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Article

Life Cycle Sustainability Assessment: An Index System for Building Energy Retrofit Projects

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Abstract: As a major contributor to global energy consumption and greenhouse gas emissions, the building sector is crucial in shaping energy and climate change policies. Understanding building energy consumption is essential for developing effective policies, and comprehensive datasets and analyses are increasingly important. This paper outlines a structured methodology for developing a sustainability assessment index for building energy efficiency retrofits throughout a building's life cycle, covering the design, construction, use, and out-of-use phases. It highlights the interdependencies among these phases, with the design plan influencing energy efficiency and material selection, the construction plan ensuring these goals are met, and the plans for energy management, demolition, and resource recovery focusing on sustainable practices. The keys to energy-efficient retrofits are sustainable materials, energy-efficient equipment, and green technologies, which help reduce energy consumption, emissions, and operating costs. Oversight and regulation are necessary to maintain standards. This research combines a literature review, surveys, interviews, the Delphi method, and an analytic hierarchy process (AHP) to develop a comprehensive evaluation system, categorizing 20 factors across a building's life cycle and assigning weights based on environmental, economic, and social dimensions. The system provides a scientific basis for assessing the sustainability of energy efficiency programs, validated through consistency testing.

Keywords: sustainability assessment index; hierarchy analysis process (AHP); life cycle; building energy retrofit (BER)

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1. Introduction

Global building energy consumption accounts for approximately 31% of total energy consumption [1], while in China, it represents about 45% of total energy consumption [2]. Building energy consumption is a major source of carbon dioxide emissions worldwide and significantly impacts urban environmental quality and human health [3]. When new construction constitutes a small proportion of the overall building stock, energy retrofitting is a crucial and impactful measure for enhancing the environmental performance of the construction industry [4]. Building energy retrofit (BER) is essential for achieving energy savings, promoting green and low-carbon buildings, addressing climate change, and advancing sustainable development [5,6]. Without BER projects, the construction and building sector will continue to be a major contributor to the global warming potential [7]. As many existing buildings require retrofitting, it is a critical strategy for reducing carbon emissions in the global building sector.

In 2015, the United Nations introduced the Sustainable Development Goals to guide a shift towards sustainable development, addressing social, economic, and environmental dimensions [8]. At the 75th United Nations General Assembly on 22 September 2020, China committed to peaking their carbon dioxide emissions by 2030 and to achieving carbon neutrality by 2060 [9,10]. Since then, China has clarified its carbon neutrality goals and strategies, actively addressing global climate and environmental challenges. Constrained by technological limitations and design standards, many office buildings constructed at the turn of the 20th and 21st centuries in China face issues such as low energy efficiency, inadequate indoor environmental quality, and outdated functionality. Consequently, assessing the sustainability of energy-saving green retrofits for these existing office buildings is essential for advancing building energy efficiency in China and achieving the strategic goals of controlling the total energy consumption and reducing carbon emissions.

The construction industry's activities generate significant carbon emissions from both upstream and downstream industries, known as indirect carbon emissions. Therefore, assessing the environmental impact of construction activities requires a life cycle perspective [11], which includes the design, construction, use, and end-of-life stages of a building [12]. The carbon emissions associated with the construction industry encompass the entire industrial chain. Most existing research on BER primarily focuses on energy savings and economic benefits [13–16], often neglecting the embedded emissions and social impacts of these programs. To address this research gap, this study developed a life cycle sustainability assessment indicator system for building energy efficiency retrofit projects. The system provides a comprehensive framework for evaluating the environmental, economic, and social impacts of BER projects in the context of China. It is designed to guide the decision making on sustainable retrofits and ensure that public building energy efficiency strategies align with the broader goals of energy efficiency, carbon reduction, and sustainable development in China's building sector. This study addresses the following research questions:

RQ1: What are the key indicators for assessing the environmental, economic, and social impacts of BER projects?

RQ2: What are the weights of the indicators used in the assessment system?

RQ3: How to develop and validate a comprehensive assessment system?

2. Literature Review

2.1. Building Energy Retrofit (BER)

BER, the process of improving the energy efficiency and sustainability of existing buildings, has gained significant attention in recent years due to its potential to address environmental concerns and achieve sustainable development [17]. Effective policy frameworks are essential in facilitating these retrofits. Liu et al. [18] examined building green retrofit policies in China, highlighting the need to understand barriers and develop relevant policies. Their research emphasized the importance of coordination, standardized procedures, and financial incentives. Similarly, Liu et al. [19] reviewed building green retrofit policies in China, emphasizing instruments such as command and control, economic incentives, technology, information, certification, and organizational measures. Shen et al. [20] highlighted the importance of integrating climate change considerations into retrofit projects by assessing future climate scenarios to ensure long-term sustainability and resilience.

Technical advancements and economic assessments are critical for understanding the feasibility and impact of retrofit measures. Mukhtar et al. [21] conducted a techno-environ-economic assessment of heat pump system retrofit in housing stock, highlighting the potential energy conservation and efficiency benefits. The authors of [22] focused on the environmental impacts and costs of residential building retrofits, emphasizing the need for comprehensive assessments to optimize their environmental performance and cost-effectiveness. Streicher et al. [23] explored optimal building retrofit pathways, considering the stock dynamics and climate change impacts, underscoring the importance of long-term impacts and stock turnover.

