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Review

Smart Building Technologies for BIPV-Based Low-Carbon Energy Retrofitting: A Critical Review

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Abstract

The significant share of the building sector in global final energy consumption and subsequent CO_2 emissions makes this sector a pivotal element in decarbonization pathways through energy retrofitting strategies. However, integrating effective solutions such as smart building technologies and building-integrated photovoltaic (BIPV) systems into energy retrofitting projects faces critical challenges, including fragmented evidence-based knowledge, discrepancies in assessment methods, and the complexity of coordinating multiple systems. This critical review synthesizes the fragmented body of literature to present a comprehensive framework for implementing smart building technologies in BIPV-driven energy retrofitting, using a structured PRISMA-based protocol, multiple technological taxonomies, and statistical analysis. The study presents three major novel contributions to this field: (i) a retrofit-depth classification of smart building technologies and further categories aligned with intervention intensity; (ii) a retrofit phase-based key performance indicator (KPI) framework; and (iii) a performance-priority decision matrix linking performance levels to technological measures across four primary performance goals: carbon emission reduction, cost optimization, grid flexibility and renewable self-sufficiency. Statistical analysis reveals a notable imbalance in the existing research landscape where physical interventions, such as system replacements and renewable system integration, dominate the literature, while the application of digital monitoring and control systems and social/readiness KPIs are significantly underrepresented. The findings further demonstrate that integrated technological solutions are more frequently associated with higher performance improvement. This study and proposed performance-priority decision matrix further provide evidence-based practical guides for researchers, practitioners, and policymakers to implement and promote effective and climate-focused smart building retrofitting strategies.

Keywords: smart buildings; energy retrofit; building-integrated photovoltaic; climate change mitigation; performance metrics; smart retrofit

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1. Introduction

Climate change and its environmental consequences are now widely recognized as severe global challenges demanding urgent, transformative actions across all economic sectors worldwide [1]. Thus, numerous national policies and international programs have been established to transform socioeconomic systems towards a decarbonized future, with a central focus on transitioning from fossil fuels to renewable and efficient energy systems [2,3]. In this global agenda, the building sector plays a pivotal role in achieving

the decarbonization targets due to its significant and persistent share in global final energy consumption and the associated greenhouse gas (GHG) emissions [4,5].

The substantial share of the building sector, added to the increasing need for global housing and the urbanization trend, makes this sector the focal point and integral element for sustainable development and climate change mitigation plans [6,7]. The statistical evidence in the literature underlines the profound environmental impacts of the building sector, estimated to be responsible for approximately 30–40% of final energy consumption and GHG emissions globally [8]. Many studies confirm this range of contribution and report the building sector as accountable for around 36% of final energy consumption and 39% of energy-related carbon dioxide (CO_2) emissions [9–12]. Statistics in developed regions, such as European Union (EU) member states, reaffirm the high share of the building sector in final energy consumption and GHG emissions, estimated at around 40% and 32%, respectively [13,14], while in the United States (US) the building sector reportedly accounts for 41% of final energy consumption and 39% of CO_2 emissions [15]. These facts collectively confirm that the building sector is of paramount importance to be included in decarbonization and climate change mitigation plans worldwide.

Nevertheless, the climate change impact of the building sector is not limited to new construction, since vast and long-lasting existing stock was mainly constructed before the advent of modern energy codes and therefore characterized by low energy performance and high operational GHG emissions [16]. The projections indicate that between 75% and 90% of the existing building stock in the EU will remain in service by 2050, with low energy performance for the following decades [17,18]. Reportedly, 60% of US residential buildings were constructed more than three decades ago [19], making the existing building stock a critical sector in energy and environmental action plans aligned with decarbonization and climate change mitigation targets.

Moreover, the slow rate of new construction, which is estimated at around 1.2% per year in the EU [20], adds to the complexity of building decarbonization, indicating that with a sole focus on new construction, achieving sectoral decarbonization is statistically impossible. Thus, energy retrofitting of existing buildings has been recognized as an indispensable and high-priority action plan to improve the energy and environmental performance of the overall building sector, particularly in developed countries [21,22]. Therefore, ambitious policy frameworks have been established to accelerate the renovation of the building sector around the world. For instance, EU member states aim to cut GHG emissions by 55% by 2030 and become climate-neutral by 2050 (relative to 1990 levels), with a focus on energy-efficient and decarbonized building stock as a central pillar of such international targets [22]. To achieve these targets, the renovation rate in this sector must increase from the current rate (around 0.4–1.2% per year) [23] to a sustained rate higher than 3% per year, along with accelerated energy retrofitting of the existing building stock [24].

Despite the successful implementation of energy codes to improve operational energy performance in buildings, studies highlight a critical point in the narrow use-phase-oriented approach to building energy performance, given the risk of load shifting from the use phase to other buildings' life-cycle phases [25]. This phenomenon occurs when buildings are highly equipped with energy-efficient materials and systems, such as a significant amount of insulation or advanced technical systems, to reduce operational energy use, while increasing the associated environmental impact in other building life-cycle phases, such as manufacturing, transportation, installation, maintenance, end of life, etc., known as the embodied impact of buildings. Projections indicate that while operational phases account for 70–90% of a building's life-cycle energy compared to 10–30% of embodied impact, the new buildings constructed by 2050 will have an almost equal share of operational and embodied impacts [26]. This confirms the necessity of a holistic life-cycle thinking approach

in designing new buildings and retrofit projects to avoid the load-shifting phenomenon and reduce the overall building's life-cycle impact through implementing a full life-cycle assessment (LCA).

Smart Retrofitting and the Role of Smart Technologies in Building Decarbonization

The integration of on-site renewable energy sources (RESs) plays a significant role in decarbonizing building energy use, as indicated by policies such as the Renewable Energy Directive [27]. However, the common RESs integrated into buildings, such as building integrated photovoltaic (BIPV) systems, are non-programmable and lead to a temporal mismatch between energy generation and building energy demand due to the variable rate of energy generation and demand [28]. This causes substantial complexities in the efficient management of electrical systems, making it crucial for building systems to develop the capacity for demand-side management at the building level [29]. In response to these challenges, the traditional, unidirectional power grid is being transformed into a smart grid (SG), an advanced electricity grid system that utilizes automated and sophisticated control systems to enable energy transmission between the building and the grid [30]. Likewise, the buildings are expected to transition from passive energy consumers to active grid-responsive agents capable of dynamically adapting their energy usage to external signals, including on-site generation and grid electricity supply [31].

Therefore, a smart building (SB) in such a context is defined as a near-zero-energy building (nZEB) with a high degree of flexibility to manage energy demand and generation efficiently and effectively according to local climate conditions, user needs, and grid requirements, utilizing a wide range of smart technologies [32]. In other words, an SB can effectively manage its on-site RESs and adapt its operation profile with on-site renewable energy generation and grid conditions, as well as communicating with other buildings and grid infrastructure to respond to the energy needs of the building efficiently, minimizing the reliance on grid electricity and lowering the load on grid infrastructure [33]. Given the importance of integrating RESs into existing building stock and smart grid systems, smart retrofitting (SR) in this context can be interpreted as the effective application of SB principles to the existing building stock as a process to transform existing buildings into SBs to enable them to respond to the varying conditions of climate and grid systems. Thus, SR aims not only to reduce energy consumption as the primary target in traditional energy retrofitting but also to create intelligent, adaptable, and grid-interactive buildings that can actively contribute to resilient and decarbonized energy systems.

Despite the rapid and significant technological advancement in SBs, the implementation of SR in the existing building sector faces several challenges, such as fragmented knowledge, lack of a comprehensive and standardized assessment method and application levels, as well as the complexity of coordinating and applying the required systems within an energy retrofitting project. In more detail, despite the numerous key performance indicators (KPIs) suggested for measuring SB performance, the choice and application of these KPIs in different phases of an energy retrofitting project requires a framework from a practical perspective. Likewise, smart technologies for transforming existing building stock into SB require a retrofit-oriented classification that helps building designers and engineers make informed and efficient decisions for different levels of energy retrofitting. Therefore, given these identified gaps, this critical review aims to synthesize the fragmented body of knowledge and present a comprehensive and structured framework for decarbonizing the building sector through integration of RES-based smart energy retrofitting, including smart building technologies and KPIs for different depths of SR in the existing building sector.

Although several reviews have addressed BIPV, automation, KPIs, and technologies separately, such as Al Dakheel et al. [33] reviewing the smart building features and KPIs,

and Zhang et al. [34] focusing on the grid interaction of zero-energy buildings, this study focused in particular on smart technologies and KPIs in a retrofit-oriented framework emphasizing the role of BIPV and associated technologies and KPIs.

The present study, based on a critical review of the literature, was designed to provide a practical guide for researchers, practitioners, and policymakers by addressing the main required performance metrics and core technologies within different phases of SR projects and various retrofitting levels of existing building stock. The novel contributions of the present study are as follows.

- Providing a review-derived and retrofit-depth classification of smart building technologies linked to BIPV for shallow, medium, deep, and cross-cutting enablers through a detailed classification of smart technologies to be implemented in smart building energy retrofitting according to different levels of retrofitting, including shallow, medium, and deep retrofitting levels, as well as cross-cutting enabling technologies.
- Organizing the KPIs by retrofit phases (e.g., baseline and planning, implementation and operation, and post-retrofit assessment) and linking them to technology categories through a detailed review of smart technologies and key performance indicators applicable in energy retrofitting, complemented with statistical analysis on their distribution and concentration across different retrofit depths and implementation stages.
- Converting the review evidence into a performance-priority decision matrix through developing a performance-priority decision matrix as a decision-support system to make informed decisions for prioritizing the most effective technologies and appropriate KPIs.

