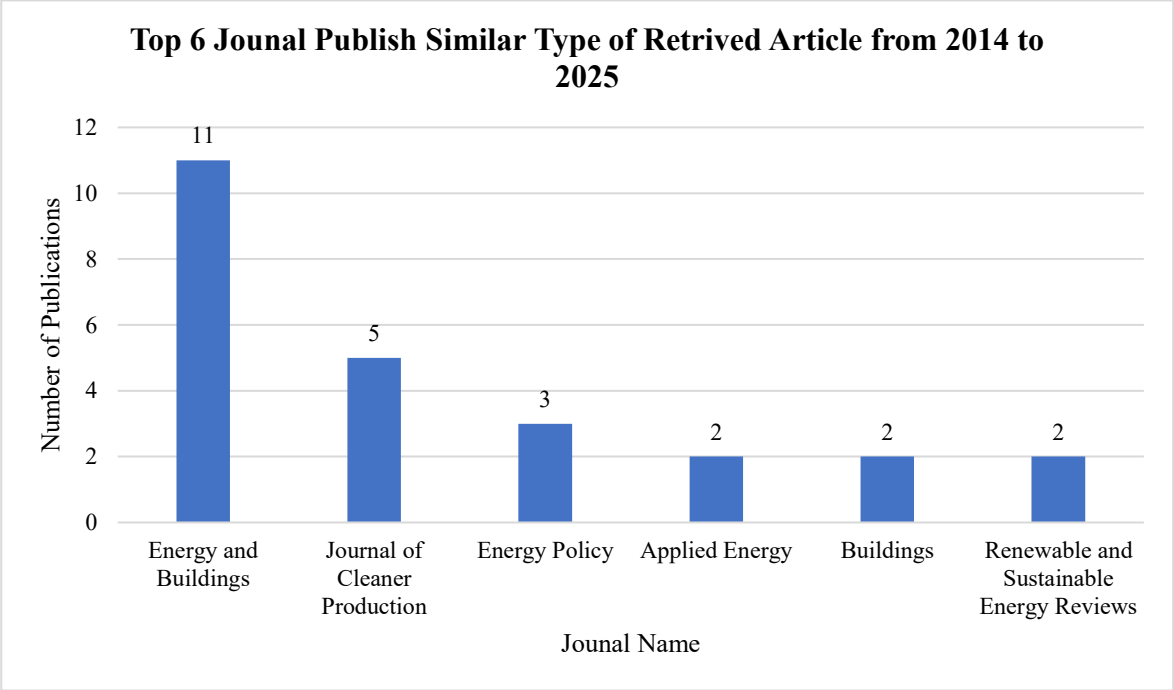

Figure 12: Top 6 Journal Publish Similar Type of Retrieved Article from 2014 to 2025

This journal is followed by the Journal of Cleaner Production which has published 5 articles, and Energy Policy published 3 articles. The remaining trio of Applied Energy, Buildings, and Renewable and Sustainable Energy Reviews contributed 2 articles each as well. Such a distribution emphasizes the importance of the more specialized journals and particularly those concerning the strategic energy performance of the built environment and its sustainability. This suggests that the research community in this area targets journals that

have a high methodological relevance and direct connection to building energy technologies, policy retrofitting, and strategic building remodelling. For the thesis, this could mean that this is where the more fundamental highly cited works will most likely be found in terms of journal selection for literature reviews or for publication of a manuscript.

Appendix 2: Table of Comprehensive Retrofit Analysis by Category, CO_2 & Energy Reduction, Cost, and Payback