Decision-making frameworks and resilience considerations are vital for effective retrofits. Ongpeng et al. [24] proposed a multi-criteria decision analysis framework for sustainable energy retrofits, emphasizing multiple criteria such as energy efficiency, environmental impacts, and economic feasibility. Mirzabeigi et al. [25] studied the impact of building retrofitting on thermal resilience during power failures, highlighting the importance of ensuring thermal comfort and resilience. Elsharkawy and Zahiri [26] emphasized the significance of occupancy profiles in determining the post-retrofit indoor thermal comfort, the overheating risk, and the energy performance, highlighting the need to consider occupants' behavior and preferences. Li et al. [27] explored optimizing energy efficiency and thermal comfort, emphasizing the balance between the energy savings and occupants' comfort.

2.2. Sustainability Assessment Methodology and Indicator System

The sustainability assessment methodology and indicator system (SAMIS) is a comprehensive approach to evaluating the sustainability of BER throughout its entire life cycle. This methodology integrates various existing sustainability assessment tools and standards, including life cycle assessment (LCA) and environmental impact assessment. Kaur and Garg [28] highlighted the need for a holistic approach that considers multiple dimensions of sustainability in urban assessments. Similarly, Carlson and Pressnail [29] emphasized the importance of integrating environmental, social, and economic indicators in urban sustainability assessment. Sharifi [30] provided an overview and bibliometric analysis of urban sustainability assessment, stressing the need for comprehensive frameworks to address the complexity of urban systems.

The application of Environmental, Social, and Governance (ESG) sustainability indicators in construction has gained significant attention. Kempeneer et al. [31] analyzed ESG indicators in real estate, proposing a behavioral framework for future research and emphasizing user perspectives and social and environmental impacts. Lee et al. [32] investigated enhancing zero-energy building operations with a solar power prediction model using automatic machine learning, highlighting advanced technologies' role in optimizing building performance. Redlein et al. [33] presented case studies on ESG monitoring and optimization solutions, demonstrating their potential to improve building performance and financial returns.

Prefabricated buildings and ESG attributes are pivotal in enhancing sustainability. Li et al. [34] proposed a modularity clustering approach to analyze economic development and ESG attributes in prefabricated building research, highlighting their potential for improving building sustainability. Kim and Chang [35] reviewed construction project-level-based ESG and its potential to improve building sustainability. Daszyńska-Żygadło et al. [36] investigated how the largest European construction companies communicate ESG impacts, emphasizing the importance of transparency. The extensive research on ESG indicators in construction covers user perspectives, modeling architecture, solar power prediction, decision-making systems, monitoring solutions, green standards, modularity clustering, contract frameworks, project-level ESG, and communication.

SAMIS aims to provide a comprehensive methodology for assessing the sustainability of BER by integrating insights from these studies. It considers the environmental, social, and economic dimensions, incorporates smart city indicators, and uses ranking and weighting techniques for indicator prioritization. SAMIS also emphasizes adaptability and context specificity, ensuring its applicability to various urban contexts. In conclusion, SAMIS represents an integrative approach to sustainability assessment for BER. By incorporating insights from various methodologies and indicator systems, SAMIS offers a robust framework that considers the entire life cycle of projects and the complexity of urban systems. This methodology advances sustainable practices in engineering management and supports informed decision making for BER.

3. Research Methodology

3.1. Life Cycle Assessment (LCA)

LCA is a comprehensive methodology used to measure the environmental, economic, and social impacts of a product or service [37,38]. The first step in selecting indicators is to confirm the scope of the study [39]. The entire life cycle of a building is cradle-to-grave, including the design, construction, use, and end-of-life phases. The design phase involves initial planning and decisions, such as material selection and energy efficiency design. The construction phase includes practices during building construction, such as waste management [40], energy, and resource use. The use phase looks at the performance of the building during use, such as the daily consumption of energy and water, maintenance costs, etc. The end phase involves building demolition or renovation, including the demolition process and material recycling.

Therefore, this paper takes the design, construction, use, and end-of-life phases into consideration. Integrating LCA into the development of a sustainability assessment index for building energy efficiency retrofits ensures a comprehensive evaluation of the building's environmental impacts. This method supports more informed decision making and aligns energy efficiency strategies with broader sustainability objectives, such as lowering the carbon footprint and conserving resources. By combining LCA with AHP, this research offers a strong framework for assessing and enhancing the sustainability of buildings across their entire life cycle.

3.2. The Delphi Method

This study adopted the Delphi method and finally determined the evaluation indexes by soliciting the opinions of 16 experts in the industry, statistically processing the results, providing feedback to the experts, soliciting the opinions again, and repeating the process. Experts in the energy-saving retrofit of existing buildings were invited to screen the alternative evaluation indicators using the Delphi method. Experts judged each evaluation index's influence degree, which was divided into five levels. When each expert judged the degree of influence of each evaluation indicator, he or she was not required to rate all the indicators but only to rate his or her familiar field in combination with the corresponding evaluation indicators, which was a critical difference from the traditional Delphi method. The Delphi method is an intuitive predictive technology approach that synthesizes multiple experts' experiences and subjective judgments [41]. A structured approach collects and synthesizes expert opinions and judgments about a particular subject or issue to provide helpful information for the research process [42,43]. This process usually involves multiple rounds of anonymous written surveys, with feedback formed after each round of surveys, which is repeatedly solicited, summarized, revised, and technically processed, and eventually aggregated into a broadly agreed-upon view of the experts.

