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Status, Challenges and Future Directions in the Evaluation of Net-Zero Energy Building Retrofits: A Bibliometrics-Based Systematic Review

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Abstract: Net-zero energy building (NZEB), an initiative to address energy conservation and emission reduction, has received widespread attention worldwide. This study aims to systematically explore recent challenges in NZEB retrofit research through a mixed-method approach and provide recommendations and future directions. A review of 106 documents (2020–2024) retrieved from the Web of Science and Scopus databases found that the globalization of NZEB retrofit research is unstoppable. Assessment methods are diverse, ranging from modeling energy efficiency (using different software such as DesignBuilder 7.0, PVsyst 7.4, EnergyPlus 24.1.0, etc.) to multi-attribute decision-making methods (e.g., DEMATEL-AHP/ANP-VIKOR) and comparative analysis. Current assessment metrics are dominated by economic benefits (e.g., net present value, dynamic payback period, and total operating cost) and energy consumption (e.g., electricity consumption and generation), with less consideration of environmental impacts (e.g., carbon reduction), as well as comfort (e.g., thermal comfort and indoor comfort). The study found that current challenges mainly include “Low economic feasibility of retrofitting”, “Building retrofit energy code irrationality”, and “Insufficient understanding, communication, and trust between stakeholders”. To overcome these challenges, the study also proposes a framework of strategies to address them, including (1) maximizing natural space, (2) introducing a tenant equity system, (3) upgrading waste management, (4) strengthening energy monitoring, (5) establishing complete life cycle mechanisms, (6) providing systemic solutions; (7) promoting the use of low-carbon building materials, and (8) increasing policy support.

Keywords: systematic review; net zero energy building; Web of Science; Scopus; bibliometric analysis; retrofit challenges; renewable energy; sustainability; applied science

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1. Introduction

A net-zero energy building, also known as a zero-energy building or a zero-carbon building, is a building that has zero or near-zero net energy consumption, i.e., a balance between the amount of energy it produces and the amount of energy it consumes over a year, through the use of advanced energy efficiency measures and renewable energy technologies in its design, construction, and operation [1]. The concept originated in the 1970s because of the energy crisis. Still, it was not until the beginning of the 21st century that “net zero” became an explicit goal in building design and sustainability [2]. It has also been argued that meeting the annual balance alone is insufficient to adequately describe a net-zero energy building and that the interaction between the building and the energy grid needs to be addressed [3]. Decarbonizing the construction sector, which accounts for 40% of global energy consumption and 36% of total greenhouse gas emissions, is critical to mitigate climate change [4]. With increased environmental awareness and technological advances, net-zero energy buildings are being widely promoted and applied worldwide. The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) has set a goal of NZEB marketability by 2030 [5]. As early as September 2016, the China Construction Association (CCA) drafted "Best Practice Cases of Ultra-Low/Near-Zero Energy Buildings in China" under the guidance of the Ministry of Housing and Urban–Rural Development [6]. The revised version of the EU Energy Efficiency in Buildings Directive introduces the concept of "near-zero energy buildings", which is required for all new and existing buildings needing major retrofitting from 2021 onwards [7]. Malaysia plans to have all new public and private buildings (on average) in the zero-energy building category by 2030 [8]. A classic example is the "SURIA 16" strategic partnership project between Universiti Putra Malaysia (UPM) and Tenaga Nasional Berhad (TNB) for installing solar photovoltaic systems [9]. As depicted in Figure 1, through the New Energy Supply Agreement (SARE), GSPARX installed solar systems at 12 locations, including various buildings such as mosques, parking lots, and a floating solar project called SURIA Floating & Walkway @ Eng UPM. This mega project is geared to deliver 16.18 MWp in capacity. It benefits UPM by reducing electricity by RM 114 million over 25 years, with an installation cost of RM 45 million funded by TNB [10]. It can also reduce CO_2 emission by 15,655 metric tons per year, equivalent to minimizing the greenhouse gas emission from 3187 vehicles per year or carbon absorption by 242,320 tree seedlings planted over ten years [11].

Figure 1. "SURIA 16" project.

As the subject has caught fire and research has increased, some scholars have begun to conduct literature reviews on it. Most of the reviews were limited to conceptual clarification and policy analysis [2]. For example, the Australian study by Louise et al. argues that the NZEB concept may apply to new and existing buildings to have a tangible impact on overarching issues such as greenhouse gas emissions, sustainability, and consumer protection from electricity price increases [12]. Satola et al. reviewed the policy frameworks for net-zero buildings in Norway, the United Kingdom, the United States, and Singapore. They found an urgent need for harmonized and transparent international and national standards to ensure consistency in the life cycle assessment of buildings [13]. Christopher et al.'s study, on the other hand, conducted a literature review from the perspective of renewable energy technologies (RETs) and found that most RETs are usually unstable and intermittent, fluctuating widely over hours or days [14]. Brown et al.'s literature review, on the other hand, found that in addition to government policy factors, a lack of knowledge, climate issues, and cost issues were identified as the main barriers encountered by the Australian NZEB industry [15]. The review by Li et al. discusses strategies for applying net-zero energy (NZE) building technologies (i.e., achieving net-zero non-renewable energy consumption on-site) to poultry houses, arguing that any modifications to existing technologies should be based on a careful consideration of the physiological needs of poultry (e.g., ambient temperatures, air quality, availability of feed and water, etc.) [16]. Falana's review categorized the impediments solely due to crucial stakeholder engagement and the relationship with a complete life cycle of net-zero carbon building development [17]. Noh et al.'s study, also from a renewable energy perspective, found that the evaluation of NZEB practices should include an assessment of the building's energy balance, occupant comfort, and interaction with the energy grid [18]. The application of Building Integrated Photovoltaics (BIPV) in NZEB has also received attention, with studies finding that the building envelope size, height, glazing material, light transmission, etc., have significant impacts on meeting NZEB standards and that it is important not to focus solely on roof-integrated PV [19]. A multi-case review in China identified significant advantages and room for incremental development in promoting BIPV in China [20]. Unfortunately, there are currently no studies that have focused the review theme on a retrofit evaluation. This study aims to fill this gap by combining bibliometrics with a systematic review to provide a comprehensive picture of the status, challenges, and future directions in NZEB retrofit and evaluation.

The rest of the paper unfolds as follows: Section 2 provides detailed information on the methodology of this study; Section 3 presents the results of this study; Section 4 discusses the current challenges encountered in NEZB retrofitting and strategies to deal with them; and Section 5 summarizes the research and points out limitations.

2. Materials and Methods

PRISMA, known as Preferred Reporting Items for Systematic Reviews and Meta-Analyses, is a set of standardized specifications for the quality of research in systematic reviews [21]. It applies to published literature reviews containing primary data sources [22]. This study builds on the guidelines provided by the PRISMA on transparency and the quality of systematic review reporting [23]. It aims to improve systematic reviews' scientific validity and comparability [24,25]. Referring to previous classical studies, Figure 2 illustrates the steps of conducting a systematic literature review using the PRISMA protocol and quantitative analysis through bibliometric analysis to achieve the research objectives [14,26].