Compared to the existing classification and decision-support approaches, the added value of this study lies not in the individual concepts, but in their integration into a single evidence-based framework, which is intended as a synthesis and practical tool rather than a conceptual taxonomy. Furthermore, the role of retrieved smart technologies and KPIs in achieving climate change mitigation goals will be discussed and highlighted. Therefore, this research follows a structure comprising first a review and discussion of the major research themes in the field, second examining the available and well-implemented smart and BIPV-linked technologies in energy retrofitting phases, and third reviewing and discussing KPIs for SR and their role in the evaluation of energy retrofit and climate change mitigation goals. Finally, the discussion provides the decision-support system that represents the most effective technologies and KPIs to be implemented for each primary performance goal in an energy retrofitting project.

2. Materials and Methods

The research started with a structured PRISMA review protocol to retrieve and identify advances in smart and BIPV-linked technologies applied to the building sector for enhancing energy and environmental performance aligned with climate change mitigation goals (Figure 1 and Table 1). The search primarily focused on Scopus and Web of Science platforms due to their extensive coverage of peer-reviewed journals. The publications written and indexed in these platforms from 2020 to mid-2026 were considered to ensure the analysis reflected the state-of-the-art developments in the field of SB and BIPV-linked technologies and performance assessment. The search window was set from 2020 to 2026 to capture the post-EU Green Deal period, focusing on recent advances in BIPV, smart technologies, and energy retrofitting studies, and therefore prioritizing recency over historical coverage. However, foundational work in this field before 2020 is reflected by including review articles covering original research published before 2020.

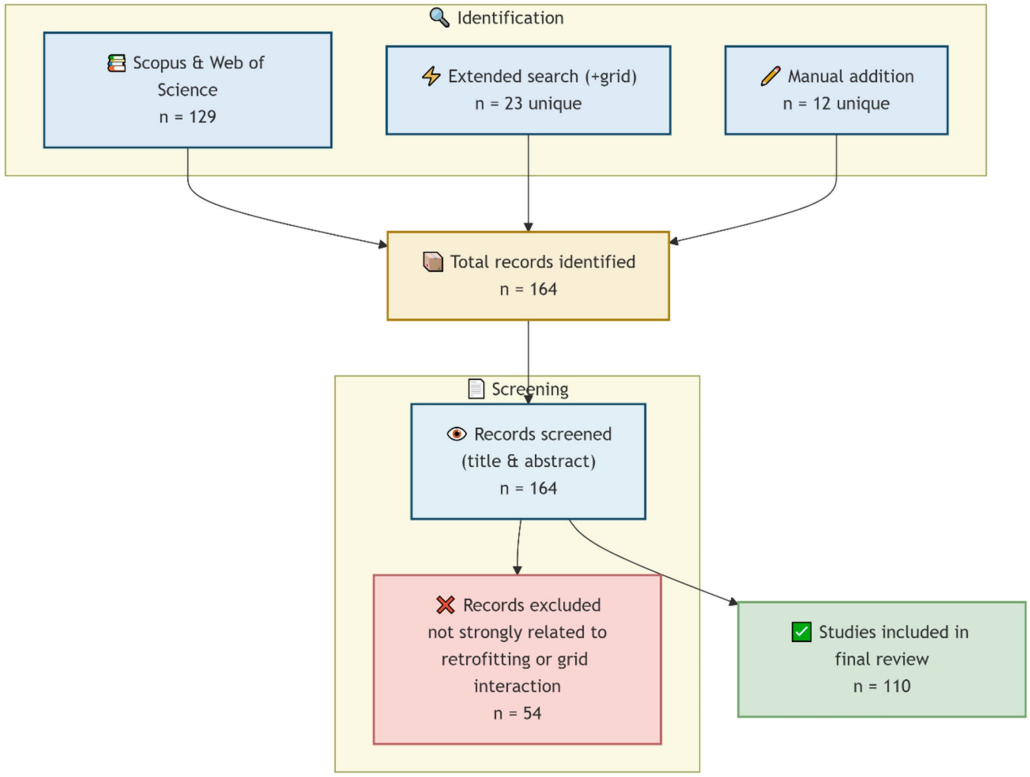


Figure 1. PRISMA protocol-based review process of the literature.

Table 1. The PRISMA protocol and structured review steps implemented in this study.

PRISMA Steps	Summary of Actions in This Review
Identification: Phase 1	Primary search in Scopus and Web of Science (2020–mid 2026) using the adapted syntax: ("building" AND ("PV" OR "BIPV" OR "photovoltaic") AND ("retrofit" OR "refurbishment" OR "renovation") AND ("carbon" OR "GHG")). This yielded 129 unique publications.
Identification: Phase 2	Search extended by adding the term "grid" to capture literature on building–grid interaction (retrieved 23 unique additional publications)
Identification: Phase 3	Manual addition of 12 unique publications to ensure comprehensive coverage of relevant works.
Screening	Retrieved records were manually screened. Studies with strong connection to building retrofitting or energy grids were kept.
Inclusion	Overall, 110 publications were included for further analysis.
Data extraction: Phase 1	Systematic extraction of smart and digital technologies applied in buildings, followed by categorization according to depth of energy retrofitting (shallow, medium, deep, and cross-cutting enablers).
Data extraction: Phase 2	Extraction of key performance indicators (KPIs) from the selected publications, categorized according to retrofitting and implementation phases (baseline evaluation, implementation and operation, and post-retrofit operations).
Synthesis framework	Following a retrofit-oriented classification of smart building technologies and KPIs, the effectiveness of each technology group is discussed across varying KPIs.
Methodological contribution	Establishment of a retrofit-oriented smart technology and KPI framework based on retrofit depth and implementation phase to unify terminology and support decision-making, and proposing a performance-priority decision matrix in low-carbon energy retrofitting.

A set of keyword combinations, including ("building" AND ("PV" OR "BIPV" OR "photovoltaic") AND ("retrofit" OR "refurbishment" OR "renovation") AND ("carbon" OR "GHG")), was used to capture studies that addressed BIPV-linked technologies and carbon-sensitive building refurbishment. Although the primary focus of this review is on BIPV systems performing as on-site renewable energy sources and building envelope components simultaneously, the search was extended by including conventional building-applied photovoltaic systems to ensure more extensive coverage of the literature. The search was extended by adding "grid" to the search process to ensure a broader picture of the literature connected to energy grids. Moreover, further research papers were added manually to the final pool to ensure comprehensive coverage of the literature.

The initial search was then narrowed to keep the most relevant publications through title and abstract screening. The retrieved publications were reviewed manually, and only those that explicitly addressed either smart building technologies or BIPV application and building–grid interaction were included in the final round of review (110 publications in total). Studies addressing the main focus of this research, particularly the application of smart technologies in building energy retrofitting or performance enhancement through building–grid interaction, were kept for further analysis of the applied smart and digital technologies and performance assessment criteria.

Figure 1 and Table 1 present the structure of the review process following the PRISMA protocol, including the search strings, inclusion and exclusion criteria, and data extraction steps. The analytical framework of this review consisted of three main steps. First, the selected publications are systematically examined to extract the implemented smart and digital technologies in buildings and then categorized according to the depth and level of building energy retrofitting. Second, the KPIs in the selected publications are extracted and categorized according to the retrofitting and implementation phases. Third, the technologies and performance metrics applicable in different implementation phases and different depths of energy retrofitting are discussed in an integrated framework that helps elucidate the link between each technology and KPIs for smart retrofitting.

Furthermore, a detailed statistical analysis was performed to characterize the research landscape and identify the potential research gaps in the literature. Different statistical methods were employed in Python (v3.13) (NumPy (v2.2), SciPy (v1.14), and scikit-learn (v1.6)), such as a rank-frequency (Zipf) power-law model for distributional characterization of research across categories and overall concentration analysis by the Herfindahl–Hirschman index (HHI) and Gini coefficient to quantify the concentration and inequality levels in the research landscape within the two predefined taxonomies (i.e., smart building technologies and KPIs). The HHI and Gini coefficient were calculated and used as descriptive measures of concentration and imbalance across technology and KPI categories, where the Gini coefficient is derived from the Lorenz curve of cumulative category share and the HHI is computed as the sum of squared shares of categories. HHI values below 0.15, 0.15–0.25, and above 0.25 represent low, moderate, and higher levels of concentration, respectively. It must be noted that these indicators depend on the category granularity and sample composition and complement the frequency counts by statistically showing whether the literature is concentrated around a few categories.

3. Results

The initial analysis of the retrieved literature demonstrated a variety of interlinked solutions in the existing research field, as shown in Figure 2. The keyword co-occurrence plot reveals a complex and incomplete relationship, lacking a clear structure to show how various smart solutions can contribute to smart and low-carbon buildings. Nevertheless, Figure 2 illustrates the link among photovoltaic systems and several smart and foundational systems,

such as zero-energy buildings, smart grids, storage systems, demand-side management, and solutions such as machine learning methods. Although such a visualization of the co-occurrence of research keywords is crucial for achieving a general understanding of existing solutions in the literature, it needs further elaboration to provide a practical guide for implementing smart building technologies within a low-carbon retrofitting framework. Therefore, this critical review presents a comprehensive framework through integrating the retrieved solutions within a holistic approach across different retrofit depths.