The Delphi method can give full play to the role of all experts and brainstorming. Its anonymity dramatically reduces the problems that can arise in group decision-making, such as the influence of dominant individuals, social pressures, and irrelevant or unhelpful exchanges, thus ensuring that everyone's ideas are fully expressed. At the end of the round, a moderator is required to summarize the expert opinions as a basis for the next round. Due to the highly subjective nature of Delphi studies, multiple iterations allow for the revision of previous judgments and help to identify and measure consensus or disagreement among experts.

3.3. Analytic Hierarchy Process (AHP)

The analytic hierarchy process (AHP) is commonly used for assigning weights and prioritizing among identified indicators and is particularly suited to dealing with quantitative analysis problems. It is a multifactor decision analysis method that combines qualitative and quantitative analyses [44]. The AHP is stratified in the order of the overall objective, sub-objectives at each level, evaluation criteria, and specific alternatives. This method can handle multi-objective and multi-criteria decision-making problems and decompose complex decision-making problems into hierarchical structures, making them more straightforward to understand and analyze [45]. By solving the eigenvectors of the judgment matrix, it obtains the priority of each element at each level, concerning a particular element in the previous level. Lastly, through the weighted summation of the final weights of the alternatives in the overall objective, the final weights with the highest values are determined as the optimal program.

The questionnaire survey in this study was designed to gain a deeper understanding of experts' opinions and the importance ratings of indicators related to building energy retrofits. It aimed to assess the rationality of these indicators and collect data on their perceived importance. The survey was based on the 20 evaluation indicators identified earlier and consisted of two parts: (1) questions about the respondents' background and (2) pairwise comparisons of the indicators to evaluate the life cycle sustainability of building energy retrofits. The process for the questionnaire using AHP is shown in Figure 1. First, the questionnaire was designed based on the initially selected indicators, with questions crafted to be direct to avoid misunderstanding or bias. This study used a standard 9-point scale for pairwise comparisons. After designing the questionnaire, data were collected by distributing 20 questionnaires, of which, 16 were recovered, resulting in a recovery rate of 80%. This study collected the responses from 16 surveys, with all the participants possessing substantial expertise and experience in building energy retrofit projects and coming from relevant organizations. The scores from these 16 experts were used to calculate the weighting of each indicator. When using the AHP method, the number of experts typically ranges from 5 to 30. For instance, Ayyildiz and Taskin Gumus [46] surveyed 5 experts, Tsai et al. [47] surveyed 15 experts, Pathak et al. [48] surveyed 8 experts, Marzouk and Sabbah [49] surveyed 23 experts, and Alyamani and Long [50] surveyed 10 experts. Abadi and Moore [51] surveyed 10 experts and 10 non-experts. In this research, 20 experts were initially invited, and qualified responses were received from 16 of them, meeting the requirements for the AHP method. The collected data were then counted and analyzed, followed by a consistency test. If the consistency test failed, the questionnaire was reissued, and the iterative process was repeated several times until the consistency test was passed to ensure the validity of the results.

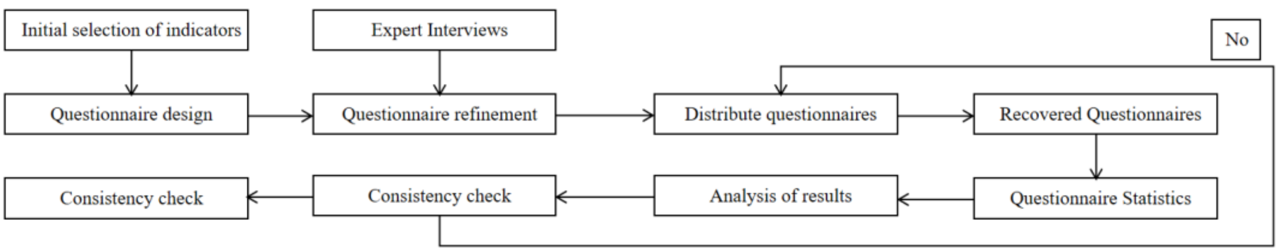

Figure 1. Questionnaire design process.

4. Assessment Framework Development and Results

4.1. Sustainability Indicator Identification

The selection of evaluation indicators in this study was guided by the following principles. The first principle is comprehensiveness and purposefulness. Indicators must cover the entire lifecycle of public building energy retrofit projects, from the initial design phase to demolition. This includes reflecting cost-benefit aspects during operation, as well as technology choices, construction, and usage phases. The focus is on relevance and specificity to the evaluation goals rather than the sheer number of indicators. The second principle is comparability. Indicators should be quantitatively comparable to ensure an objective assessment of retrofit projects. They need to align with those used in past assessments to maintain consistency. For example, if greenhouse gas emissions were previously used, this study should also include similar environmental quality monitoring indicators. The third principle is practicality. Selected indicators should be practical and feasible, effectively reflecting various dimensions of the retrofit projects. They must be clearly defined and support the collection of necessary data to ensure the evaluation is operational and actionable. The fourth principle is universality. To enable comparisons across different regions and building types, indicators should have strong universality and be widely used. Indicators specific to a few projects should be limited or avoided to ensure broad applicability and relevance.