The Scopus and Web of Science databases were selected as the most extensive proprietary databases for searching the extant literature. They are particularly well suited for searching the literature based on architecture and building disciplines [27]. This combination of databases has been used to explore "Zero Energy Building Technology Options and Strategies for Climate Change Mitigation", "Life Cycle Energy Analysis of Buildings", and "Dynamic Facades in Buildings". It has shown an excellent fit [28–30]. Combining these two databases results in a more complete search of the available scientific literature. The selection with energy efficiency goals was based on the most recent research on net-zero energy buildings to ensure the use of established terminology. In reference to previous studies [31,32], search terms included (1) emission reduction targets, (2) energy as a metric, (3) diverse project sizes and types, and (4) types of upgrades, as shown in Table 1.

Table 1. Search terms applied in Scopus and Web of Science.

Abatement Goal	Unit	Scale and Typology	Upgrading Type
Nearly zero Net zero Zero Low	Energy	Dwelling House Building Office	Retrofitting Refurbishment Modernization Renovation

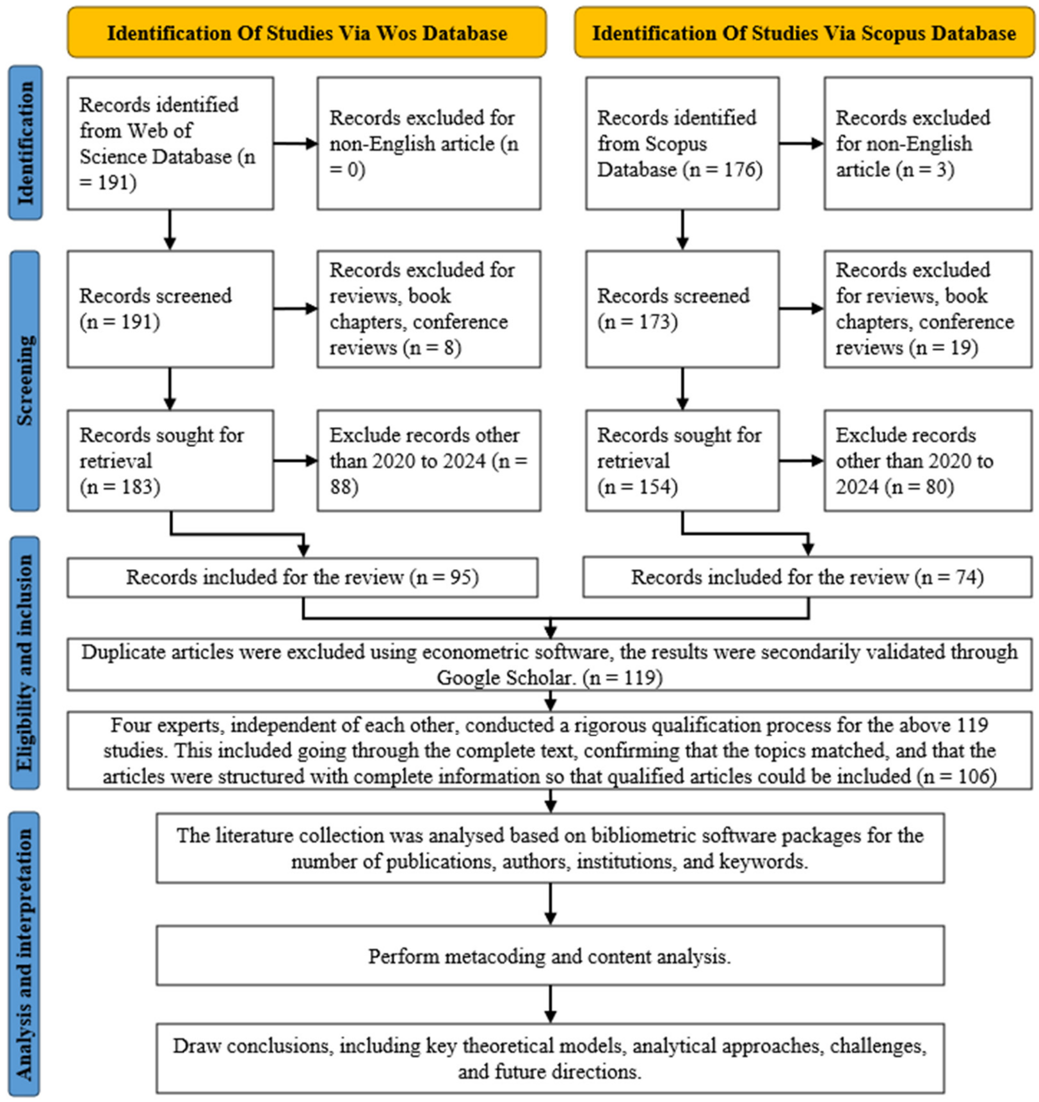

Figure 2. Research process.

As indicated in Table 2, the established search terms were combined into a single search query for each database using its specific search syntax, which also allowed Boolean and proximity operators. Document titles, abstracts, and keywords were searched in Scopus, while titles, abstracts, and author keywords were searched in Web of Science. Both databases consider British and American spelling variations. Concerning previous research [33,34] in the field and to ensure that the research is cutting edge and that the information required for the content analysis is complete, the eligibility criteria for literature inclusion were as follows: (1) publication year—between 2020 and 2024; (2) language—English; (3) type of article—research article; (4) topic—retrofitting of existing buildings; and (5) study content—a clear description of the location of the study, methodology, evaluation metrics, and limitations.

Table 2. Retrieve code applied in Scopus and Web of Science.

Databases	Retrieve Code
Scopus	TITLE-ABS-KEY ((“low” OR “nearly zero” OR “net zero” OR “zero”) PRE/2 (energy) AND (“dwelling” OR “house” OR “building” OR “office”) AND (“retrofitting” OR “refurbishment” OR “modernization” OR “renovation”) AND (“evaluation”))
Web of Science	TS = (((low OR “nearly zero” OR “net zero” OR zero) NEAR/2 (energy)) AND (dwelling OR house OR building OR office) AND (retrofitting OR refurbishment OR modernization OR renovation) AND (evaluation))

The search was conducted on 1 July 2024 and found 74 documents in Scopus and 95 in Web of Science. RStudio 3.6's Bibliometrix® package was used to remove 50 papers (as they were either duplicates or inaccessible), leaving 119 documents. The results were secondarily validated using Google Scholar. In the end, the 119 papers were qualified by four independent experts who browsed through the full texts. The 106 documents remaining after screening were analyzed and reviewed in two steps. The first step was to examine their metadata using Biblioshiny® to select bibliometric charts representing the annual scientific output, thematic evolution, most represented countries, and keywords. This analysis used the bibliometric metadata fields included in the search results, such as the title, keywords, authors and country of publication, and year of publication. The purpose of a bibliometric study is to provide an overview of the field of study. The second step of the literature review (36 strongly related articles) was to manually analyze the full text of the publications. These 36 studies are the result of a comprehensive selection based on four main principles: (1) fresher articles (date of publication), (2) highly cited articles, (3) high-impact factor articles, and (4) accessibility. The following themes were extracted for this review: (1) research location, (2) evaluation methods, (3) evaluation indicators, and (4) research limitations.