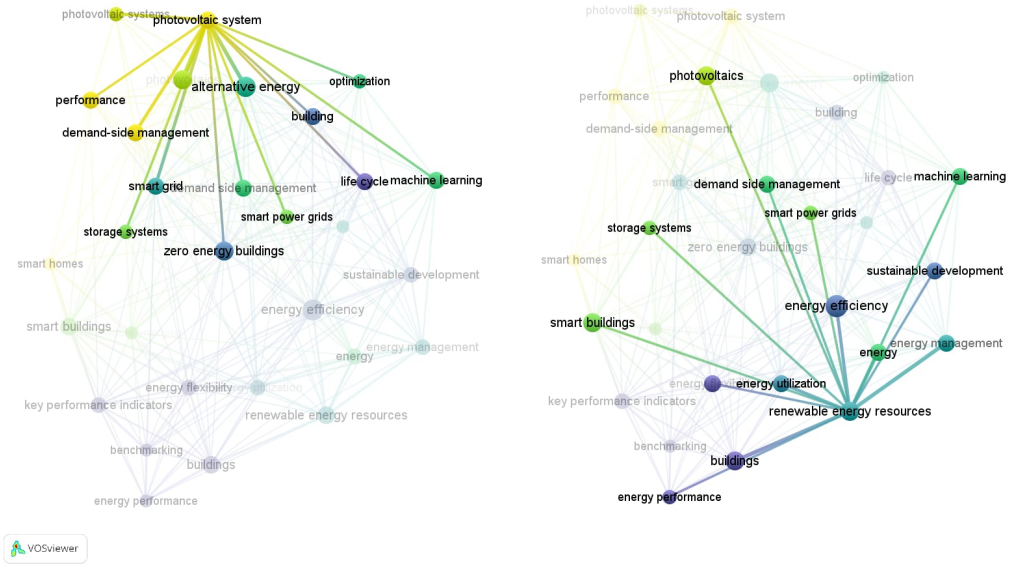


Figure 2. Co-occurrence map of research keywords in the retrieved literature on smart building technologies and assessment.

Following the aforementioned retrofit depths, this section presents the results of the literature review on how smart and digital technologies are addressed in the body of the literature, supported by quantifying the share and frequency of smart building solutions categorized into different retrofit depths. Moreover, each category of smart solutions is described and discussed within a retrofit-oriented framework for climate change mitigation goals. Likewise, KPIs implemented in the literature are reviewed and quantitatively discussed to elaborate on the strengths and research gaps in this research field. These findings and results in this section contribute to establishing a comprehensive and retrofit-oriented framework for implementing smart technical solutions for climate change mitigation, through a follow-up discussion on links and interdependencies of smart technological solutions and performance criteria of smart retrofitting strategies.

3.1. Smart and Digital Technologies Across Different Energy Retrofitting Depths

A critical challenge in transforming existing buildings into high-performance and low-carbon buildings is how to select technologies that align with the project's constraints and intended depth of retrofitting. Unlike new construction, a retrofitting project must consider and balance several aspects, including but not limited to technical feasibility, cost constraints, occupant disruption, and compatibility with existing building systems. The classification presented in this study organizes the smart technologies into three retrofit depths—shallow, medium, and deep retrofit levels—supplemented by cross-cutting enablers, in which each category of smart technologies is aligned with the degree of physical intervention. Based on the technologies applied in the reviewed studies, each study might be assigned to one or more technology categories, where shallow retrofits are identified as non-invasive interventions adding monitoring, sensing, or controls without replacing

envelope components and primary mechanical systems; medium retrofit involves addition or partial replacement of systems without the need for complete system and envelope overhaul; while deep retrofit requires major replacement or overhaul of HVAC, façade, and electrical systems. Furthermore, when relevant, the studies that implemented more than one technology type are assigned to different technology categories to fully represent the technology application landscape in this review.

As illustrated in Figure 3 and based on the summary presented in Table 2, the results reveal several important patterns across the application of smart technologies that contribute to climate change mitigation goals. The four plots presented in Figure 3a–d collectively highlight that this research field is expanding beyond traditional control systems towards increasing attention to systemic upgrades emphasizing renewable integration. At the same time, the distribution of frequencies highlights an imbalance in how different retrofit depths are tackled with the implementation of technological solution categories. It shows that medium retrofitting is dominating the literature with 124 occurrences, of which 63% and 37% focused on renewable integration and flexibility assets, respectively. Deep retrofitting represents a smaller share (i.e., 33 occurrences) strongly associated with system replacement. The overall technological solution distribution and the realized share of system replacement (11.1%), flexibility assets (15.5%), and renewables integration (26.3%) that together constitute around 53% of the technological references reflect the dominance of those technological solutions with direct and measurable impact on energy performance. Although smart solutions such as building automation and control and digital monitoring and control, both with approximately 5% coverage in the literature, are relatively underrepresented, despite their potential to enhance energy performance and management.

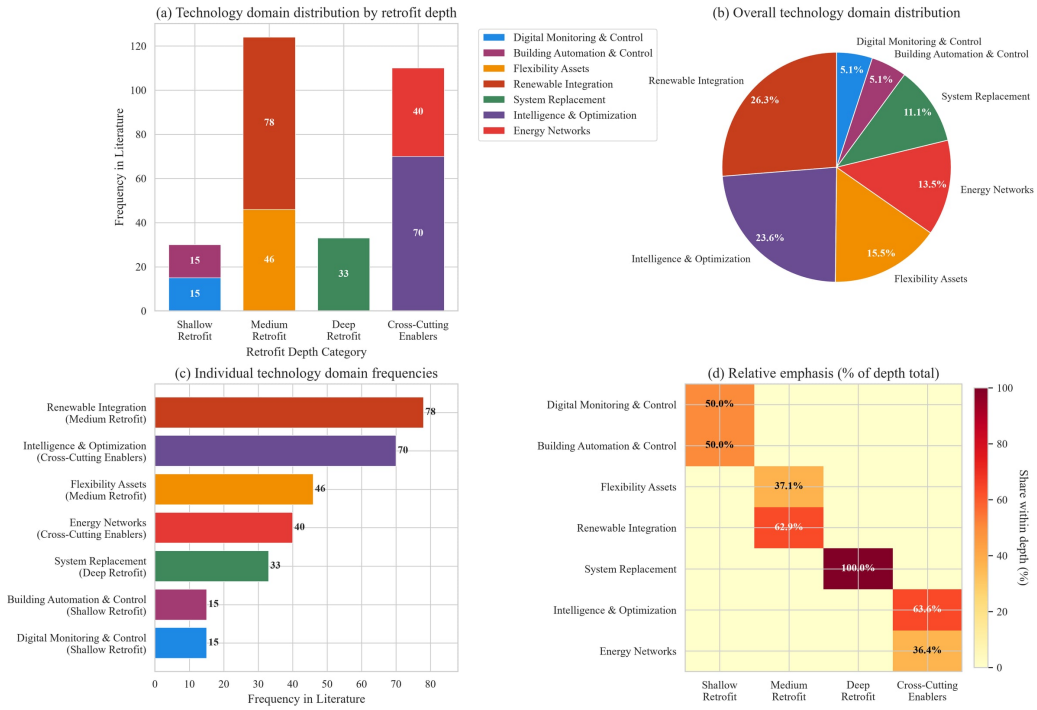


Figure 3. Frequency and share of smart technological solutions in the literature.

The statistical analysis of the reviewed literature shows a mean frequency of 42.4 (95% CI: 26.4–59.4) and a standard deviation of 24.6 (95% CI: 11.3–30), demonstrating substantial variability where the renewable integration and intelligence and optimization methods dominate the literature, while digital monitoring and control and building automation and control remain notably underrepresented (Figure 4a). The rank–size relationships in

Figure 4b follow a near-Zipfian distribution, while few dominant technology groups attract a disproportionate share of publications. Furthermore, the analysis of the Herfindahl–Hirschman index (HHI) in Figure 4d shows an HHI equal to 0.184 within the moderate concentration range (0.15–0.25), reaffirming that although the literature is not dominated excessively by a single technology group, a noticeable skew still exists. Further inequality analysis, shown in Figure 4c by plotting the Lorenz curve and calculating the Gini coefficient (=0.3), also confirms the moderate inequality of the application of different technological groups in the literature. Collectively, these findings reveal a concentration pattern in which some technological solutions, such as digital and monitoring controls, received disproportionately low research attention. This imbalance suggests that the research remains physical system-oriented rather than digital solution-oriented, even though the latter is crucial to realize smart and adaptive systems for climate change mitigation goals. This finding suggests opportunities for future studies to integrate smart and data-driven approaches with physical retrofit strategies to support more holistic initiatives for low-carbon building refurbishment.