The indicators for evaluating the sustainability of building energy efficiency retrofits encompassed nine areas: people, policy, energy and resources, technology, society, materials and facilities, program management, environmental impacts, and economic impacts. The first step in selecting these indicators was to define the study's scope, which covered the entire life cycle of a building from cradle to grave. This included the design phase, involving the initial planning, material selection, and energy efficiency design; the construction phase, focusing on practices such as waste management and resource use; the use phase, which assesses the building's performance including daily energy and water consumption and maintenance costs; and the end phase, which covers demolition or renovation including the demolition process and material recycling. A summary of impact indicators based on a synthesis of relevant literature is shown in Table 1.

Table 1. Primary selection indicators.

No.	Classification of Indicators	Content of the Indicators
1	Key personnel	Investors, designers, constructors, users, facility management teams, maintenance staff, demolition units, waste handlers, stakeholders, others
2	Policy oversight	Government energy efficiency policies, land grant restrictions, waste disposal regulations, environmental protection standards, safety regulation policies
3	Energy and resources	Natural resources, new energy applications, resource recycling, energy efficiency, water resource improvement
4	Technology	Application of new technology programs, practical application of green technology, waste recycling and reuse technology, dismantling equipment
5	Social	Public monitoring and advice, government regulation, safety and health regulation, user habits
6	Materials and equipment facilities	Materials and equipment use
7	Program management	Spatial planning, building design plan, construction plan, operation structure, construction model, energy management plan, maintenance plan, demolition plan, waste management plan, resource recovery plan
8	Environmental impacts	Important environmental issues, environmental quality testing
9	Economic impacts	Cost control, socio-economic levels, trading and subsidies

The four phases of a building's life cycle—design, construction, use, and demolition—support and influence each other due to the need for quality control, craftsmanship, and optimized design. Energy-saving retrofit impact indicators can be attributed to four aspects, which are the key personnel, programs, resources and technologies, and the supervision and regulations. The indicators for evaluating the life cycle sustainability of BER are shown in Table 2.

The key personnel aspect included investment units, design units, construction units, users, facility management teams, maintenance personnel, demolition units, waste disposal personnel, and stakeholders. While investors and constructors focus on the initial costs and efficiency, users and facility managers prioritize functionality and comfort. Demolition units and waste handlers impact the end-of-life phase. Designers, stakeholders, and maintenance staff are crucial for energy efficiency, with designers directly affecting sustainability, stakeholders shaping project goals, and maintenance staff ensuring operational efficiency.

Table 2. Indicators for evaluating life cycle sustainability of BER.

No.	Stage	Key Factors	Sub-Factors
1	Design stage	Key personnel	Designers
2	Design stage	Key personnel	Stakeholders
3	Design stage	Program	Natural resources
4	Design stage	Program	Architectural scheme
5	Design stage	Resources and technology	Materials and equipment selection
6	Design stage	Resources and technology	Application of new technology
7	Construction stage	Program	Construction scheme content
8	Construction stage	Resources and technology	Important environmental problem
9	Construction stage	Resources and technology	Material facilities and cost control
10	Construction stage	Supervision and regulation	Public scrutiny and advice
11	Construction stage	Supervision and regulation	Government supervision
12	Use stage	Key personnel	Maintenance personnel
13	Use stage	Program	Energy management plan
14	Use stage	Program	User usage
15	Use stage	Resources and technology	Energy efficiency
16	Use stage	Resources and technology	Green technology energy saving use
17	Use stage	Supervision and regulation	Environmental quality monitoring
18	Out-of-use stage	Program	Demolition and management plan
19	Out-of-use stage	Program	Resource recovery program
20	Out-of-use stage	Resources and technology	Waste recovery and reuse technology

The program aspect included space planning, building design, construction, operation structure, energy management, maintenance, demolition, waste management, and resource recovery plans. Key elements impacting energy efficiency include the building design program, construction program, and energy management plan. These elements ensure the appropriate sustainable materials selection, construction practices, and long-term energy strategies. The demolition and resource recovery plans focus on eco-friendly demolition and material reuse.

The resources and technologies aspect included the use of materials, equipment, and green technologies that directly affect a building's energy efficiency. Sustainable materials and energy-efficient equipment can significantly reduce energy consumption. The development and application of green technologies are vital for improving energy efficiency, reducing greenhouse gas emissions, and lowering operating costs.

The supervision and regulation aspect included the specific supervision and regulation needed to manage the numerous units involved in retrofit projects and to ensure energy efficiency. This helps prevent deviations and maintains the project's sustainability goals.

4.2. Judgment Matrix

For the indicators in the same level, the judgment matrix of the evaluation indicators was constructed sequentially by comparing the degree of importance of each indicator to a factor in the previous level in two by two, denoted as P.

Assuming that the evaluation target is A, the evaluation indicators and F = {f1, f2, f3, . . ., fn}, then the judgment matrix P is constructed as Equation (1) shows

$$P = \begin{matrix} f11 & f12 & f13 & f1n \\ f21 & f22 & f23 & f2n \\ \ldots & \ldots & \ldots & \ldots \\ fn1 & fn2 & fn3 & fnn \end{matrix} \quad (1)$$

where fij denotes the relative importance value of the factor where i = 1, 2,...n; j = 1, 2,...n). Based on a two-by-two judgment of the indicators at the criterion level, obtained using Santy's 1–9 scaling method, as shown in Table 3.

Table 3. Examples of pairwise check.