Main Category	Retrofit Level	Category/Type of Retrofit	CO2 Reduction	Energy Reduction	Cost (Investment)	Payback (Years)	Citation
Building Envelope	Deep Retrofit	External insulation and window replacement (Masonry ~1900)	Not specified	44% (heating 46%, cooling 31%)	Not specified	Not specified	Lops et al. (2025)
Building Envelope	Moderate Retrofit	External wood fiber insulation and window replacement	Not specified	9% (heating 10%, cooling 12%)	Not specified	Not specified	Lops et al. (2025)
Building Envelope	Deep Retrofit	Thermal plaster (aerogel/hydraulic lime) + windows (Heritage)	Not specified	29% (heating 45%, cooling 17%)	Not specified	Not specified	Lops et al. (2025)
Building Envelope	Level 1	Better insulating windows & doors, flow-reducing water taps	Up to 65%	58% (primary energy)	Additional investment	13-14 years	Gustafsson et al. (2016)
Building Envelope	Level 2	Roof insulation (195mm) + facade insulation (80mm)	Up to 65%	Further reduction	Higher than Level 1	19-23 years	Gustafsson et al. (2016)
Building Envelope	Optimized	Windows (single/double/triple), wall & roof insulation	Not specified	36.4-44.1%	$85,000-$205,000	25-51 months (2-4 years)	Jia et al. (2024)
Building Envelope	Basic	Thermal insulation (walls, roofs, floors), standard windows	Not specified	20%	€2.44/m²	Not specified	Li & Shui (2015)

Main Category	Retrofit Level	Category/Type of Retrofit	CO2 Reduction	Energy Reduction	Cost (Investment)	Payback (Years)	Citation
Building Envelope	Passive Measures	Thermal insulation of walls, roofs, floors; efficient windows	Indirect	Up to 70%	Variable	Not specified	Arapi (2021)
Building Envelope	Major	Insulated walls + glass corridors (floors 3,6,8,10,12)	Not specified	12.16% (EUI reduction)	Estimated moderate	~5.52 years	Satriopratomo et al. (2025)
Building Envelope	Major	Insulated walls + glass corridors (floors 1-12)	Not specified	31.28% (EUI reduction)	Higher cost	~5.83 years	Satriopratomo et al. (2025)
Heating System	Level 1	Programmable thermostats, LED lighting, weatherization	4.568 Mt/year	7,551 GWh/year	$2,014 million	0.4 years	Krarti & Dubey (2017)
Heating System	Level 2	Efficient cooling systems, HVAC improvements, appliances	13.134 Mt/year	21,710 GWh/year	$10,696 million	2.7 years	Krarti & Dubey (2017)
Heating System	Active Measures	Air & ground source heat pumps + district heating	Direct CO2 reduction	15-30% further reduction	Higher investment	Not specified	Arapi (2021)
Heating System	Heating System Upgrade	Oil/electric to ASHP, GSHP, or biomass	Up to 80%	Significant decrease	Varies by system	Depends on subsidies	Wu et al. (2017)
Renewable Energy	Level 2 with RES	High-efficiency photovoltaic system integration	Not specified	25.5% cooling reduction	Included in envelope cost	~13.2 with incentives	Stasi et al. (2025)
Renewable Energy	NetPlus Target	Level 2 + heat pump + surplus energy generation	Not specified	Net positive (up to 173%)	Included	Reduced with incentives	Stasi et al. (2025)
Renewable Energy	Rooftop Solar	Solar panels with optimized sizing	Not specified	Contributes to 36.4-44.1%	Included in investment	Part of 25-51 months	Jia et al. (2024)

Main Category	Retrofit Level	Category/Type of Retrofit	CO2 Reduction	Energy Reduction	Cost (Investment)	Payback (Years)	Citation
Renewable Energy	PV Integration	Photovoltaic panels for net-zero energy	Avoided emissions	Complete energy balance	Incremental cost	Depends on incentives	Maaouane et al. (2023)
Renewable Energy	Solar Thermal + PV	Solar thermal and photovoltaic systems	Up to 69.5 kgCO2/m²/yr	Significant heating reduction	401-593 EUR/m² LCC	Varied, high measures	Hirvonen et al. (2019)
Rating Standards	5-star rating	Minimum insulation + single to double glazing	Implied moderate	Heating-cooling 114-149 MJ/m²	~$2,812 AUD additional	Variable; often long	Tushar et al. (2022)
Rating Standards	6-star rating	Enhanced insulation + improved glazing	Greater than 5-star	Heating-cooling 70-114 MJ/m²	~$3,009 AUD additional	Improved financial	Tushar et al. (2022)
Rating Standards	7-star rating	Increased insulation + double glazing	More significant	Heating-cooling 52-83 MJ/m²	~$3,104 AUD additional	Shorter payback, IRR improves	Tushar et al. (2022)
Rating Standards	8-star rating	High insulation + efficient glazing	High	Heating-cooling 25-54 MJ/m²	$3,834 AUD	Payback improves, NPV grows	Tushar et al. (2022)
Rating Standards	Over 8-star rating	Max insulation (R9 ceiling, R4 walls) + best glazing	Highest	Lowest energy load	~$6,548 AUD	Payback increases, cost effectiveness limits	Tushar et al. (2022)
Nearly Zero-Energy Buildings	Deep Renovation	Very low energy level refurbishment (Sems Have)	Not specified	54% (190 to 87 kWh/m²/yr)	~€9.7 million (~€2,666/m²)	~8-9 years	Rose et al. (2019)
Nearly Zero-Energy Buildings	Deep Renovation	Very low energy level refurbishment (Traneparken)	Not specified	48% (139.1 to 93.4 kWh/m²/yr)	~€6 million	~5-6 years	Rose et al. (2019)