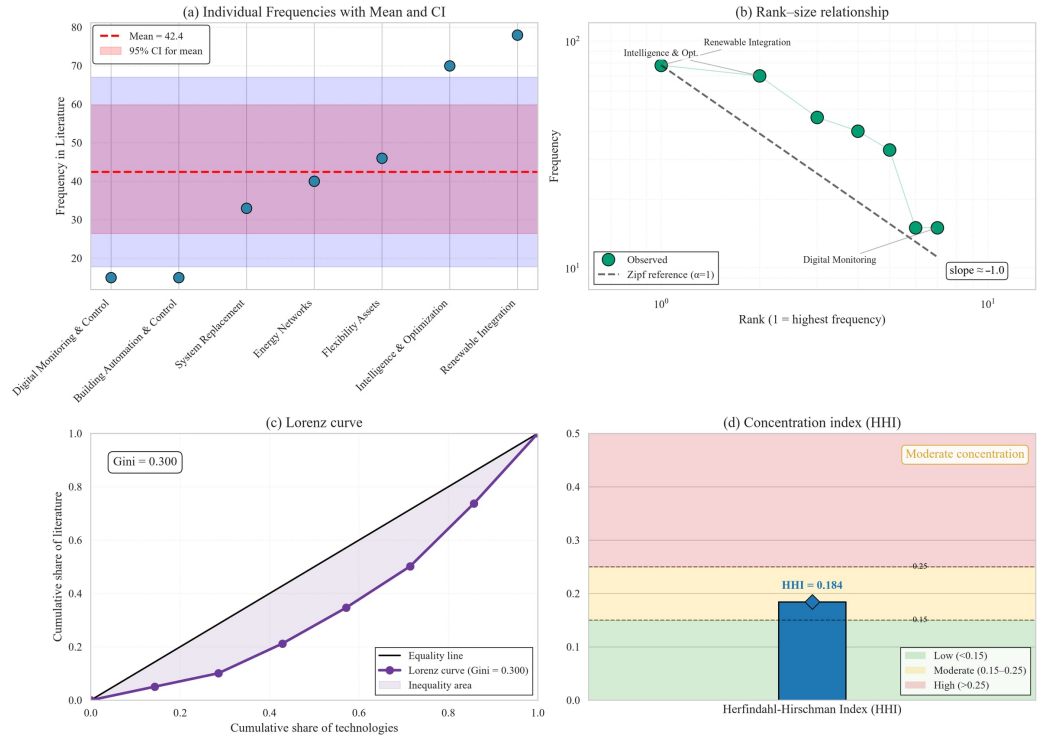


Figure 4. Statistical analysis of concentration level and distribution of technological solutions in the literature.

Describing the retrofit depths in more detail, the shallow retrofits prioritize rapid and minimal interventions primarily based on digital monitoring and control and building automation upgrades to improve operational efficiency without altering a building's physical envelope or mechanical system configuration. The first technological domain in this phase focuses on digital monitoring and control using smart meters, indoor air quality sensors, CO_2 sensors, and temperature sensors, which help enhance visibility and measurement of energy consumption patterns and environmental quality controls. Such technologies are essential for enabling data-driven scheduling of heating, ventilation, and air-conditioning (HVAC) systems as well as artificial lighting systems. Studies show that the application of edge-computing methods using non-intrusive load monitoring, sensors, and appliance management leads to a reduction in energy costs by 55% [35].

Building automation and control systems (BACSs) and home energy management systems (HEMSs) represent the next category in shallow retrofits, providing intelligent coordination of existing systems through smart HVAC controllers, occupancy-responsive algorithms, and rule-based or predictive control. This domain accounts for half of the citations among shallow measures, appearing in fifteen distinct references, revealing its significance in shallow smart building retrofits. Reviewed studies highlight that applying HVAC controls can decrease the heating demand by 51 percent, maintaining thermal comfort up to 97–99 percent of the time [36]. Furthermore, cloud-based model predictive control (MPC) coupled with BIPV battery configuration can reduce annual running costs and CO_2 emissions by 6% and 9.8%, respectively [37].

Medium-depth retrofits involve significant changes, primarily through the implementation of distributed flexibility resources and renewable energy systems such as battery energy storage systems (BESSs), thermal energy storage (TES), and electric vehicles (EVs). Their contribution to decarbonization goes beyond mere energy savings to include proactive load management, peak reduction, and grid support. Studies confirm the effectiveness of incorporating HEMSs with BIPV and battery storage to enhance the PV self-consumption rate to near 100 percent [38], and a holistic renovation including the application of technologies classified as flexibility assets, such as BESSs and TES, can increase the primary energy saving by 86 percent [32]. Another study highlighted the effectiveness of BESSs and a hydrogen storage system to reduce CO_2 emissions by 6.3–21.5 tons/year [39]. A different study shows that adding a BESS to a PV-heat pump configuration can yield an extra 11.7% reduction in CO_2 emissions [40]. More studies elaborated on the potential of integrating a static battery coupled with EV2B and PV systems to mitigate net carbon emissions by approximately 180 tons while reducing the annual electricity bill by around 28 percent [41]. Furthermore, other studies focusing on coupling BIPV and thermal energy storage systems confirm that such integration in residential building retrofits framework leads to total life-cycle CO_2 emissions of approximately 21.5 percent and around 35 tons of CO_2 equivalent over 30 years of building service life [42].

Alongside these flexibility resources, renewable integration technologies such as rooftop solar panels, heat pumps, and CCHP systems form the foundation of medium-depth decarbonization and remain among the most thoroughly investigated aspects of retrofit design. Reviewed studies on the application of renewable energy sources (RESs), such as BIPV systems, show that integration of RESs with flexibility assets, including energy storage systems, enhances independence, flexibility, and stability indices [43] and reduces operational costs (3–18%), peak demand (6–22%), and grid fluctuations by around 30–50% [44]. Moreover, such ESS integration with green energy sources can reduce CO_2 emissions by 35 percent, as reported in another study [45]. Other studies show that the combination of PV and building envelope upgrades reduced operational carbon emissions by 94% compared to a pre-retrofit scenario [46]. In Austria, PV systems coupled with heat pumps achieved a 45–60% reduction in CO_2 emissions in multi-family houses [47]. Another study demonstrates that rooftop PV on multi-apartment buildings covers 57% of annual electricity demand, reducing CO_2 emissions by 4 tCO_2 per building per year and achieving a payback period of 7 years [48]. Moreover, studies show that a water-source heat pump coupled with photovoltaic–thermal (PVT) panels can reach a seasonal coefficient of performance (COP) of 6.1 and 36% of primary energy savings [49].

Deep retrofit approaches require significant structural and systemic changes, often expensive measures, but are capable of achieving the greatest long-term reductions in carbon emissions. This category, for instance, encompasses complete HVAC system replacements with smart heat pumps, extensive façade-integrated PV systems, and thorough mechanical–electrical system replacements. These technologies emerge within the same wide reference

framework as medium-depth measures, indicating a significant overlap among studies that focus on renewables, storage, and system replacements. Furthermore, technologies such as BIPV systems as part of the building envelope perform beyond electricity generation and affect building envelope physics and thermal characteristics; therefore, they can impact multiple performance areas, suggesting multidimensional performance evaluations to be carried out.

Deep retrofits typically entail substantial embodied carbon and require thorough life-cycle assessments. Nonetheless, when approached strategically, they achieve optimal efficiency benchmarks, considerable decreases in heating and cooling demands, and enduring compatibility with forthcoming grid-interactive services.

Studies show that although holistic and deep retrofit scenarios, such as replacing HVAC systems alongside the application of RESs, require higher investment and embodied carbon emissions, the long-term economic, energy, and environmental benefits justify the initial carbon-intensive interventions [25]. For instance, a study shows that replacing a gas furnace with an air-source heat pump can reduce the annual CO_2 emissions by 18.6–38.9%, depending on the weather conditions [40]. Another study in the UK shows that replacing a gas boiler with an air-source heat pump coupled with PV systems reduces CO_2 emissions by 77% [50].

Another study on rural houses in a severe cold climate showed that replacing coal-based heating systems with a PV integrated with air-to-water heat pumps, a natural gas heater, and a PV integrated with an electric boiler can reduce CO_2 emissions by 51–90% and lead to a 7% reduction in life-cycle costs [51]. Moreover, additional smart solutions, including digital elements such as control algorithms integrated into intelligent heat pumps, guarantee ongoing optimization even after installation, setting deep retrofits apart as comprehensive changes rather than standalone actions.

Across all levels, cross-cutting enablers such as optimization algorithms, simulation platforms, and artificial intelligence (AI)/machine learning (ML) models play an increasingly essential role. These tools enable predictive control, performance forecasting, and optimal scheduling for flexible and renewable systems. Studies show the effectiveness of such techniques during the design and operation phase of smart building systems, highlighting the computational advantages by enhancing the optimization process with lower computational costs and power while ensuring high accuracy [52]. Studies show that the application of ML-based surrogate models in design optimization can accelerate the computational process 20-fold that of a non-ML-based process while keeping the accuracy of the results near 100 percent [53].

Table 2. Smart technology classification in a retrofit-oriented framework.

Retrofit Depth	Technology Domain	Technologies	Notes/Retrofit Applicability	References
Shallow (low-intrusion, fast impact)	Digital monitoring and control	Smart meters, measuring devices, indoor air quality sensors, CO_2 sensors, temperature sensors, weather stations	Easily deployable, low cost, immediate operational impact	[32,37,54–65]
	Building automation and control	Smart HVAC controllers, energy management systems, BACSs, HEMSs	Non-invasive upgrade, enhances existing systems	[32,36–38,44,57,60,63–70]

Table 2. *Cont.*

Retrofit Depth	Technology Domain	Technologies	Notes/Retrofit Applicability	References
Medium (moderate intervention)	Flexibility assets	Battery energy storage systems (BESSs), thermal energy storage (TES) tanks, EV charging interfaces	Requires investment but delivers high carbon savings and flexibility	[32,37–40,42–45,49,53,59,60,62–67,69–94]
	Renewable integration	Rooftop photovoltaic (PV), heat pumps, combined cooling, heating, and power (CCHP)	Robust and central to decarbonization	[32,37–51,53–59,61–68,70–81,83–88,90–118]
Deep (structural/system overhaul)	System replacement	HVAC replacement, façade integration with BIPV	High cost/embodied carbon, but long-term mitigation	[17,47–51,54,55,59–61,66,76–78,80,81,83–88,93,98,101,103,107–110,112,113]
Cross-cutting enablers	Intelligence and optimization	Optimization algorithms (genetic, predictive), simulation engines and platforms, AI/ML prediction models	Required across all retrofit scales for carbon-optimal operation	[32,36,37,39,40,42–51,53–67,69,71–81,83,85–93,95–99,101–104,106–114,116]
	Energy networks	Community microgrids, EV-to-grid integration, smart grid	Multi-building retrofit synergies, grid decarbonization enabler	[32,43–45,47,51,56–60,62–65,70,73,74,76,78–81,83,85–90,93,94,96,99,106,115–118]