3. Results

3.1. Results of the Bibliometric Analysis

3.1.1. Annual Issuance of Significant Publications

Figure 3 shows the articles published in major journals on the topics reviewed in this study between 2020 and 2024. The journals include *Energies*, *Energy and Buildings*, *Applied Energy*, *Sustainability*, *Building Simulation*, *Buildings*, and *Journal of Cleaner Production*. Overall, the number of articles published increased year by year over this period, with the journal *Energy and Buildings* publishing the most significant number of articles in 2022 and the following years, remaining at around 8 articles, while the number of articles published in the journal *Energies* gradually increased from 0 in 2020 to 9 in 2024, showing a significant growth trend. Other journals such as *Applied Energy*, *Sustainability*, *Building Simulation*, and *Buildings* also show a year-on-year increase. This indicates that this topic is receiving more and more attention from scholars and reflects the significance of this study.

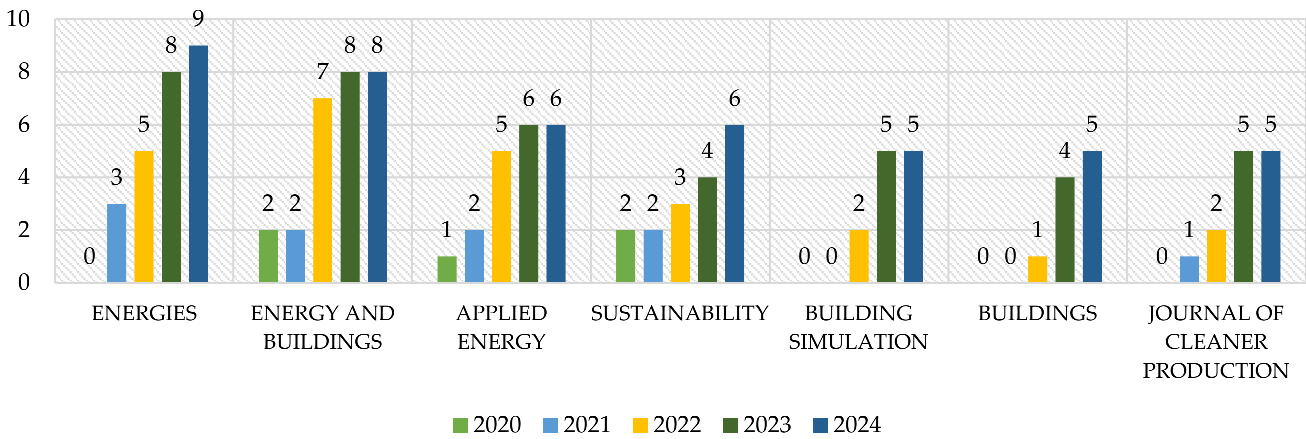

Figure 3. Annual issuance of significant publications.

3.1.2. Top Ten Highly Cited Articles

In academia, the number of citations is regarded as one of the indicators of research quality and impact [35]. Table 3 summarizes the top ten highly cited articles on this theme. The highly cited literature usually contains essential theories, methods, or findings [36]. Identifying this literature helps to disseminate this knowledge to the broader academic community, thereby influencing more researchers and practitioners. Second, it reflects current hotspots and trends in the research field. By analyzing this literature, researchers can understand which issues are receiving widespread attention and where research is heading in the future. It is worth noting that the top ten highly cited articles in the literature are from 2020 to 2022, which means that more influential articles have not appeared in the last two years and expresses the urgent need to find breakthroughs under the topic.

Table 3. The top 10 highly cited articles.

Paper	DOI	Total Citations	TC per Year	Normalized TC
Zhao et al. (2021) [37]	10.1155/2021/6638897	39	9.75	2.82
Hong et al. (2021) [38]	10.1007/s12273-021-0778-7	39	9.75	2.82
Opher et al. (2021) [39]	10.1016/j.jclepro.2020.123819	38	9.50	2.75
Figueroa-Lopez et al. (2021) [40]	10.1016/j.jobe.2021.102607	35	8.75	2.53
Hong et al. (2020) [41]	10.1016/j.enbuild.2020.109959	30	6.00	2.00
Rabani et al. (2021) [42]	10.1016/j.buildenv.2021.108159	29	7.25	2.10
Albatayneh et al. (2021) [43]	10.3390/en14102946	23	5.75	1.66
Mitchell et al. (2020) [44]	10.1016/j.enbuild.2020.110240	22	4.40	1.47
Colclough et al. (2022) [45]	10.1016/j.enbuild.2021.111563	21	7.00	2.57
Apostolopoulos et al. (2022) [46]	10.1016/j.scs.2022.103921	20	6.67	2.45

3.1.3. Keyword Co-Occurrence Network

A keyword co-occurrence bibliometric analysis is a method of analysis that examines the phenomenon of co-occurrence between feature items in the literature [47]. The strength of the association between keywords is measured by counting the co-occurrences between them, thus revealing the association of information in the literature [48]. In this study, a network diagram was generated using Bibliometrix® to provide insights into the data selected for the eligibility phase of the PRISMA protocol and to show the crucial keywords in the data. The Walktrap algorithm was chosen for this study as a method for community discovery based on the idea of random wandering. Its key idea is to use random walks on the graph to determine the distance metric between vertices and between communities. It is considered to surpass previous methods in terms of the quality of community structure and is one of the best methods in terms of runtime [49]. The steps of the Walktrap algorithm are as follows [50]: First, the similarity between vertices is computed by random wandering. Then, hierarchical clustering is performed using these similarities to merge neighboring communities. Finally, the division with the largest modularity is selected as the best community structure.

Regarding similarity computation, the Walktrap algorithm uses a random wandering probability matrix to compute node similarity. The similarity between nodes i and j is calculated by Euclidean distance as follows:

$$r_{ij} = \| D^{-1}P_i^t - D^{-1}P_j^t \| \quad (1)$$

where D is the degree diagonal matrix of the node and P_i^t is the probability of going from vertex i to vertex j in the tth step.

Referring to previous studies, in this study, the number of nodes was set to 50, the minimum number of edges was set to 2, and the rest were default parameters. As depicted in Figure 4, differences in the brightness and transparency of the keyword colors shown in the visualization indicate keyword interconnections. At the same time, the nodes' sizes highlight the keywords' prominence in the literature. The larger the node of the item, the higher the weight in the network [51]. The distance between the circles also represents the relevance between the keywords, emphasizing co-occurring links [52]. Thus, if two keywords are located close, their link is more robust. Since "performance", "optimization", "design", and "consumption" have the most prominent circles on the network diagram, they have the highest weight in the literature. This also indicates that these keywords are hot research topics within the evaluation field. "Residential buildings" is also a recurring keyword, suggesting that most of the evaluations on retrofitting are related to residential buildings on a global scale. Another noteworthy point from the network diagram is the range of keywords related to potential solutions for evaluation. Keywords such as "education", "decision-making", "sensitivity analysis", "multi-objective", "life cycle assessment", and "cost" all have significant weights. They are interlinked with the evaluation clusters, suggesting that these elements are frequently discussed.