Main Category	Retrofit Level	Category/Type of Retrofit	CO2 Reduction	Energy Reduction	Cost (Investment)	Payback (Years)	Citation
Nearly Zero-Energy Buildings	Net-Zero Target	Building producing surplus energy after efficiency measures	Not specified	Net positive (up to 173%)	Included in retrofit	Reduced with incentives	Stasi et al. (2025)
Integrated Programs	Level 3 Deep Retrofit	Cooling system replacement, daylighting, deep envelope	28.553 Mt/year	47,195 GWh/year	$21,392 million	2.3 years	Krarti & Dubey (2017)
Integrated Programs	Whole EER Project	Combined heat source, outdoor heating network, envelope	Based on gas savings	Gas 50,150 m^3/yr; electricity 49,410 kWh/yr	$375,240.3 USD	15.9 years (IRR 2.27%)	Liu et al. (2018)
Integrated Programs	Building 12 Complete	External walls, windows, HVAC system, fresh air retrofit	Implied via coal savings	25.7% actual conservation (vs 50.2% theoretical)	$357,083 USD (~35.08 USD/$m^2$)	28.2 years (IRR 3.06%)	Liu et al. (2018)
Active Systems & Controls	HVAC Efficiency Upgrade	Upgraded HVAC with higher EER and COP	Indirect via energy	Significant reduction	Higher capital cost	Not specified	Maaouane et al. (2023)
Active Systems & Controls	LED Lighting Upgrade	70% reduction in lighting power density	Indirect	Contributes to overall savings	Included in envelope cost	Not specified	Maaouane et al. (2023)
Active Systems & Controls	Smart Controls & HVAC	Upgrade of HVAC, lighting, controls	Significant CO2 reduction	>20% building energy decline	Varies widely	Variable, long payback	Nita et al. (2023)
Active Systems & Controls	Daylighting Controls	Daylighting controls + cooling system optimization	Included in Level 3	Part of 47,195 GWh/year	Included in capital	Included in 2.3 years	Krarti & Dubey (2017)

Main Category	Retrofit Level	Category/Type of Retrofit	CO2 Reduction	Energy Reduction	Cost (Investment)	Payback (Years)	Citation
Advanced Materials	PCM-Integrated Walls	Phase-change material in brick cavities/mortar	Indirect	40-50% cooling/heating load reduction	Moderate to high	Variable; mid to long-term	Lachheb et al. (2024)
Advanced Materials	Thermal Plaster (Aerogel)	Aerogel + hydraulic lime plaster for heritage buildings	Not specified	29% total energy (45% heating, 17% cooling)	Not specified	Not specified	Lops et al. (2025)
Advanced Materials	Aerogel Insulation	Aerogel-based thermal insulation plaster on facades	50% reduction	68% heating; 40% electricity	Not quantified in study	Not specified	Sofronievska et al. (2024)
Advanced Materials	PCM in Thermal Storage	PCM modules in hot water/heat supply systems	Indirect via fuel reduction	Up to 90 kW thermal capacity	Moderate to high initial	4-5 years typical	Lazariev & Sukhodub (2025)
Control Systems	Programmable Thermostats	Automated temperature management + optimization	4.568 Mt/year	7,551 GWh/year	$2,014 million	0.4 years	Krarti & Dubey (2017)
Control Systems	Heat Recovery Ventilation	Mechanical ventilation with heat recovery	Up to 56.5 kgCO2/m²/yr	Moderate heating reduction	348-541 EUR/m²	Varied payback	Hirvonen et al., (2019)
Control Systems	Building Automation	Smart controls and building management systems	Indirect	Variable based on optimization	Higher investment	Variable	Maaouane et al. (2023)