Scale	Degree of Importance
1	A is as important as B when comparing the two indicators.
3	A is slightly more important than B when comparing the two indicators.
5	A is more important than B when comparing the two indicators.
7	A is more strongly important than B when comparing the two indicators.
9	A is extremely strongly important than B when comparing the two indicators.
2, 4, 6, 8	Denotes the intermediate value of the above neighboring judgments.
The inverse of 1–9	Indicators of the importance of B over A.
1	A is as important as B when comparing the two indicators.
3	A is slightly more important than B when comparing the two indicators.
5	A is more important than B when comparing the two indicators.
7	A is more strongly important than B when comparing the two indicators.

To build a hierarchical structure model in the AHP, start by defining the overall goal at the top. Identify the key criteria that influence the decision and break these down into sub-criteria. List the alternatives at the bottom of the hierarchy. Arrange these elements in a clear, logical structure to guide the decision-making process. This paper took the whole life cycle sustainability evaluation of building energy retrofit as the overall objective A. This objective served as the foundation for the assessment, guiding the analysis of various factors that influence sustainability outcomes throughout the entire life cycle of the retrofit process. The whole life cycle included the design, construction, use, and end-of-life phases. This study evaluated how the relative importance of different elements (denoted as F1, F2, F3, and F4) with respect to the overall objective were assessed through expert judgment. A scoring table, as shown in Table 4, was created based on this expert evaluation.

Table 4. Expert scores (a, b, c, d, e, and f in the table represent the scores obtained, and the eigenvectors W = {x1, x2, x3, x4} of the above matrix were calculated, i.e., the weight values of the evaluation factors F1, F2, F3, and F4 are x1, x2, x3, and x4, respectively).

A	F1	F2	F3	F4
F1	1	a	b	c
F2	1/a	1	d	e
F3	1/b	1/d	1	f
F4	1/c	1/e	1/f	1

4.3. Weight Vector Determination

Using a hierarchical single sort on the previous layer of an element will reveal the elements in this layer. For the order of importance, the specific calculations can be based on the judgment matrix A, and the calculations must ensure that they comply with the conditions of the eigenroot and the eigenvector of $A\omega = \lambda_{max}\omega$. Here, the largest eigenroot of A was λ_{max}, the regularized eigenvector corresponding to λ_{max} was ω, and ω_i was the component of ω, which referred to the weight value and corresponded to the single ordering of its corresponding elements. The judgment matrix was used to calculate the weights (weight coefficients) of each factor a_{ij} on the target layer. The calculation steps (square root method or sum method) for the weight vector (ω) and the maximum feature (λ_{max}) are shown in the following:

(1) Multiply the product of each row's judgment matrix score by nth power, as shown in Equation (2).

$$\overline{\omega_i} = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}, (i,\ j = 1,\ 2,\ 3, \ldots, n) \quad (2)$$

(2) The weight vector is obtained after normalization, as shown in Equation (3). The data were normalized even if the sum of the elements in the vector was equal to 1; the

elements of A were found for the same level of factors as for the previous level, and for the relative importance of a factor depending on the ranking weight value.

$$\omega_i = \frac{\overline{\omega_i}}{\sum_{i=1}^{n} \omega_i}, \ (i,\ j = 1,\ 2,\ 3, \ldots, n) \tag{3}$$

(3) Determine the largest characteristic root of the matrix, as shown in Equation (4).

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(A\omega)_i}{\omega_i} \tag{4}$$

4.4. Consistency Check

In the AHP method, the consistency check is a crucial step for ensuring the relative importance scores provided by the experts are logically consistent. To ensure consistency in the decision-makers' judgments about the relative importance of the entries in the pairwise comparison matrices at all levels, a consistency test should be conducted [52]. This study used the following consistency index CI to test the consistency index of judgment, where CI = 0 indicated that the judgment matrix was completely consistent, and the larger the CI was, the more serious the degree of inconsistency of the judgment matrix was. The random consistency index (RI) is a value obtained from randomly generated matrices, and it varies depending on the size of the matrix. The consistency ratio (CR) was used for measuring the consistency of the judgment matrix. The calculations of CI and CR are shown in Equations (5) and (6), respectively.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5}$$

$$CR = \frac{CI}{RI} \tag{6}$$

The CI was the consistency check index, and n was the order of the judgment matrix. The CR was the test coefficient. The RI was derived from simulations performed by Saaty, which involved generating 1000 simulations of random pairwise comparison matrices [53–56]. This process helps in establishing a benchmark for what constitutes a random level of consistency in a matrix. The values obtained from these simulations were then used to create the RI table, which provided the expected consistency indices for matrices of different sizes. Table 5 displays these RI values for various matrix orders.

Table 5. Values of RI.

Matrix Order n	1	2	3	4	5	6	7	8	9	10	11	12	13
R.I.	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54	1.56

If $CR < 0.1$, it indicated that the degree of consistency of judgment matrix A was considered to be within the tolerance range; at this time, the eigenvectors of A could be used to carry out the calculation of the weight vector. If $CR \geq 0.1$, it was considered that the judgment matrix A failed to pass the test, and could not be used as a fraction of the components in ω [57]. At this time, consideration was given to the correction of the judgment matrix A until it could meet the consistency required.