Furthermore, the latest technological solutions focusing on energy networks at building clusters and community level are discussed in different studies as effective solutions to increase energy efficiency, cost-effectiveness, and environmental benefits through smart and flexible energy sharing at building cluster levels [34]. Collectively, the presented classification of smart technological solutions in this study underscores a spectrum of technological approaches, ranging from digital metering and monitoring to comprehensive structural transformation, connected by rising degrees of intelligence, control, and integration of renewables. Shallow retrofits quickly enhance building efficiency by utilizing current infrastructure. Medium retrofits introduce flexible and renewable assets that transform energy dynamics, and deep retrofits completely reorganize the building's energy framework. This multilayered viewpoint shows that smart technologies are not only additions, but act as a unified ecosystem where digital and physical elements evolve together. Future studies should focus more on measuring the relationships between retrofit depths, especially how minor digital enhancements can enhance medium and deep physical interventions, as well as on assessing the embodied carbon trade-offs associated with deep retrofits.

3.2. Key Performance Indicators Across Different Retrofit Phases

A holistic assessment of SR requires a multidimensional range of indicators to capture the whole life cycle of the intervention from identifying baseline performance, through implementation and operation, to confirming post-retrofit advantages. The KPI framework summarized in this review includes multidimensional KPIs covering technical, economic, ecological, and social aspects and correlates them with the sequential stages of the retrofit process. This framework not only represents the complexities of retrofit decision-making but also emphasizes the interconnections among energy demand, system adaptability, renewables integration, and occupant or system awareness and preparedness. For example, in a residential BIPV-based retrofit project, the baseline and planning phase requires calculating

the energy demand and carbon baseline KPIs; the implementation and operation phase needs several KPIs, such as self-consumption, self-sufficiency, flexibility, etc., for meticulous design and operation schemes; and post-retrofit assessment involves carbon and energy savings as well as economic payback KPIs to measure the effectiveness of implemented retrofit measures. These KPIs are applicable to different building typologies, with particular consideration of the limitations of each building type, such as commercial buildings with limited roof area and high electricity load, emphasizing technical KPIs such as grid interaction, and in residential buildings where the saving-to-investment ratio might be the most critical KPI for the decision-makers.

KPIs retrieved from the literature show a comprehensible, yet uneven landscape in how performance evaluation criteria are conceptualized and applied across different retrofit implementation phases. Based on the classification presented in Table 3, Figure 5a–d illustrates four plots that collectively illustrate how the literature prioritizes certain KPI clusters, particularly those related to the energy performance baselines, system interaction, and efficiencies, while other aspects, such as social and readiness-oriented criteria, are less represented and applied. This imbalance highlights a strong technical orientation of the current body of research, as well as the needs and opportunities for a more holistic and multidimensional assessment framework and implementation.

Table 3. Smart building KPI classification in a retrofit-oriented framework.

Retrofit Phase	KPI Domain	KPIs	Retrofit Applicability	References
Baseline and planning	Energy demand and carbon baseline	Energy consumption, net direct energy, energy density, carbon dioxide emissions, net carbon emissions	Identify high-impact retrofit targets; quantify starting carbon footprint	[32,36,37,39,40,42–51,53,55–60,62,64–69,72–81,83–88,90–93,95–115]
	Economic baseline	Initial investment cost, operating cost, life-cycle cost	Define retrofit affordability and financing gap	[38,39,43–45,50,53,59,60,62,64,65,67,68,70,71,81,85–88,90–93,95,109,110,112,113,116,118]
Implementation and operation	Retrofit effectiveness (efficiency gains)	Performance efficiency, system efficiency, energy demand reduction, optimized load curves, performance ratio	Verify retrofit effectiveness in reducing demand and emissions	[37,39,40,42,44–51,55–57,59–62,64,66,72–77,80,81,83–88,95–101,103,104,106–109,111–114]
	Flexibility and demand response	Flexibility capacity index, shiftable flexible load, load-shifting factor, peak shaving indicator, flexibility utilization efficiency, independence index, load match index	Evaluate retrofit-enabled load shifting and demand flexibility	[32,36,38,43–45,53,59,60,60,62,65,67,69–71,81,84–87,89,90,94,118]
	Renewable integration	Self-consumption index, self-sufficiency index, PV utilization ratio, onsite energy fraction	Ensure retrofit enhances renewable integration and avoids curtailment	[32,37,39,40,42,45–51,53–67,71–81,83–88,90–92,95–105,107–114]
	Grid interaction and stability	Grid export/import, peak-to-average ratio, loss of load probability, grid robustness factor, autonomy rate, stability index	Retrofit's contribution to stabilizing the grid and reducing fossil backup	[32,36–38,40,42–45,48,51,53,56,58–60,62–67,69,70,73,74,76,77,80,81,83–90,93,94,109–111,114,116–118]

Table 3. *Cont.*

Retrofit Phase	KPI Domain	KPIs	Retrofit Applicability	References
Post-retrofit assessment	Carbon and energy savings	CO_2 emission reduction, emission index, primary energy savings, net annual energy exchange	Quantify the achieved climate mitigation	[32,36,37,39,40,42,44–51,53,55–62,64–68,72–81,83–90,95–104,106–113]
	Economic payback and value	Payback period, net present value, levelized cost of energy, flexibility cost benefits, internal rate of return, savings-to-investment ratio	Show long-term retrofit cost-effectiveness and carbon value	[37–40,44–51,53,55,56,59–62,64–68,70–75,77–80,83,85–92,94,95,98,100–107,109,110,112,113,117,118]
	Social and readiness	Smart readiness indicator, functionality levels for BACSs, forced/delayed flexibility factors, social acceptance	Track user acceptance and readiness of retrofitted buildings for the smart grid	[32,55,59,63,69,79,118]

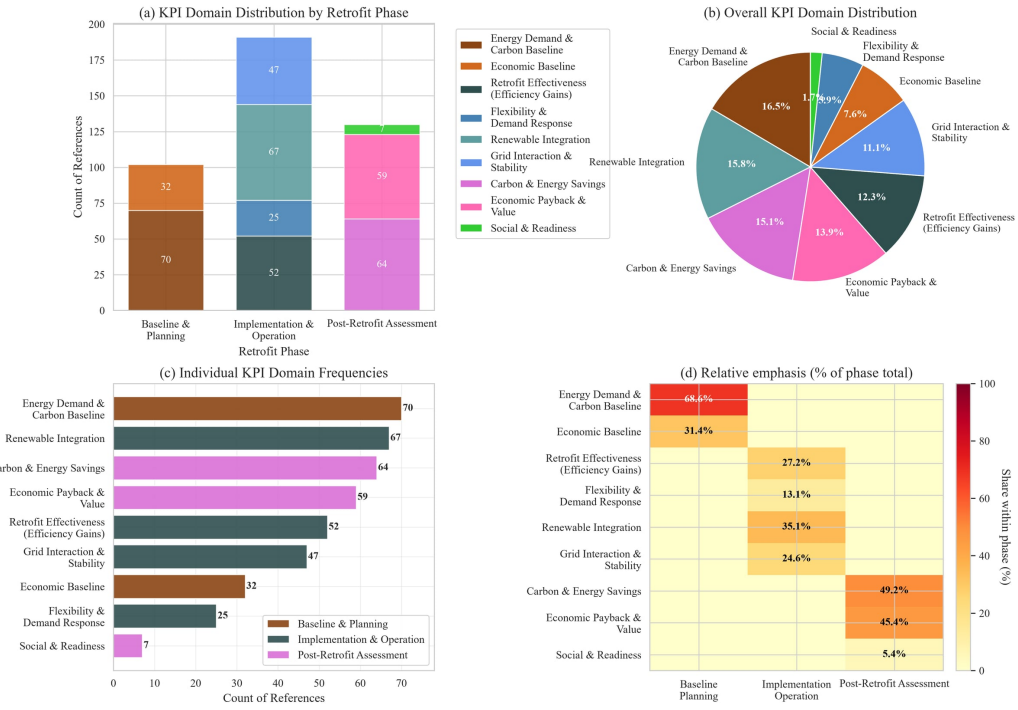


Figure 5. Frequency of KPIs applied in smart building performance assessment in the literature.

The distribution across different retrofit implementation phases demonstrates that the operation phase has the highest concentration of KPIs in the literature, particularly with a focus on retrofit effectiveness (35.8% for KPI application in the operation phase). This indicates that the main body of the literature is concerned with establishing robust measurement during the operational stage, while KPIs oriented towards post-retrofit phases, as well as baseline and planning, are relatively less applied despite their crucial role in planning, evaluation, and validation of real-world performance. The overall KPI distribution highlights a relatively balanced focus within the technical KPI category, including energy and carbon baseline (16.5%), grid interaction and stability (11.1%), efficiency gains (12.3%), and combined economic factors (appx. 21.2%).