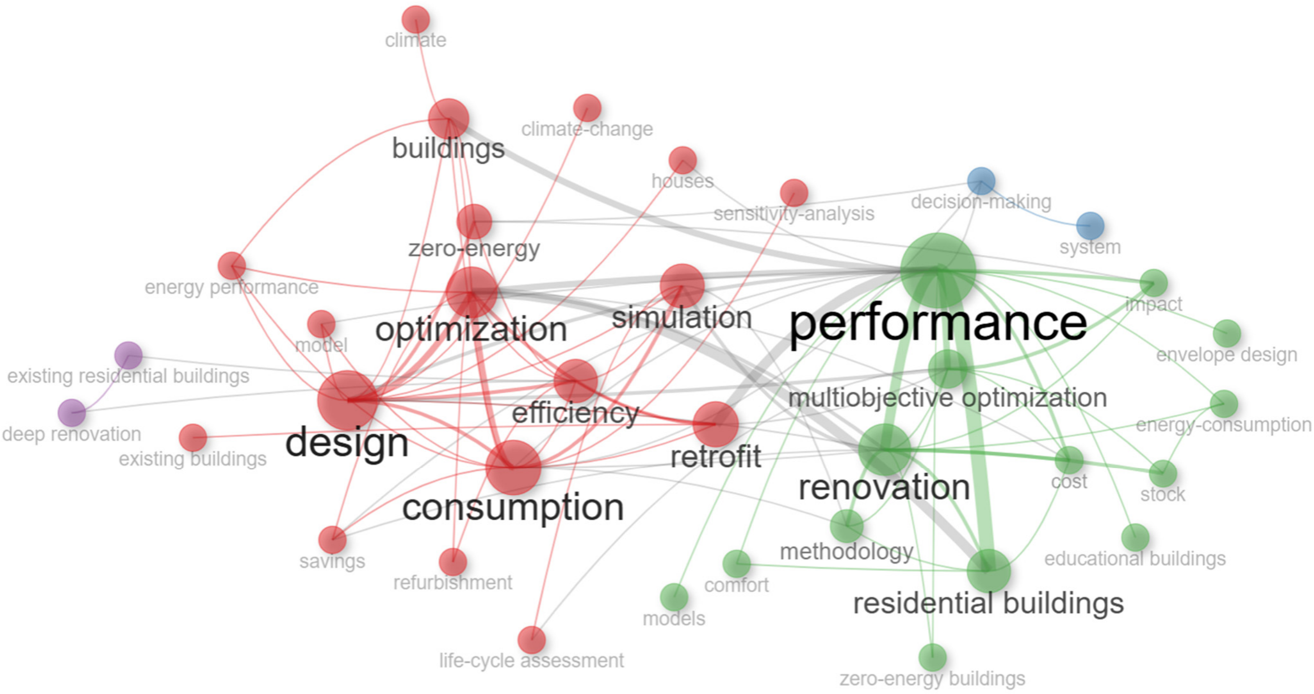

Figure 4. Keyword co-occurring network.

3.2. Results of the Content Analysis

Table 4 compiles various methodologies used to evaluate the retrofit of Nearly Zero Energy Buildings (NZEBs) across different regions. Each entry in the table details each study's source, location, method, evaluation indicators, and limitations. The current research covers several world regions, including Turkey, China, Poland, Sweden, UAE, USA, Japan, MENA, Europe, South Korea, Pakistan, Italy, Lithuania, and Portugal, demonstrating the globalization of NZEB retrofit studies. Evaluation methods are also diverse, ranging from modeling energy efficiency analysis (using different software such as DesignBuilder, PVsyst, EnergyPlus, etc.) to multi-attribute decision-making methods (e.g., DEMATEL-AHP/ANP-VIKOR) and case studies. Scholars have tried to assess the effectiveness of NZEB retrofit from multiple perspectives using different strategies. The assessment indicators cover economic benefits (e.g., net present value, dynamic payback period, and total operating cost), energy consumption (e.g., electricity consumption and generation), environmental impacts (e.g., carbon reduction), and comfort (e.g., thermal comfort and indoor comfort). The diversity of indicators also represents that there is currently no industry consensus or standard paradigm for evaluation systems. Many studies have specific limitations, such as only considering cost effectiveness, only applying to PV retrofit projects, only targeting cold regions, small sample sizes, and not considering the building life cycle. In addition, most of the studies were conducted for specific application scenarios, such as hospital buildings, multi-story wood-frame buildings, brick-frame dwellings, and wall-mounted PV systems, which led to different evaluation methods and indicators for various application scenarios.

Table 4. NZEB retrofit evaluation methodology.

Source	Location	Method	Evaluation Indicators	Limitations
[53]	Turkey	Modeling energy performance (DesignBuilder)	Payback period (NPV)	Only cost effectiveness was considered.
[54]	China	Modeling energy performance (PVsyst 7.2)	Dynamic payback period (NPV)	Only for photovoltaic retrofit projects
[55]	China	Modeling energy performance (Dest-C)	Net present value (NPV) ratio	Only for cold regions
[56]	China	Modelling energy performance (EnergyPlus)	Economic and carbon reduction benefits	Only for a colored radiant cooling wall retrofit
[57]	China	Logic-AHP-TOPSIS method	Upfront investment, payback period, heating cost savings	Only available in Lanzhou, China.
[58]	Poland	DEMATEL-AHP/ANP-VIKOR method, modelling energy performance (ArCADia-TERMOCAD)	Total operating costs, compliance with air quality parameters, the impacts of the building and its facilities on the surrounding environment, total building completion time, etc.	The choice of decision criteria needs to be tailored to the specifics of the decision maker's preferences.
[59]	Sweden	Modeling energy performance (Grasshopper/Rhinoceros 3D/EnergyPlus)	Thermal performance of buildings	Small sample size
[60]	United Arab Emirates	Case study	Reduction in cooling load	Only for energy-saving retrofits with high solar reflectance index (SRI) coatings
[61]	China, USA, Europe	Multiple case studies	Benefits, costs, heat sources, and technology	Small sample size
[62]	Japan	Modeling energy performance (BEST)	Heat, power generation	The impact of the amount of hot water obtained from the HFCs on reducing the building's energy consumption cannot yet be determined.
[63]	Middle East and North Africa (MENA) region	Modelling energy performance	Orientation, window location and size, glazing type, wall and roof insulation levels, lighting fixtures, appliances, and the efficiency of heating and cooling systems	Building envelope insulation needs to vary by climate.
[64]	European	Comparative analysis (actual data)	Energy, the function of the house, and its internal comfort	The local competition and the described concept of post-competition use influenced the energy efficiency assessment.
[65]	China	Parameter reverse identification and load forward calculation	Internal heat gain	Only for integrated building envelopes
[66]	United State	Comparative analysis (actual data)	Electricity consumption and generation	Historical average data, such as weather conditions, usually do not match actual operating conditions.
[67]	Singapore	Modeling energy performance (RNSYS 17)	Energy savings and annual cost (NPV)	The setting of economic parameters has a considerable impact.