4.5. Results

A clear hierarchical framework was finalized. This framework categorized the indicators into multiple tiers: primary sustainability goals, critical assessment criteria, and specific indicators. The framework was intended to provide a comprehensive and balanced perspective that considers building sustainability's economic, social, and environmental dimensions. The goal level is a system of life cycle sustainability indicators for BER, the guideline level is the four stages of a building's full life cycle, and the program level is the corresponding evaluation indicators for each stage.

Table 6 reflects the final evaluation indicator weights, with the data arranged in descending order to illustrate the level of importance of the indicators more clearly. The ranking of the weights of the four stage intermediate levels for the decision objectives was determined. The weights of the design and occupancy phases were much larger than those of the construction and end-of-use phases, indicating that the design and occupancy phases are considered more important than the construction and end-of-use phases for building energy retrofit projects in this statistic.

Table 6. Ranking of intermediate tier's weighting of decision-making goals.

Middle Tier Elements	Weights
Design stage	0.4256
Use stage	0.3472
Construction stage	0.1183
Out-of-use stage	0.1089

The weighting of the decision objectives at the program level was ranked as shown in Table 7. Material and equipment selection has the highest weighted program, with a weight of 0.1551, indicating that selecting appropriate materials and equipment is the most critical consideration in building energy efficiency retrofit programs. The energy management plan ranked second with a weight of 0.1241, reflecting how important it is for programs to manage energy use and optimize the energy efficiency in the overall program. The application of new technology and energy efficiency occupy the third and fourth positions, with weights of 0.1009 and 0.0871, respectively, indicating that using technology to improve energy efficiency is a priority. On the other hand, maintenance personnel and public scrutiny and advice had lower weights of 0.0125 and 0.0104, respectively, but were still regarded as components of sustainability assessment despite their relatively low weights.

Table 7. Program-level weighting of decision-making objectives.

Life Cycle Phase	Evaluation Indicators	Weights
Design	Material and equipment selection	0.1551
Use	Energy management plan	0.1241
Design	Application of new technology	0.1009
Use	Energy efficiency	0.0871
Out-of-use	Resource recovery program	0.0641
Design	Natural resources	0.0622
Construction	Important environmental problem	0.0529
Use	Green technology energy saving use	0.0523
Design	Architectural scheme	0.0515
Use	User usage	0.0391
Design	Designer	0.0341
Use	Environmental quality monitoring	0.0322
Out-of-use	Waste recovery and reuse technology	0.0274
Construction	Material facilities and cost control	0.0259
Design	Stakeholder	0.0218
Out-of-use	Demolition and management plan	0.0173
Design	Construction scheme content	0.0156
Construction	Government supervision	0.0134
Use	Maintenance personnel	0.0125
Construction	Public scrutiny and advice	0.0104

Based on the results of the pairwise comparisons, the Consistency Ratio (CR) was calculated to be less than 0.1. The CR was calculated using Equation (5), with the results for each stage shown in Tables 8–11. Table 12 shows the weighting for each phase and the consistency check results. The calculations were made with the help of Microsoft Excel, thus simplifying the AHP calculation process.

Table 8. Scores corresponding to each indicator at the design stage.

Design Stage	Designer	Stakeholder	Natural Resources	Architectural Scheme	Material and Equipment Selection	Application of New Technology	ω_i	CR
Designer	1	2	0.3333	0.25	0.3333	0.5	0.0802	0.0991 < 0.1
Stakeholder	0.5	1	0.3333	0.5	0.2	0.25	0.0512	
Natural resources	3	3	1	2	0.3333	0.25	0.1461	
Architectural scheme	4	2	0.5	1	0.25	0.3333	0.121	
Material and equipment selection	3	5	3	4	1	3	0.3644	
Application of new technology	2	4	4	3	0.3333	1	0.2371	

Table 9. Score corresponding to each indicator at the construction stage.

Construction Stage	Construction Scheme Content	Important Environmental Problem	Material Facilities and Cost Control	Public Scrutiny and Advice	Government Supervision	ω_i	CR
Construction scheme content	1	0.2	0.3333	2	2	0.1318	0.0968 < 0.1
Important environmental problem	5	1	4	3	3	0.4474	
Material facilities and cost control	3	0.25	1	2	3	0.2192	
Public scrutiny and advice	0.5	0.3333	0.5	1	0.5	0.0882	
Government supervision	0.5	0.3333	0.3333	2	1	0.1134	

Table 10. Score corresponding to each indicator at the use stage.

Use Stage	Maintenance Personnel	User Usage	Energy Management Plan	Energy Efficiency	Green Technology Energy Saving Use	Environmental Quality Monitoring	ω_i	CR
Maintenance personnel	1	0.3333	0.1667	0.1429	0.25	0.2	0.0359	0.0770 < 0.1
User usage	3	1	0.25	0.3333	0.5	3	0.1126	
Energy management plan	6	4	1	2	3	4	0.3573	
Energy efficiency	7	3	0.5	1	3	2	0.2509	
Green technology energy saving use	4	2	0.3333	0.3333	1	3	0.1505	
Environmental quality monitoring	5	0.3333	0.25	0.5	0.3333	1	0.0928	

Table 11. Score corresponding to each indicator at the out-of-use stage.

Out-of-Use Stage	Demolition and Management Plan	Resource Recovery Program	Waste Recovery and Reuse Technology	ω_i	CR
Demolition and management plan	1	0.3333	0.5	0.1593	0.0518 < 0.1
Resource recovery program	3	1	3	0.5889	
Waste recovery and reuse technology	2	0.3333	1	0.2519	

Table 12. Corresponding scores for each stage of the whole life cycle.