Statistical analysis of the reviewed literature exhibits a moderate concentration with a mean frequency of 47 (95% CI: 33.1–59.6) and standard deviation of 21.5 (95% CI: 9.6–27.2)

where "energy demand and carbon baseline" and "social and readiness" appear as the most and least frequently addressed performance domains with a noticeable variation (Figure 6a). The rank–size relationship (Figure 6b) follows a semi-Zipf distribution. At the same time, KPIs related to renewable integration and carbon and energy saving emerge as the most frequent KPIs in the literature, suggesting that technical and environmental performance, along with economic performance, are dominant criteria in the literature, while social and user-oriented aspects are less represented.

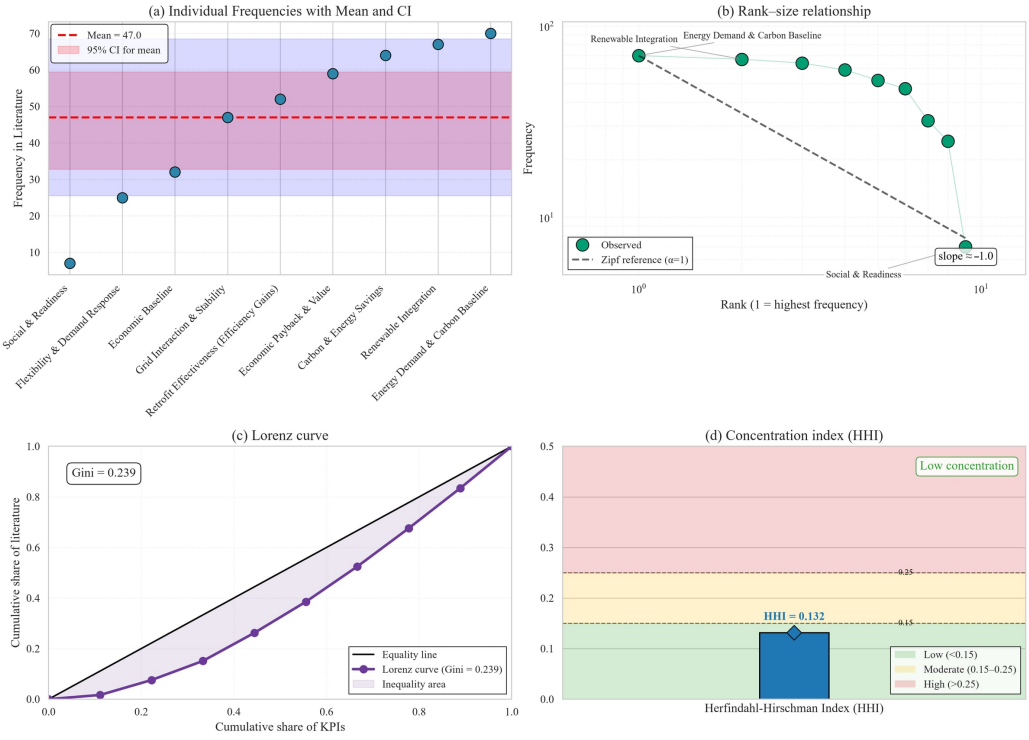


Figure 6. Statistical analysis of the concentration level and distribution of KPIs in the literature.

Furthermore, analysis of the concentration level in Figure 6d shows an HHI index equal to 0.132, within the range of low concentration (<0.15), highlighting that no single KPI category significantly dominates the literature; however, the demonstrated low frequency of studies on social and readiness performance criteria highlights the need for further research attention. This fact is reaffirmed by the analysis of the Gini coefficient shown on the Lorenz curve in Figure 6c, which highlights moderate inequality in the research landscape, mainly impacted by low research attention on the social aspects compared to technical, environmental, and economic performance criteria.

Given the review results presented in Table 3, the most used economic indicators across different retrofit phases in the literature are the initial investment costs, operating costs, life-cycle costs, net present value, payback period, levelized cost of energy, internal rate of return, and savings-to-investment ratio; however, it must be noted that the results across different studies by these indicators are not directly comparable, since they strongly depend on macro and microeconomic parameters such as regional electricity tariffs, incentive schemes, installation and construction costs and market prices, discount and inflation rates and the definition of system boundaries.

The findings also highlight that the existing body of literature prioritizes the quantitative performance indicators reflecting building-level and broader system integration, while social and readiness indicators, with only 1.7% coverage, reveal a substantial gap for addressing occupant behavior, acceptance, and socio-technical aspects essential for successful implementation of smart retrofitting measures. In this review, social/readiness KPIs are

defined as socio-technical indicators that capture the preconditions and user-connecting capacity for smart retrofit, such as occupant acceptance, comfort, awareness and readiness, at both organizational and technical scale and those indicators for measuring the occupant-centric technology design. The low share of social and readiness indicators in the research landscape can be explained by several factors, such as the technical orientation of the research literature, lack of standardized social/readiness metrics, and data availability constraints. Also, it must be noted that this low coverage is observed in research publications and does not necessarily represent its share in actual retrofit projects in practice. In summary, the strong orientation of the KPIs in the literature towards technical, economic, and environmental aspects indicates the need and potential to extend the research field towards a more socio-technically integrated and holistic framework for a comprehensive and balanced assessment of smart and climate-aware retrofit strategies.

3.3. Analyzing KPI Improvements by Application of Smart Technologies in Low-Carbon Retrofitting

As introduced in the previous sections, the effectiveness of low-carbon retrofitting solutions relies on the appropriate implementation of several technological strategies, measured by a diverse set of KPIs. In this section, the reported ranges of KPI improvements in the literature across various KPI categories and the effectiveness of each technology group are analyzed, supported by a detailed review and statistical analysis of the findings in the reviewed literature. For this purpose, the reported KPIs and applied technologies in the literature are categorized into 17 and 8 groups, respectively. The objective is to i) characterize the distribution of reported improvements, ii) identify which technology groups deliver the most substantial benefits per KPI, and iii) highlight the inherent variability arising from different study contexts as an essential analysis for evidence-based decision-making to prioritize technology application as well as research and development efforts. As illustrated in Figure 7, for each KPI category, a box-and-whisker plot is constructed to show the distribution and observed range of KPI improvements (in percentages) in the literature, and the overlaid points represent the midpoint values for each technology group within each KPI category. Such illustrations and analyses represent the expected KPI improvement ranges and distribution and the potential of technological strategies simultaneously.

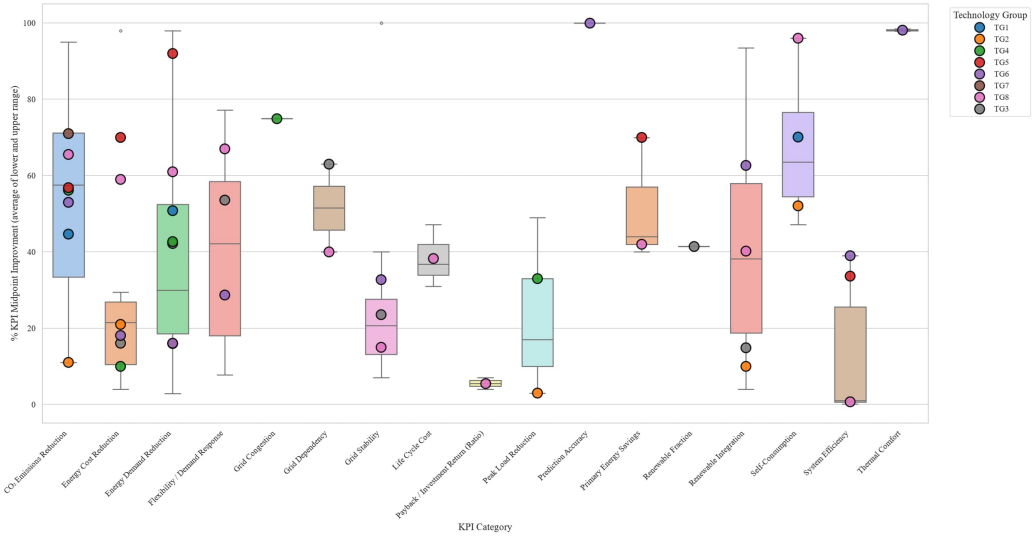


Figure 7. Range of various KPI enhancements by application of different technology groups; TG1: heat pumps, TG2: solar photovoltaics, TG3: energy storage, TG4: envelope upgrade, TG5: biomass and hybrid renewables, TG6: control and optimization, TG7: grids, TG8: integrated retrofit package.

The results in Figure 7 reveal that KPI values span a very wide range, as low as 0.8% (carbon emission with night ventilation scenarios [109]) to as high as 127% (energy demand reduction by nZEB-compliant scenarios [111]). However, the majority of values lie between 20% and 70%, indicating that most interventions offer meaningful, albeit variable, performance improvement. Likewise, the median overall performance improvement across all categories is approximately 47%, with an interquartile range (IQR) of 24–70% representing a broad disparity that could be attributed to variation in baseline conditions, climate zones, building types, and modeling assumptions present in the literature.

CO_2 emission reduction is one of the most widely reported KPI categories, with studies reporting reductions ranging from 11% to 95% for deep retrofitting with grid decarbonization [99]. Overall, the results show median, IQR, and min-to-max values equal to 57.8%, 40%, and 11% to 95% that indicate the high potential of reducing CO_2 emissions through the combination of retrofit strategies and the fact that half the studies achieved around 60% or higher levels of reduction, where the low bounds are mainly attributed to single-technology implementation (e.g., TG1 and TG2), while the upper bound comes from the application of holistic and integrated solutions (e.g., TG7 and TG8). Likewise, the KPI category of energy demand reduction represents a wide range, with median, IQR, and min-to-max values of 30%, 37.8%, and 3–98%. The upper range of energy demand reduction is reported to be achievable through integrated and holistic retrofit solutions (TG8) and the application of hybrid renewable systems (TG6), where minimum reductions beyond 70% to 90% are reported in different studies [107,109].