Table 4. *Cont.*

Source	Location	Method	Evaluation Indicators	Limitations
[68]	China	Modeling energy performance (TRNSYS)	Building energy use and renewable energy generations, economic cost, load matching, and grid interaction	A simplified battery model did not consider the battery's energy loss during charging, storage, and discharging.
[69]	United State	Modeling energy performance (ASHRAE Inverse Modeling Toolkit (IMT))	Measured data on building energy consumption and photovoltaic power output	The effects of the building orientation, envelope improvements, and HVAC system upgrades using calibrated simulation models were not considered.
[70]	Iraq	Modeling energy performance (TRNSYS/TRNBuild)	Energy consumption rate and cost	Failure to consider the impact of passive structures
[71]	European	Modelling energy performance (SketchUp/Open Studio/EnergyPlus)	Electricity and primary energy consumption	The ability to use energy building modeling to describe the hourly heat demand of a building is not possible.
[72]	European	Differential sensitivity analysis (DSA), elementary effects method	Interest rates, building and equipment maintenance costs, structural element costs, and electricity prices	Small sample size
[73]	South Korea	Comparative analysis (actual data)	Operational energy consumption and total environmental costs	Energy measurement masks the complexity of building energy flows and ignores the large-scale thermodynamics (economic, cultural, informational, etc.) surrounding the building.
[74]	Pakistan	Modelling energy performance (HOMER Pro)	Solar radiation potential, operating costs, initial capital costs, energy generated by PV, payback period, and NPV costs	Only for hospital buildings
[75]	Italy	Modeling energy performance (FATA-e®)	Electricity demand (sum of HVAC, hot water, and artificial lighting), PV generation, electricity absorbed from the grid, and PV surplus exported to the grid	Only for multi-story timber buildings
[76]	China	Sensitivity analysis	Building geometry, building envelope thermal performance, equipment energy efficiency, and internal heat sources	The range of applications is limited by geography and building type.
[77]	China	Modeling energy performance (TRNSYS/RETScreen)	Tilt angle, orientation, volumetric ratio, PV conversion efficiency, location, and power generation	The difference between the simulated and calculated results is about 10%.
[78]	South Korea	Modeling energy performance (TRNSYS)	Passive element S/V ratio (surface-to-volume ratio) for the building type, building orientation, final energy consumption, and investment costs for active elements (building-integrated PV)	Failure to consider the life cycle of a net-zero energy building

Table 4. *Cont.*

Source	Location	Method	Evaluation Indicators	Limitations
[79]	Italy	Preferred method of sorting organization	Energy consumption, life cycle costs, carbon emissions, property values, and indoor comfort standards	Assumed spatial changes in appreciation of NZEB buildings in the property market
[80]	Lithuanian	Multi-Attribute Decision Making Methods for Optimal Solutions (MADM-opt)	Heat exchange, relative air humidity, air temperature, air flow rate, surface area-to-volume ratio, noise insulation, and annual heat demand	For brick dwellings only
[81]	Lithuanian	Primary energy consumption formula	Average power generation, wind speed, wind turbine capacity, conversion efficiency, and turbine power consumption	For wind turbines only
[82]	China	Modelling energy performance (EnergyPlus)	Baseline cooling demand, typical incident solar radiation, direct solar transmittance, and percentage of solar energy savings from exterior shading blinds	The external shading devices were not quantified only for external louver sunshade shading performance and geometric (e.g., slat width and shape) and physical (e.g., front and rear side slat solar reflectance) parameters.
[83]	Portugal	Primary energy consumption formula	Renewable energy ratio (RER) and onsite energy fraction (OEF)	Options for exporting energy carriers (e.g., electricity) are always better than options for self-consumption energy generated on-site.
[84]	Italy	Modeling energy performance (HOMER Pro\PV Sol)	User well-being, energy and greenhouse gas savings, and cost optimization	Only for photovoltaic power plant projects
[85]	Japan	Comparative analysis (actual data)	Spectral variation, solar radiation, electricity generation	For wall-mounted PV systems only
[86]	Italy	Comparative analysis (actual data)	Building load, photovoltaic power generation, indoor comfort	Only for typical Mediterranean climates
[87]	Belgium	Comparative analysis (actual data)	Thermal comfort and energy parameters	No post-occupancy qualitative assessment was considered regarding thermal comfort.
[88]	China	Energy efficiency assessment method based on time-series current simulations	Proportion of energy storage capacity, annual electricity use, yearly electricity consumption, energy efficiency, and stakeholder income	System costs do not include the cost of losses from poor power quality.

4. Discussion

4.1. Challenges of NZEB Retrofit

Table 5 details the technical, economic, social, and policy challenges in assessing NZEB retrofits. First, there are the technical challenges. For example, most cities need higher coverage and more data related to older buildings. However, collecting and analyzing building energy efficiency data on a large scale are complex and time-consuming and require multiple resources [89]. Factors such as the structural load-bearing capacity or layout of older buildings also limit integration with many large installations. Indeed, current modeling methods cannot capture all the geometric features in the category represented by the prototype [90]. There is also a lack of real-time optimization models for carbon reduction at the building design stage, limiting our ability to accurately estimate and optimize carbon emissions. Digital and intelligent technologies are crucial for zero-energy building retrofits, while data privacy and systems integration are also topics worthy of in-depth research. The next challenge is economic. For example, net-zero energy retrofits typically require significant capital investment in technology upgrades, engineering and construction, and materials procurement [91]. This can be burdensome for many homeowners, especially if returns are difficult to obtain in the short term. For example, in China, most energy efficiency retrofits are generated by policy guidance and government subsidy incentives [92]. However, owners' enthusiasm for energy efficiency retrofits inevitably fades as incentives end or are scaled back. The third is the social challenge, where mutual understanding is too romantic for citizens or potential partners (e.g., developers, distributors, engineers, and space planners) who are less familiar with modern approaches in the energy sector [93]. The fourth is the policy challenge. For example, building codes and guidelines vary widely across climatic regions and countries, as do the amounts of incentives [94].

Table 5. Challenges of NZEB retrofit.

Categorization	ID	Challenge	Validation Reference
Technology	T1	Mechanisms of solar cell aesthetics and carrier transport layers and interfaces	[95]
	T2	Air source heat pumps are prone to failure in cold climates.	[96]
	T3	Failure to consider operational and occupant behavioral changes	[97]
	T4	PV systems are prone to module ruptures, inverter failures, performance degradation, and other failures.	[98]
	T5	High initial construction costs	[99]
	T6	Energy simulation does not provide the best results because many potential system configurations are untested.	[100]
	T7	Failure to consider the aging of the power generation system	[101]
	T8	Implicit carbon in the life cycle of a building is not considered.	[102]
	T9	Insufficient use of new technologies, such as digital twins and artificial intelligence algorithms	[103]
	T10	Modeling methods cannot capture all the geometric features in the category represented by the prototype.	[104]
Economics	E1	The payback period is about 10 years.	[105]
	E2	Dynamic electricity and oil prices hinder the accuracy of cost measurements.	[106]
	E3	Financing mechanisms and incentives	[107]
	E4	Uncertainty in energy supply markets makes people pessimistic and reluctant to make decisions.	[108]
	E5	Life Cycle Cost Analysis (LCCA) indicators are not comprehensive.	[109]
	E6	Using energy storage systems (electrical and thermal) increases losses, increasing the energy demand and electricity bills.	[110]
	E7	Lack of standardized value assessments for sustainable buildings	[111]
Society	S1	Most communities have not yet published up-to-date measurements of NZEB's success, and no data on its energy performance exist.	[112]
	S2	Limited information on climate change data	[113]
	S3	Insufficient understanding, communication, and trust between stakeholders	[114]
	S4	The currently applied NZEB retrofit technologies are dominated by solar photovoltaics, with a small share of other energy sources such as wind, biomass, and micro-hydro.	[115]
	S5	Lack of platforms to integrate data, including city castle maps, building information, building models and projects, and energy networks	[116]
	S6	Public awareness of NZEB remains low.	[117]
	S7	The immaturity of innovative city systems, smart grids, smart meters, and local energy trading platforms	[118]
	S8	The complex impact of urban density on costs	[119]
	S9	Lack of NZEB building professionals such as owners, facility managers, building design engineers, and builders	[120]
	S10	Conflict of interest with traditional electricity suppliers	[121]
	S11	Regional differences in types of renewable energy	[122]
	S12	Instability and variations in regional climate and local weather conditions	[123]
	S13	Fewer members of the public, businesses, or NGOs are involved and on board in realizing zero-energy buildings.	[124]
Policy	P1	Localization of standards and requirements, such as source and supply requirements, timescales, emission sources, and grid connections	[125]
	P2	Decarbonization strategies and mechanisms are not in place in lagging countries.	[126]
	P3	The region does not have a policy for excess electricity to be recovered by the national grid.	[127]
	P4	Incentive policies such as subsidies and tax breaks are not provided.	[128]
	P5	Lack of consensus on the definition and calculation of NZEB	[129]
	P6	Delays in the NZEB approval process	[130]