Overall Evaluation System	Design Phase Sequencing	Construction Phase Sort	Use Stage Sort	Dismantling Phase Sequence	ω_i
Design phase sequencing	1	3	2	3	0.4256
Construction phase sort	0.3333	1	0.3333	1	0.1183
Use stage sort	0.5	3	1	5	0.3472
Dismantling phase sequence	0.3333	1	0.2	1	0.1089

5. Discussion

5.1. Design Phase

In the design phase of the building energy life cycle sustainability assessment, the indicators were ranked as follows: material and equipment selection, new technology utilization, natural resources, building program, design responsible personnel, and stakeholders. The disparity between the highest and lowest weight values was 0.1333.

Material and equipment selection held the highest weight of 0.1551. Experts emphasized that the choice of appropriate materials and equipment has a profound direct impact on energy savings, significantly influencing the building's energy efficiency, environmental impacts, and long-term maintenance costs. The literature indicates that using environmentally friendly building materials can reduce the environmental impact by 10% compared to conventional materials under similar conditions [58]. New technology utilization ranked second, with a weight of 0.1009. Advanced technologies, such as intelligent control systems and sophisticated energy management tools, are crucial for optimizing buildings' energy consumption. Technological innovations enhance energy efficiency and minimize energy loss, making them vital for improving overall building sustainability. The effective use and protection of natural resources is essential for reducing the environmental burden and promoting ecological balance. Rational resource use is fundamental to achieving sustainable development goals and reducing long-term environmental impacts. The building program, which encompasses spatial layout, functional use, and aesthetic considerations, significantly influences the building's energy demand and user behavior. Early design decisions are crucial for preventing potential energy consumption issues and ensuring subsequent energy efficiency and the minimal environmental impact. Although design-responsible personnel and stakeholders have comparatively lower weights, their roles are critical. The competence of designers and the involvement of stakeholders, such as owners, users, and regulatory agencies, directly affect the building's performance and energy efficiency, impacting the project's overall sustainability.

In summary, the highest weight was assigned to material and equipment selection due to its direct correlation with initial energy efficiency and operational costs. New technology utilization followed closely, as it drives significant improvements in energy efficiency and building performance. Effective resource use is also crucial, given its direct link to environmental impact and lifecycle costs. The roles of design personnel and stakeholders, while less weighted, are nevertheless vital for the project's success and sustainability.

5.2. Construction Phase

In the construction phase of the building energy life cycle sustainability assessment, the indicators were ranked as follows: critical environmental issues, material facilities and cost control, construction plan content, government regulation, and public monitoring and suggestions, with a weight disparity of 0.3592 between the highest and lowest values.

Critical environmental issues received the highest weight, underscoring their significance in project sustainability. This category encompasses construction waste management, pollution control, and minimization of ecological impacts. The effective management of these environmental issues is crucial for protecting local ecosystems, reducing negative effects on surrounding communities, and ensuring compliance with environmental regulations and sustainability goals. Material facilities and cost control are also vital aspects of construction management. Efficient material selection and cost control are essential for the economic sustainability of the project. Proper management minimizes waste, reduces costs, ensures the project remains within budget, and enhances overall economic efficiency. Construction plan content involves the detailed planning and scheduling of the project. A well-developed construction plan is critical for optimizing resource utilization, minimizing delays, and ensuring timely project completion. Effective planning contributes significantly to the sustainability of the retrofit process. Government regulation ensures adherence to legal standards and regulations, including safety and environmental protection guidelines. Strong regulatory frameworks drive compliance with industry standards and promote sustainability throughout the construction process. Although Public Monitoring and Suggestions were weighted relatively lower, they play an important role in enhancing project transparency and social responsibility. Community feedback and public participation foster greater acceptance and social sustainability of the project, contributing to increased public trust and satisfaction.

The weighted rankings indicate that sustainability during the construction phase relies heavily on effective environmental protection measures, meticulous material and cost management, and rigorous planning. These factors collectively optimize resource use, minimize environmental impacts, and meet regulatory and community expectations. Government regulation and public scrutiny support and safeguard the construction process, ensuring that all activities are conducted in an environmentally, economically, and socially responsible manner, thus contributing to the long-term sustainability of building energy retrofit projects.

5.3. Use Phase

In the use phase of the building energy life cycle sustainability assessment, the indicators were ranked as follows: energy management plan, energy efficiency, use of green energy-saving technologies, user behavior, environmental quality testing, and maintenance personnel, with a weight disparity of 0.3214 between the highest and lowest values.

The energy management plan held the highest weight, emphasizing its critical role in ensuring long-term building energy efficiency. This plan involves monitoring, controlling, and optimizing energy use to minimize consumption and maintain sustainability. A robust energy management program ensures the consistent implementation of energy efficiency measures, thereby reducing operational costs and environmental impact. Energy efficiency is directly indicative of the success of energy retrofits. This involves reducing overall energy consumption and enhancing the efficiency of energy use, which significantly lowers energy costs and greenhouse gas emissions during the building's operational phase. The use of green energy-saving technologies is crucial for improving buildings' energy efficiency. Technologies such as efficient heating and cooling systems, intelligent lighting, and automated control systems support the goals of energy management plans, contributing positively to both environmental and economic sustainability. User behavior significantly influences buildings' energy consumption. Energy-saving practices can be encouraged through user training and awareness, which directly impact energy use. Thus, user behavior is a key element in achieving successful energy retrofits. Environmental quality testing involves the continuous monitoring of indoor air quality, temperature, and humidity. This monitoring is essential for managing the building environment and addressing issues arising from energy efficiency measures. Lastly, maintenance personnel, while ranked lowest, are responsible for keeping energy-efficient systems in optimal condition. Though their role does not directly affect energy efficiency, proper maintenance ensures the effectiveness and durability of energy efficiency measures, supporting their long-term success.