The energy cost reduction represents a more compact view with a lower median compared to the previous categories, 21.5%, although the wide range between min-to-max reductions suggests that application of different technology groups might lead to high variation in economic benefits, while the specific macroeconomic parameters in each context can determine and impact the economic benefits, as discussed in [91]. The review reveals that a minimum reduction in energy costs can be achieved by application of non-invasive technologies such as intelligent and optimization algorithmic solutions (e.g., AI/ML methods categorized in TG6), and the highest energy cost saving can come from hybrid renewable systems (TG5) and integrated retrofit packages (TG8), by which an energy cost saving of over 70% is achievable [107,109]. Payback and investment return, however, are displayed with a narrow range of reduction mainly derived from studies with a focus on thermal and electrical storage systems coupled with BIPV systems that indicate an achievable SIR (shown as the ratio in Figure 7) of 4, suggesting a high economic return [91,92].

Flexibility/demand response KPIs, along with other technical KPI groups such as renewable integration/utilization, peak load reduction, self-consumption, grid dependency, and grid stability, are also represented in a wide range of potential improvements, as shown in Figure 7. In particular, the reported enhancement in performance for flexibility and demand response KPIs shows a median of 42% with an IQR and min-to-max range of 53% and 8–77%, approximately reaffirming the high potential of smart technological solutions while varying values of performance achievement across different studies. Alongside the integrated retrofit package (TG8), technological solutions based on thermal energy storage systems, often enhanced by phase-changing materials (PCMs), are reportedly effective strategies to improve flexibility and demand response, with a load-shifting index up to 67% [32]. Another study in Hong Kong showed that the application of the hierarchical demand optimization method can decrease the grid fluctuation rate by 30%, 44%, and 50% [44]. Likewise, another study reveals that integrating RESs and energy storage systems enhanced by a new optimized demand management system using the virulence optimization algorithm (VOA) and earthworm optimization algorithm (EWOA) can reduce the peak-to-average ratio (PAR) by 76.19% and 73.8%, respectively [62]. Furthermore, other

studies focusing on KPIs such as PV self-consumption and associated advantages in grid stability and lowering grid dependency revealed that the application of TES at an ML-based optimum size can enhance self-consumption from 41% to approximately 60%, reduce annual electricity export and peak power injection to the grid by 31.7% and 21.2%, respectively, and reduce imported electricity from the grid by 24% [42], benefiting grid stability while preserving cost efficiency [53] and elaborating on the effectiveness of integrated solutions for optimizing the performance of RES applications through optimization and control strategies for energy storage and demand response management.

4. Discussion

Following the review of implemented technologies and KPIs in the literature to elaborate on the effectiveness of each technological category, this section presents a performance priority-based technology selection matrix. The selection matrix acts as a decision-support tool established based on the qualitative and quantitative performance of each technology category derived from the literature review in this study, enabling informed decision-making in selecting the most effective technologies for a given performance goal. For this purpose, Table 4 represents the decision matrix categorized into four groups of primary performance goals. For each, top recommended technologies and complementary systems, along with the KPIs, are reported according to the findings from the literature review. Likewise, Figure 8 complements the findings shown in Table 4 by summarizing the potential benefits of each technology domain across the performance objectives qualitatively (Figure 8a), as well as the quantitative range of KPI improvements observed in the literature by the implementation of one or a combination of technological solutions (Figure 8b). Technological categories in Figure 8a are rated comparatively (i.e., low, medium, high) and discussed based on the relevance to each performance group in the literature and the impact of each technological category on each performance goal reported across the literature. The performance priority-based decision matrix is developed in three main steps. First, four primary performance goals are defined based on the review findings in the previous sections. Second, the technology categories are assessed based on the application frequency and the reported range of KPI improvement. Third, a comparative relevance score (i.e., low, medium, high) is assigned based on the strength and consistency of evidence from the literature. It must be noted that this matrix is a screening and prioritization tool rather than a formal multi-criteria optimization model; therefore, for project-specific decisions, the matrix should be combined with formal multi-criteria decision analysis reflecting local weights and constraints. The matrix covers four major performance areas: carbon emissions, cost optimization, grid flexibility and stability, and renewable self-sufficiency. The matrix distinguishes between grid flexibility and renewable self-sufficiency since they refer to different performance goals; however, they are related in specific cases.

Table 4. Performance priority-based decision matrix highlighting the recommended and complementary technologies for primary performance goals.

Primary Performance Goal	Recommended Technologies	Complementary Systems	Key Performance Indicators	Evidence from the Literature Best Performance Observed
Carbon emission	BIPV + heat pumps + ESSs	Smart controls, BACSs, HEMSs	CO_2 emission reduction	Technological solution: BIPV + BESSs + heat pump + full envelope retrofit Reported enhancement: 97.44% CO_2 reduction [75]
Cost optimization	BIPV + heat pumps	BESSs, TES, efficient HVAC, smart controls, BACSs, HEMSs	Life-cycle cost (LCC), NPV, payback period	Technological solution: BIPV+ heat pump + full envelope Reported enhancement: 47.2% reduction in LCC [101]

Table 4. *Cont.*

Primary Performance Goal	Recommended Technologies	Complementary Systems	Key Performance Indicators	Evidence from the Literature Best Performance Observed
Grid flexibility and stability	BIPV + ESSs + demand response management	BESSs, TES enhanced by PCM, smart controls	Peak load reduction/PAR reduction/grid fluctuation reduction/flexibility capacity	Technological solution: BIPV + BESSs Reported enhancement: 63% reduction of grid dependency [74]
Renewable self-sufficiency	BIPV + ESSs	TES, smart controls, demand response systems	Self-sufficiency rate/BIPV self-consumption/load cover factor	Technological solution: BIPV + AWHP Reported enhancement: Self-consumption rate of 70.4% [47]

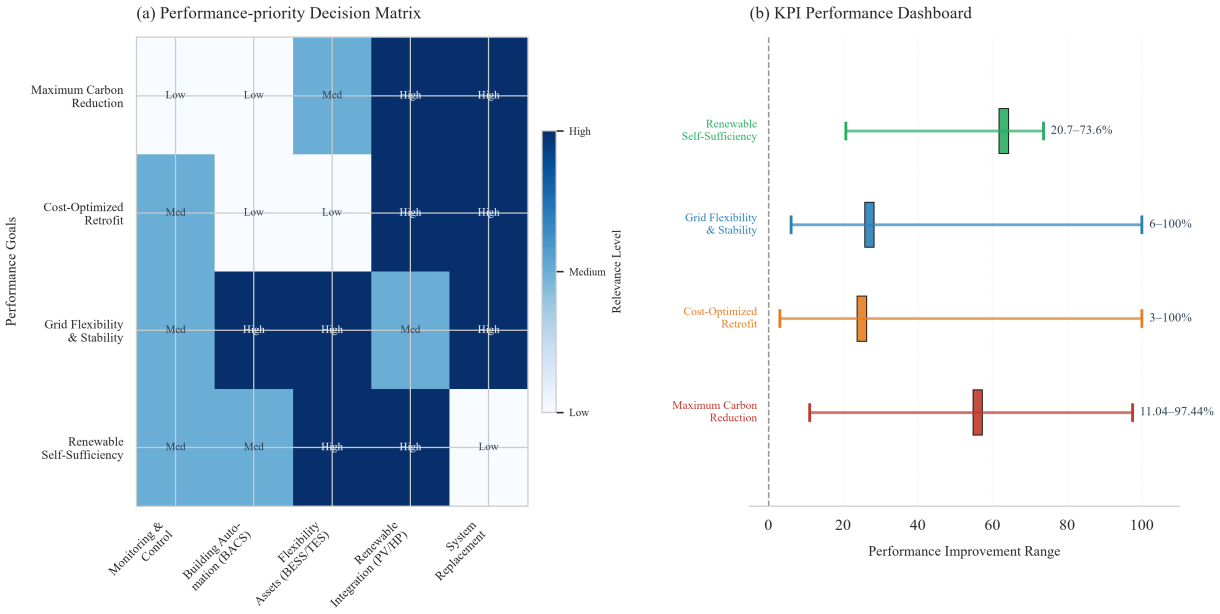


Figure 8. Performance-priority decision matrix (**a**) and the range of expected KPI enhancements from the literature (**b**).

Practitioners can use the performance-priority decision matrix through a six-step procedure: (1) defining the primary performance goal, (2) characterizing the building, context, and constraints, (3) screening the recommended and complementary technologies represented in the matrix and Table 4, (4) checking the expected KPI range in Figures 7 and 8 against the project targets, (5) verifying the economic and technical feasibility of the specific project, and (6) selecting the KPIs (Table 3) to be monitored during and after implementation.

The KPI performance analysis (Figure 8b) shows that CO_2 reduction represents the widest and highest range (11–97%) achieved by the combination of applied technological categories. However, it must be noted that the upper value of 97.44% is reported in a single study focusing on operational CO_2 emissions and therefore should be regarded as an upper-bound single case rather than a representative value, since the median performance improvement in this KPI category is found to be approximately 58%, as illustrated in Figure 7. It must be noted that the reduction range of CO_2 emissions revealed in this review must be interpreted cautiously since in most reviewed studies and reported results, the CO_2 reductions refer mainly to the operational impacts, and many studies lack a whole-life-cycle assessment approach or comparable system boundaries, making the results challenging for direct comparison or benchmark establishment given the fact that exclusion of embodied impacts associated with BIPV systems and retrofit measures leads to overestimation of environmental impact reduction. Furthermore, it should be highlighted that the reviewed

studies cover various geographic and climate conditions where the productivity of photovoltaic systems, heating and cooling energy demand, and HVAC system performance might vary significantly. Therefore, the impact of climate conditions must be considered when interpreting and comparing different studies since they also impact the scale of realized emission reduction as well as other technical, environmental, and economic indicators.