Note: The above challenges are derived from [53–88] and are secondarily validated by the validation references.

4.2. Strategies for Promoting Net-Zero Energy Building Retrofits

This study develops eight strategies to promote retrofitting older buildings with zero-carbon emissions to address these challenges, as illustrated in Figure 5. Not only does it contribute to urban regeneration to combat climate change and improve energy efficiency but it also promotes technological innovation, improves indoor environmental quality, and creates employment opportunities, which are vital for sustainable development.

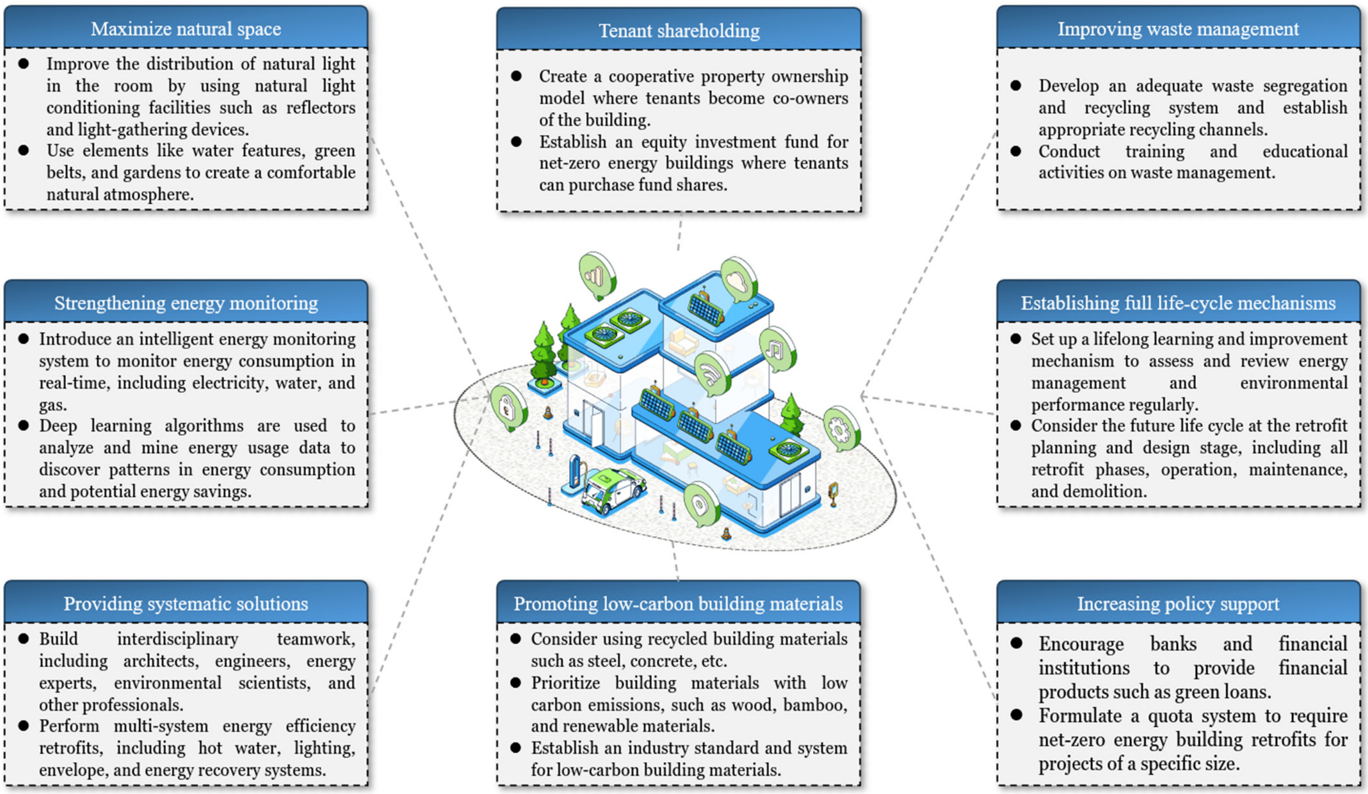

Figure 5. Strategies for promoting net-zero energy building retrofits.

4.2.1. Maximizing Natural Space

Maximizing natural space in net-zero energy building retrofits contributes to the environmental quality and comfort of the building. There are various ways to maximize natural space in a net-zero energy building retrofit. The first is redesigning the building layout to maximize natural light and ventilation. For example, by installing insulation on the interior or renovating or installing new windows, the theoretical energy consumption could still be reduced by 68% compared to the original building [131]. Second, green space should be added around or inside the building, such as gardens, lawns, and plant walls. This can provide more natural landscaping and recreational space. It is also good to introduce natural elements into the design, such as water features, green walls, and waterfalls, which can enhance the natural feel of the space [132]. We also suggest transforming older buildings with more outdoor spaces, such as terraces, balconies, and courtyards, and considering the balance of ecosystems, such as birds, insects, and plants, which can be protected and promoted through rational design. It is worth noting that the building orientation, energy-efficient windows, and vegetation types require retrofit strategies tailored to local climatic and environmental conditions, such as tropical and humid climates [133].