Appendix 3: Table of Cost Benefit Analysis

Category	Retrofit Measure	Region	Investment Cost	Energy Reduction	Cost per % Reduction	Payback Period	Economic Value	Cost-Benefit Rating	Citation
Control Systems	Model Predictive Control (MPC)	Finland	€115/m²	22.3-29.9%	€3.85-€5.15	1-3 years	€38,330-€57,500	Highest	Ramesh et al. (2024)
Control Systems	Rule-Based Control (RBC)	Finland	€55/m²	9.5-17.2%	€3.19-€5.79	2-4 years	€18,333-€36,667	Very High	Ramesh et al. (2024)
Heating System	Oil/Gas to GSHP Conversion	Finland	€350/m²	30-80%	€4.38-€11.67	4-8 years	€116,667-€311,111	High	Hirvonen et al. (2020)
Heating System	Heat Pump + MPC Controls	Finland	€300/m²	26%	€11.54	2-8 years	€100,000-€400,000	High	Ramesh et al. (2024)
Heating System	District Heating Connection	EU/Nordic	€180/m²	20-60%	€3.00-€9.00	5-12 years	€60,000-€300,000	High	Popovski et al. (2023)
Building Envelope	Roof Insulation	EU	€50/m²	10-30%	€1.67-€5.00	7-11 years	€16,667-€50,000	Very High	Wu et al. (2017)
Building Envelope	Window Replacement	EU	€55/m²	10-20%	€2.75-€5.50	13-15 years	€18,333-€36,667	Very High	Gustafsson et al. (2016)
Building Envelope	Wall Insulation	EU	€75/m²	45-50%	€1.50-€1.67	10-19 years	€25,000-€50,000	Very High	Wu et al. (2017)
Building Envelope	Basic Thermal Insulation	EU	€105/m²	15-25%	€4.20-€7.00	12-20 years	€35,000-€70,000	High	Arapi (2021)
Building Envelope	Pre-1980s House Retrofit	Finland	€497/m²	65%	€7.65	19 years	€165,667	Moderate	Hirvonen et al. (2019)

Category	Retrofit Measure	Region	Investment Cost	Energy Reduction	Cost per % Reduction	Payback Period	Economic Value	Cost-Benefit Rating	Citation
Building Envelope	1980s-2000 House Retrofit	Finland	€501/m²	62%	€8.08	18 years	€167,000	Moderate	Krarti and Dubey (2018)
Building Envelope	Post-2000 House Retrofit	Finland	€445/m²	50%	€8.90	15 years	€148,333	Moderate	Hirvonen et al. (2019)
Building Envelope	Post-2010 House Retrofit	Finland	€476/m²	45%	€10.58	16 years	€158,667	Moderate	Hirvonen et al. (2019)
Building Envelope	Deep Energy Renovation	EU	€2,183/m²	29-54%	€40.43-€75.28	5-9 years	€727,667-€1,310,000	Low	Rose et al. (2019)
Nearly Zero-Energy	NZEB Single-Family House	Denmark	€725/m²	70%	€10.36	12-18 years	€241,667-€362,500	Moderate	Simson et al. (2025)
Nearly Zero-Energy	NZEB Apartment Building	Estonia	€800/m²	75%	€10.67	12-16 years	€266,667-€355,556	Moderate	Simson et al. (2025)
Nearly Zero-Energy	NZEB Office Building	Finland	€875/m²	70%	€12.50	12-20 years	€291,667-€437,500	Moderate	Simson et al. (2025)
Integrated Programs	Level-1 (Basic) USA	USA	$2,014M (national)	26.6%	Varies	0.4 years	$671M/year	Very High	Krarti and Dubey (2018)
Integrated Programs	Level-2 (Moderate) USA	USA	$10,696M (national)	54.2%	Varies	2.7 years	$3,565M/year	High	Krarti and Dubey (2018)
Integrated Programs	Level-3 (Deep) USA	USA	$21,392M (national)	75.2%	Varies	2.3 years	$7,131M/year	High	Krarti and Dubey (2018)