The decision matrix in Figure 8a highlights that renewable integration and system replacement receive high relevance scores for maximum carbon reduction, reaffirming that deep decarbonization requires an integrated package of technological solutions at the systemic level, including generation and system upgrade. Likewise, recent studies at the urban scale on advanced energy configurations similarly emphasize integrated solutions coupling passive, active, and water-related strategies for achieving low-carbon cities, reaffirming that integrated solutions rather than isolated technologies are needed for deep decarbonization [119]. On the other hand, BACSs receive only a low relevance score since they have minimal direct impact on carbon emission reduction, which is aligned with the fact that while they can lead to reducing heating demand by 51% [36], they can only achieve high CO_2 reduction when coupled with envelope refurbishment, PV, and heat pump applications [46]. Likewise, while flexibility assets such as BESSs and TES have a direct impact on the self-consumption of RESs, they are considered secondary solutions to carbon emission reduction [52] with comparatively long environmental payback periods [42].

The KPI improvement related to economic performance, however, represents a similar range that can be attributed to the effectiveness of a combination of technological solutions to yield substantial economic benefits. As shown in Figure 8a, the technological solutions, including building automation and digital monitoring, can optimize energy performance, but they are not the primary drivers for cost reduction and do not necessarily offer minimal life-cycle cost reductions, while the highest energy cost savings come from integrated solutions such as renewables integration and full retrofit packages, often reported to achieve beyond 70% cost reduction [107] and a favorable payback period equal to approximately 7 years in some contexts [48]. A study showed that the economic justification of BESSs by their current high market price in current economic settings (e.g., feed-in tariffs, discount rate, inflation rate, etc.) can be challenging and extremely context-oriented [91]. Therefore, flexibility assets receive a low relevance score to the economic performance due to high required capital investment and longer payback periods.

As shown in Figure 8b, the grid flexibility and stability performance can range between 6% and 100% with applied technologies, where the flexibility assets (i.e., BESSs and TES) and system replacement both receive a high relevance score for the grid flexibility and stability performance (Figure 8a), which is supported by the fact that a holistic retrofit including the application of BESSs and TES can increase energy saving by 86% [32] and reduce grid fluctuations by approximately 50% [44]. The medium relevance score for renewable integration in grid flexibility and stability performance reflects that while PV integration lowers electricity import from the grid, it requires complementary energy storage systems to provide significant flexibility services [38,43]. On the other hand, renewable integration and flexibility assets both receive a high relevance score for the renewable self-sufficiency performance, which can be justified and validated by studies showing that PV systems coupled with BESSs can achieve nearly 100% self-consumption [38], as highlighted in Figure 8b as well.

Overall, the discussion of Table 4 and Figure 8 provides a clear and practical guide tailored for effective technology selection in a retrofitting framework where BIPV is aimed to be the main driver of achieving climate change mitigation goals aligned with technical efficiencies based on current knowledge represented in the literature. It should be highlighted that the results indicate that integrated technological solutions outperform the

implementation of a single technological scheme; however, the lack of studies that analyze the effectiveness of single technology application (e.g., digital monitoring, sensors, etc.), as well as the insufficiency of studies focusing on social and readiness-related performance goals, remains a visible research gap to be covered in future work. Nevertheless, it must be noted that studies implementing integrated and collective technical solutions that report larger performance improvements are heterogeneous, and the reported results and achieved improvements might be sensitive to climate zones, building types, building services, system boundaries, and evaluation methods, which limit direct comparison. Therefore, this finding must be considered an indication that integrated technological solutions are more frequently associated with higher performance improvement rather than as proof that they universally and definitely outperform any single technology.

5. Conclusions

This review has critically analyzed the strategic implementation of smart building technologies for BIPV-based low-carbon energy retrofitting initiatives to help achieve climate change mitigation goals. By classifying smart technologies according to retrofit depth and categorizing KPIs based on retrofit phases, the research offers a more pragmatic and achievable approach for the decarbonization of existing building stock through the application of smart building strategies.

The analyses revealed three critical patterns in the existing research landscape. First, the distribution of applied smart technologies in the literature is heavily oriented towards physical interventions with renewable integration, flexibility assets, and system replacement, representing 26.3%, 15.5%, and 11.1% of the literature, respectively. Conversely, digital and monitoring and control and building automation and control strategies remain significantly underrepresented, and further statistical analyses in the review (HHI = 0.184 and Gini = 0.3) confirm the moderate concentration in smart building technology research, favoring medium-to-deep retrofitting strategies over shallow or cross-cutting approaches. Such an imbalance suggests that the existing research landscape is physical system-oriented rather than integrating the full potential of digitalized solutions that are crucial to achieve smart retrofitting. Second, the KPI analysis demonstrates a similarly uneven landscape, where KPI categories such as "energy demand and carbon baseline" are the most frequently surveyed criteria (16.5%), while KPIs related to "social and readiness," with only 1.7% coverage, are identified as a critical outlier, highlighting the socio-technical criteria as a substantial gap in the literature. Third, the quantitative analysis of KPI improvement demonstrates that integrated technological package solutions are more frequently associated with higher performance improvement, with the highest CO_2 emission reduction being achieved through the combination of BIPV, heat pumps, and energy storage systems.

Furthermore, this critical analysis offers three distinctive novel contributions by providing (i) a retrofit-depth classification system of applicable smart building technologies, (ii) a phase-based KPI framework to enable practitioners to map and implement the most effective smart technologies for a BIPV-based energy retrofit project, and (iii) a performance-priority decision matrix proposed in this review that provides evidence-based guidance for decision-makers by linking quantifiable performance results to technological measures across four primary performance goals—carbon emission reduction, cost optimization, grid flexibility/stability, and renewable self-sufficiency—synthesizing the best observations from the literature to inform efficient technology adoption.

The findings in this critical review also offer important implications for policy development, such as advancing the existing policy framework to encourage and incentivize integrated solutions rather than single-technology adoption to realize the synergistic benefits of combined and holistic frameworks. Furthermore, the policy framework should

accelerate the incorporation of the social readiness criteria, such as smart readiness indicators, to guarantee that technological upgrades are accompanied by occupant capacity and acceptance. Moreover, the building–grid interaction through energy storage systems and vehicle-to-grid (V2G) connection schemes should be further prioritized, given their positive impact on enhancing renewable self-sufficiency and grid stability. However, the policy recommendations must be read in light of robust and verified evidence; therefore, the policy programs must differentiate between technologies with established evidence and emerging solutions whose environmental and economic performance still requires further validation. Furthermore, this research recommends prioritizing enforceable requirements in the policy framework, including (i) mandatory smart/readiness disclosure (e.g., SRI) in renovation permits and energy performance certificates, (ii) minimum KPI reporting for large or publicly funded projects, (iii) eligibility of integrated technology packages in incentive schemes, and (iv) embodied and whole-life-cycle impact thresholds in building codes. Finally, regulatory frameworks across the world must further accentuate and necessitate the integration of whole-life-cycle assessment (LCA) methods into retrofitting projects to prevent load shifting from operational phases of buildings to embodied environmental impacts.

This critical review uses a solid analytical method to map research advances and gaps in the existing literature; however, limitations should be acknowledged when interpreting the results, including the scope and time frame of the initial search. Although the review followed a structured search methodology, it might have overlooked rapidly growing literature on AI-enabled BEMS, deep reinforcement learning for coordinated building energy management, and advanced digital platforms, including cloud-based systems and digital twins. Therefore, future work should prioritize a dedicated review of these areas in BIPV-driven energy retrofitting, particularly focusing on the role of digital twins in building energy retrofitting. It must be noted that this research's contribution, including the introduced performance-priority decision matrix, is intended to support screening and prioritization in decision-making. Its practical effectiveness has not yet been demonstrated, and should be tested through dedicated case studies and real retrofit projects. Additionally, the review findings on research gaps indicate that future research should prioritize dedicated theoretical and empirical studies on underrepresented smart technologies (e.g., digital monitoring and control systems), socio-technical KPIs, and life-cycle-embodied carbon impacts. Addressing these gaps will lead the research landscape to fully represent the transformative potential of smart retrofitting for an advanced, decarbonized built environment.

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Abbreviations

The following abbreviations are used in this manuscript.

AI	artificial intelligence
AWHP	air–water heat pump
BACSs	building automation and control systems
BESSs	battery energy storage systems

BIPV	building integrated photovoltaics
CCHP	combined cooling, heating, and power
CI	confidence interval
CO_2	carbon dioxide
DERs	distributed energy resources
EMS	energy management system
EU	European Union
EV	electric vehicle
GHG	greenhouse gas
HEMS	home energy management system
HHI	Herfindahl–Hirschman index
HVAC	heating, ventilation, and air-conditioning
IQR	interquartile range
KPI	key performance indicator
LCA	life-cycle assessment
LCC	life-cycle cost
ML	machine learning
NPV	net present value
nZEB	near-zero-energy building
PCM	phase-changing material
PV	photovoltaic
RESs	renewable energy sources
SB	smart building
SG	smart grid
SRI	smart readiness indicator
SR	smart retrofitting
TES	thermal energy storage
V2G	vehicle-to-grid

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