4.2.2. Introducing a Tenant Equity System

Introducing a tenant equity system can enhance tenant participation and responsibility in net-zero-energy building retrofit projects, thereby contributing to the sustainable development and long-term operation of buildings. It is a collection of innovative approaches designed to incentivize tenants to participate more actively. The first model establishes co-operative property ownership, where tenants become co-owners of the building. They can purchase an equity stake in the building, participate in decision-making and management as owners, and monitor the building's energy use and environmental performance [134]. The second model is a rent discount or incentive program. For example, tenants who adopt energy-saving measures or participate in environmental protection activities are given a certain percentage of rent discounts, or environmental bonuses are offered as incentives [135]. The third model is to establish an equity investment fund for net-zero energy buildings. Tenants can buy a share of the fund as one of the investors in the retrofit project and share in the benefits of the building. We also recommend linking tenant equity to voting and decision-making rights, allowing tenants to participate in decision-making on important matters, such as energy management and facility maintenance. At the same time, to ensure that tenants have complete transparency on the operations and financial status of the retrofit project, the construction company should provide relevant information and reports. In addition, this study recommends enhancing tenants' access to low-cost or free retrofit options, coupled with tenant protection mechanisms, and proactively exploring mechanisms that enable landlords to recoup the cost of retrofits while ensuring that tenants benefit from energy savings to address the issue of decentralized incentives between landlords and tenants [136].

4.2.3. Upgrading Waste Management

The importance of upgrading waste management in net-zero energy building retrofits cannot be overstated, as it reduces the negative impact of waste on the environment and maximizes the use of waste resources. First, an effective waste classification and recycling system should be established to categorize waste into different categories, such as recyclable, organic, and hazardous, and to develop corresponding recycling channels. In the case of Thailand, Malaysia, and Indonesia, for example, it must be considered that the occupants can decide to set lower values to balance the outdoor overheating so that the management strategy can be chosen according to their preferences [137]. Tenants should be actively encouraged and guided to segregate waste and promote waste resource utilization. Secondly, measures should also be taken during the remodeling construction phase to reduce the generation of construction waste. For example, the range of baseline conditions and constraints imposed by heritage values in historic buildings is a crucial factor strictly intertwined with the energy (and carbon) saving potential of the measures investigated [138]. Finally, the concept of the circular economy is advocated to focus on reusing and recycling waste resources in building renovation. For example, it can be used to reprocess waste materials for building materials or compost organic waste for landscaping. This includes developing building materials from agricultural and non-agricultural wastes [139].

4.2.4. Strengthening Energy Monitoring

Most studies do not consider real-time energy-related information [140]. Strengthening energy monitoring aims to enhance energy monitoring in NZEB retrofits to achieve comprehensive monitoring and management of energy use, thereby improving buildings' energy efficiency and sustainability. First, advanced intelligent energy monitoring systems are introduced to monitor building energy consumption in real time using energy sources such as electricity, water, and gas [18]. These systems can provide real-time data and reports to help managers promptly identify energy wastage and anomalies. For instance, by leveraging advanced digital twin solutions such as DanRETwin, building owners, facility managers, consultants, and urban planners can benefit from improved energy efficiency, enhanced comfort, systematic recommissioning, data-driven decision-making, and scalable tools for evaluating retrofit options [141]. Second, each region should establish clear energy consumption targets and goals. For example, indicators such as the energy consumption intensity and energy utilization rate should be established based on the building type and size to better measure the energy performance of buildings. On the other hand, energy efficiency analyses by Park et al. [142] show that combining photovoltaic panels, high-efficiency HVAC systems, airtight film, and LED light technology is efficient. Third, deep learning algorithms analyze energy usage data to discover energy consumption patterns and potential energy savings and identify the causes of energy waste. It has been shown that combining DL algorithms with building information modelling (BIM) technology and Internet of Things (IoT) systems enables a wide range of monitoring and sensing mechanisms within a building complex, facilitating real-time energy consumption management and indoor climate sustainability [143]. Finally, regular energy reviews and assessments are conducted to inspect and commission the building's energy systems and equipment to ensure proper operation and efficient utilization. Establishing a specialized energy management team, including energy experts, engineers, and technicians, is also necessary.

4.2.5. Establishing Complete Life Cycle Mechanisms

Net-zero energy building retrofits require an integrated consideration of all life cycle stages, from material selection to energy use and waste disposal, to achieve carbon neutrality and net-zero energy goals [144]. Multi-objective optimization models for a lifecycle cost analysis and retrofit planning can enhance decision-making by considering factors such as production, economy, and sustainability [145]. Integrating building information modeling (BIM) technology can simplify the retrofit process by providing solutions for quality control, energy analysis, costs, and life cycle assessments. First, during the design phase of the retrofit scheme, the CO_2 emission characteristics of different materials should be understood to optimize the amount of building materials used. Choosing to use local materials reduces carbon emissions during the transportation of materials. Prefabricated assembly buildings are used to improve construction efficiency and reduce raw material and energy consumption. Second, reducing energy demand and avoiding installing traditional HVAC systems are prioritized through passive designs such as internal and external sun shading, natural ventilation, and natural lighting during construction. Third, in the operation phase, energy-saving lamps and lanterns should be used to improve energy efficiency, and renewable energy sources such as solar, wind, and geothermal energy should be used to replace fossil energy sources. Energy consumption is also reduced through the automatic regulation of equipment systems. Finally, waste doors, windows, steel structures, etc., should be actively recycled and reused during the demolition and clean-up. Furthermore, Loveday et al. [146] argue that an entire life cycle mechanism should consider material and energy flows and social impacts, such as well-being and equity.

4.2.6. Providing Systemic Solutions

Creating a systematic solution is crucial. First, an in-depth understanding of energy consumption is needed. A plan to create an all-electric facility is developed to identify energy needs and plan for on-site or on-grid renewable energy to meet those needs, including electricity use, heat demand, seismic defenses, etc. Fichera et al. [147] investigated an innovative technology that simultaneously considers seismic, energy, and building retrofit in framed buildings, i.e., combining the seismic performance provided by steel trusses and the thermal performance of man-made panels, both of which are applied to the building envelope. Then, an energy consumption standard is developed for the space, the amount of electricity the space will generate every week is calculated, and a clear energy budget for achieving a net-zero energy building is created. Finally, energy systems are optimized. Efficient energy systems, such as high-efficiency split air conditioners, LED lighting, etc., are selected and an intelligent building energy management system (BEMS) is used to monitor and optimize energy use, including energy supply, energy use, energy storage, and energy scheduling. Typical designs according to different retrofit measures are also important because the solar water heater's length and the working fluid's flow rate impact the working fluid's outlet temperature and the solar water heater's overall performance. They are considered the king of cost effectiveness, while biomass boilers offer the lowest cost savings at around 53%. One study found that photovoltaic panels (24,000 kWh/year) produced more energy than wind turbines (20,000 kWh/year) in renewable energy technologies [148]. We also emphasize a tailor-made approach for specific types. For example, university buildings seem closer to office buildings regarding their typological characteristics and usage patterns than primary and secondary school buildings [149].

4.2.7. Promoting the Use of Low-Carbon Building Materials

Promoting low-carbon building materials is one of the critical steps towards achieving the zero-carbon goal. First, one should look for building materials with environmental certifications, such as LEED, BREEAM, and other certification standards. These certifications ensure that the materials meet sustainability and environmental requirements. Second, the use of recycled building materials, such as steel and concrete, should be prioritized, which helps reduce the production of new materials and carbon emissions. Using bio-based materials in refurbishment is also a key strategy because of their low global warming potential, cost-effectiveness, and recycling potential [150]. A carbon footprint assessment should be conducted during material selection to understand different materials' life cycle carbon emissions. Third, awareness of low-carbon building materials should be raised among construction practitioners and the public. This includes organizing seminars and training courses to share the latest information on low-carbon building materials or using media and social media platforms to publicize the advantages and feasibility of low-carbon building materials. Finally, we have also established an industry chain cooperation mechanism for low-carbon building materials to promote the synergistic development of the upstream and downstream of the industry chain. The cooperation among material suppliers, architects, construction units, etc., should be strengthened to jointly promote the R&D, production, and application of low-carbon building materials.