5.4. End-of-Life Phase

In the out-of-life phase of the building energy life cycle sustainability assessment, the indicators were ranked as follows: resource recovery plan, waste recycling and reuse technology, and demolition and management plan, with a weight disparity of 0.4296 between the highest and lowest values.

The resource recovery plan ranked highest, highlighting its critical role in the decommissioning phase. This plan focuses on reusing or recycling valuable building materials and structures, thus reducing the need for new resources and minimizing waste. An effective resource recovery plan maximizes resource value recovery, reduces environmental impact, and supports the circular economy, which is essential for evaluating the sustainability of building energy retrofit projects. Waste recycling and reuse technology is crucial for the efficient and safe processing of materials recovered from building waste. Advances in technology can enhance the recycling process's efficiency and the quality of reused materials. These technologies are vital for sustainable demolition and waste management, as they help reduce landfill waste, minimize environmental pollution, and contribute to the overall sustainability of construction projects. Although less weighted, demolition and management plans are fundamental for ensuring that the demolition phase adheres to sustainability principles. A well-developed demolition plan ensures efficient resource recovery and proper waste disposal. The effective implementation of such plans is crucial for protecting the environment and surrounding community, minimizing adverse environmental impacts, and maximizing waste recycling and reuse.

These indicators are inter-related. The resource recovery plan provides a strategic framework for employing waste recycling and reuse technologies, which are essential tools for executing effective demolition and management plans. A practical resource recovery plan guides the disposal process during dismantlement, while recycling technologies ensure the plan's successful implementation. Additionally, a comprehensive demolition and management plan ensures the process is orderly, compliant with codes, and environmentally beneficial. In the context of sustainability evaluation for BER, these metrics reflect the program's environmental responsibility at the end of its lifecycle. Incorporating these factors into the evaluation system ensures best practices in demolition and waste disposal, supporting overall environmental sustainability.

5.5. Practical Suggestions for the BER Market

Insights from the building energy life cycle offer suggestions for the energy market to enhance sustainability and efficiency. In the design phase, energy market stakeholders should prioritize materials and technologies that promote energy efficiency. Incentives like subsidies or tax benefits can encourage the adoption of eco-friendly materials and innovative technologies. Collaboration between designers and energy experts can lead to efficient, market-aligned solutions. In the construction phase, promoting sustainable construction practices and effective cost control is essential. The energy market should establish standards for green materials and offer incentives for projects that minimize environmental impact. Additionally, integrating regulatory frameworks and public oversight ensures projects meet sustainability goals. In the usage phase, the energy market should support advanced energy management systems and the adoption of green technologies. Incentivizing energy-efficient behaviors and expanding the market for sustainable technologies, such as smart lighting and heating, will help optimize energy consumption during the operational phase. In the end-of-life phase, encouraging the development of recycling and reusing technologies is important. The energy market can foster a circular economy by incentivizing resource recovery and reducing the environmental impact of building decommissioning.

Suggestions to improve the sustainability of BER projects can be provided based on the weighting of each indicator in each phase. The energy market should create policies that support sustainable practices across all building phases. Facilitating collaboration among stakeholders will ensure sustainability is integrated throughout the building life cycle, helping reduce energy consumption and emissions.

6. Conclusions

This paper developed a comprehensive sustainability evaluation index system for public BER projects in China, addressing the environmental, economic, and social dimensions. The evaluation system covers buildings' design, construction, usage, and demolition phases. The study established evaluation indicators and weights through a literature review, surveys, expert interviews, the Delphi method, and the AHP method. The proposed system includes four primary and 20 secondary indicators, with the environmental dimension accounting for 40% of the total weight, and the economic and social dimensions each representing 30%. The rationality and effectiveness of the index system were validated through consistency tests, offering a scientific approach to evaluating BER project sustainability. The research outcome emphasizes the weights of each phase in BER projects for evaluating the life cycle sustainability: the design phase accounts for 42.56%, the use phase for 34.72%, the construction phase for 11.83%, and the out-of-use phase for 10.89%. Energy consumption control varies across the building life cycle. In the design phase, we focused on economical, efficient plans, reducing material use, and promoting low-carbon materials. During construction, we emphasized low-carbon materials, prefabrication, waste reduction, shorter timelines, and energy-saving technologies. In the usage phase, we incorporated advanced technologies and new energy sources for low-carbon operations, while ensuring comprehensive use of materials and equipment and effective resource management during construction and demolition.

This research is crucial for promoting sustainable development in BER projects, achieving energy-saving goals, and enhancing buildings' value and competitiveness. Future research should explore integrating digital intelligence, such as BIM modeling, to better align energy consumption indicators with project documents and tailor strategies to regional climates and energy baselines. Additionally, examining strategies across different time phases, such as short-term, medium-term, and long-term, can offer further insights.

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