4.2.8. Increasing Policy Support

China, the United States, and Malaysia have all adopted policy measures to promote NEZB building retrofits. The Chinese government has set targets for carbon peaking (by 2030) and carbon neutrality (by 2060). In addition, China has promoted green building certification standards, such as three-star, gold, and diamond green building standards, to encourage low-carbon, efficient building design and construction [151]. State and federal governments in the United States have adopted various policies to promote NZEB retrofits. For example, the federal infrastructure bill includes measures such as clean energy transmission grants. It has also promoted green building certification standards such as LEED (Leadership in Energy and Environmental Design) to encourage sustainable building design and operation. The Malaysian government encourages green building development and promotes sustainable buildings through green building guidelines and certification standards. It has energy efficiency codes that require builders to use energy-efficient technologies and materials. However, some policies focus only on incentives in one area, neglecting support and promotion in other areas. Even with good policies, there are deficiencies at the implementation level, resulting in ineffective policies, including lax regulation, weak enforcement, and inadequate supervision. Many policies need long-term stability and sustainability, and frequent changes or policy uncertainties make it difficult for building owners and developers to formulate long-term plans and investments. An example is optimizing government subsidy strategies for energy retrofit of building stock [152]. Therefore, we first suggest providing long-term loan interest rate concessions for net-zero energy building retrofit projects to reduce financing costs and attract more capital. Second, an incentive mechanism for net-zero energy building retrofits should be established to reward projects with outstanding performance and significant results. Third, it is worth noting that whether policy should support large-scale solar PV self-generation depends on the economic trade-off between energy savings and seasonal costs. In the case of New Zealand, for example, where local renewable electricity costs for various alternative energy sources are low, large-scale adoption of solar NZEB is not favorable [153]. Finally, tax breaks for net-zero energy building retrofit projects, such as tax breaks for VAT and corporate income tax, should be provided to reduce the tax pressure on the projects. In northern China, Liu et al. [154] show that retrofitting heat sources and outdoor heating networks is cost-effective, while building envelope retrofitting is not, mainly due to high energy prices without government subsidies. In Ireland, where VAT on building materials and labor is currently 13.5%, only shallow retrofitting of houses is economically viable without grant incentives [155]. It has also been argued that it is impossible to estimate the number of incentives because it is not feasible to calculate the investment cost of each transformation program in each province [156]. Therefore, the policy of providing more universally applicable indicators (energy saving rate and energy savings) and more cutting-edge and accurate algorithms may be a breakthrough in solving this problem [157].

5. Conclusions

This study reviews the current state of the art in evaluating net-zero energy building (NZEB) retrofits by combining bibliometric and systematic review methods. It is found that current evaluation methods are dominated by models of energy efficiency (using different software such as DesignBuilder, PVsyst, EnergyPlus, etc.). In contrast, other methods, such as multi-attribute decision-making methods (e.g., DEMATEL-AHP/ANP-VIKOR), also play an essential role. The main evaluation metrics used cover economic benefits (e.g., NPV, dynamic payback period, and total operating costs), energy consumption (e.g., electricity consumption and generation), environmental impacts (e.g., carbon emission reduction), and comfort (e.g., thermal comfort and indoor comfort). However, the NZEB retrofit faces several challenges, including technical, economic, social, and policy challenges:

(1) Technical challenges—Restrictions are more prevalent in existing buildings than new ones. Retrofitting existing buildings to meet near-zero energy building (NZEB) standards requires overcoming technical barriers related to energy efficiency measures, renewable energy integration, and the optimization of building systems. The main issues include imperfections in the appearance of solar cells and interfacial mechanisms in the transmission layer, the susceptibility of air source heat pumps to failure in cold climates, and module breakage and performance degradation of photovoltaic (PV) systems.

(2) Economic challenges—High initial construction costs, long payback periods, poor financing mechanisms, and dynamic tariffs that affect the accuracy of cost measurements are significant barriers. Assessing the economic viability of retrofit projects involves analyzing factors such as a discounted payback period, internal rate of return, and total return on investment. This is because of the significant upfront investment costs required to implement energy efficiency measures, renewable energy technologies, and building system optimization. Such initial costs create financial barriers to retrofit projects, and feasibility often depends on the ability to recoup these investments through energy savings over time. Balancing the costs and benefits of zero-energy building retrofits in the face of uncertainty and variability in project costs is the challenge to be addressed.

(3) Cultural challenges—Insufficient public awareness of NZEB, lack of relevant data and information platforms, and insufficient communication and trust among stakeholders have hindered the advancement of NZEB retrofits. Furthermore, balancing energy performance and heritage preservation when retrofitting heritage buildings is crucial. Retrofitting heritage buildings to near-zero energy standards requires a careful consideration of preserving cultural values while improving energy efficiency, which can create conflicting priorities and challenges. In other words, combining high energy performance and renewable energy with heritage buildings poses a dilemma for retrofit practices due to the need to maintain architectural integrity and cultural significance.

(4) Policy challenges—Inadequate policy support, such as the localization of standards and requirements, lack of incentives, and delays in the approval process, have signif-

icantly affected the implementation of NZEB retrofits. Good policy change should support energy retrofit projects and empower local authorities to scale up retrofit programs across the region, often including challenges to the retail energy market and empowering local authorities and their partners. Current policies in most areas do not create opportunities for households vulnerable to energy poverty to access low-cost or free retrofit options.

In the future, net-zero energy building retrofits must be improved and developed in the following directions. First, at the technological level, research and application of new technologies, such as digital twins and cutting-edge algorithms (including the Go-Explore algorithm and the Transform reinforcement learning algorithm), should be strengthened to improve energy modeling accuracy and system operation stability. Second, better financing mechanisms and incentive policies (e.g., green credit, green bonds, government subsidy and incentive programs, and energy service company (ESCO) models) should be established at the economic level to promote investor motivation. A standardized sustainable building value assessment system should be developed. In addition, at the social level, there is a need to strengthen public education and publicity to increase awareness and understanding of NZEB and establish a comprehensive data and information platform to promote communication and cooperation among stakeholders. The data platform collects data on building energy consumption, material use, and the indoor environment and integrates data from different sources, including sensors, monitoring systems, and building management software. Finally, at the policy level, countries should introduce and improve regulations and standards related to net-zero energy buildings as soon as possible and provide policy incentives, such as subsidies and tax incentives, to promote the full implementation of NZEB retrofits. Regional climates should prepare the specification, clearly defining and identifying assessment criteria and performance indicators, such as green building certification standards, energy efficiency, and indoor air quality.

Although this study contributes to the body of knowledge in the field, there are some limitations. Firstly, the articles included in this study were mainly sourced from the Web of Science and Scopus databases, which may not cover all current research. Future reviews could expand the range of databases, including, but not limited to, well-known databases such as China Knowledge (CNKI) and IEEE Xplore.

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