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Low-Carbon Retrofitting Path of Existing Public Buildings: A Comparative Study Based on Green Building Rating Systems

Ke Liu [1,2,3,4], Jianglan Tian [1,3], Jianping Chen [1,2,3,*] and Yueming Wen [5]

1 School of Architecture and Urban Planning, Suzhou University of Science and Technology, Suzhou 215009, China
2 Jiangsu Province Engineering Research Center of Construction Carbon Neutral Technology, Suzhou University of Science and Technology, Suzhou 215011, China
3 Jiangsu Province Key Laboratory of Intelligent Building Energy Efficiency, Suzhou University of Science and Technology, Suzhou 215009, China
4 Yangtze River Delta Institute of Carbon Neutrality for Human Settlement, Suzhou 215009, China
5 School of Architecture, Southeast University, Nanjing 210096, China
* Correspondence: alanjpchen@aliyun.com

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Abstract: Existing building carbon emissions contribute to global climate change significantly. Various Green Building Rating Systems (GBRS) have considered low-carbon requirements to regulate the emissions. Low-carbon retrofitting is an important way to reduce existing building CO_2 emissions. However, low-carbon retrofitting of existing public buildings is not sufficient and systematic, and there is a lack of research on low-carbon retrofitting from the perspective of GBRS. The purpose of this study is to propose a carbon emission control framework for existing public buildings based on GBRS analysis and guide the low-carbon retrofitting. This study makes comparisons among the Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), Green Mark (GM), and Assessment Standard for Green Retrofitting of Existing Buildings (ASGREB). A low-carbon retrofit pathway for existing public buildings is proposed from the GBRS research for the first time, encompassing six aspects: materials, energy, management, innovation, site, and water, involving 15 measures. Among them, measures on energy and materials are the main considerations, with weights of 18.3% and 17.7%, respectively. Six recommendations for implementation pathways are also given. Furthermore, the necessary measures, the importance of local context and quantification, priorities of materials, and energy scopes are defined.

Keywords: existing public buildings; low-carbon retrofitting; green building rating systems (GBRS); carbon emissions; comparative study

1. Introduction

As is widely accepted, the building sector is considered very energy-intensive and to have large carbon emissions. In China, buildings are responsible for 25% of the national energy demand [1], and the rapid development of urban construction has led to the construction, operation, and demolition of buildings. Carbon emissions generated in the process account for 35% to 50% of the country's total carbon emissions [2]. In Europe, the final energy demand and greenhouse gas (GHG) emissions of residential and commercial building stocks account for approximately 40% of energy and emissions [3–5]. In the U.S., buildings account for about 40% of total energy consumption and around 33% of total energy-related CO_2 emissions [6]. A large fraction of those emissions and energy consumptions comes from existing buildings [7,8].

Studies show that the operation phase is the most energy-consuming phase [9], and existing buildings generally consume more energy due to problems such as low age standards [10]. In the face of a large stock of existing buildings with high energy consumption, relying on new buildings alone to meet energy efficiency standards is far from addressing the effective goal of reducing carbon emissions in the entire building sector. The building stock has been identified as one of the largest and mostly untapped potential targets for improving energy efficiency and mitigating greenhouse gas (GHG) emissions [3,11]. The planning of total building stock and the promotion of building retrofit have a great impact on the carbon emissions related to building construction [12]. Retrofitting existing buildings is more resource-efficient and sustainable than building new green constructions; furthermore, existing buildings are rich in cultural value, and their renovation is conducive to cultural heritage [13]. Existing buildings, especially nonresidential buildings, contribute to a significant portion of greenhouse gas emissions [14]. Energy consumption in public buildings increased drastically over the last decade. Energy saving and consumption reduction in public buildings are the key to achieving the target global temperature growth of the Paris Agreement [15,16]. Countries have set targets for the green renovation of existing buildings. China has announced its ambitious goal to peak carbon dioxide emissions by 2030 and achieve carbon neutrality before 2060 in the upgraded Nationally Determined Contributions [17]. It is required to comprehensively improve the level of green and low-carbon buildings and continue to promote the construction of key cities to improve the energy efficiency of public buildings; all key cities at or above the prefecture-level will complete the renovation task, and the overall energy efficiency will be improved by more than 20% after the renovation by 2030 [18]. In the U.S., 50% of commercial buildings will be retrofit to zero net energy (ZNE) by 2030, and 50% of new major renovations of state buildings will be ZNE by 2025 [19].

With low-carbon target as an essential indicator of building green and sustainable development, there is an increasing number of studies on the low carbonization of existing public buildings. Accordingly, studies have been conducted focusing on the cost of measures [20,21], emission control techniques [22,23], integrated management [24–26], tools and platform [4,27], and so on. Among them, Green Building Rating Systems (GBRS) could regulate the low-carbon development of buildings with different chapters and CO_2-related indicators involved [28,29]. Based on the analysis of GBRS, the characteristics and measures of the low carbonization of buildings can be successfully obtained and suggested [30–32]. Additionally, many GBRSs focus on green retrofitting of existing buildings [33,34].

According to the current knowledge, there is a consensus on the huge low-carbon and energy-saving potential of existing public buildings, and countries and regions have also put forward green transformation targets for building stocks. However, the main problem of specific measures to retrofitting the existing buildings with low carbon emissions has not been addressed in a relatively systematic way. There is a lack of systematic framework research on how to implement low-carbon renovation of existing buildings. The majority of the articles on low-carbon retrofitting of existing public buildings are based on case studies and architects' own experiences to propose corresponding strategies, and very few articles summarize and sort out specific low-carbon measures from the perspective of GBRS and form a systematic framework. Most of the studies on carbon emissions of existing buildings are mainly on residential buildings [35–37]. In comparison, the green retrofitting of existing public buildings schemes has been largely ignored [38].

To respond to the mentioned issues, this paper tries to summarize the low-carbon retrofitting path of existing public buildings based on a comparative study between some typical GBRS for existing buildings. There are four typical GBRSs are compared, which are Leadership in Energy and Environmental Design for Operations and Maintenance (LEED O + M), Building Research Establishment Environmental Assessment Method International Nondomestic Refurbishment (BREEAM INDR), Green Mark (GM), and Assessment Standard for Green Retrofitting of Existing Buildings (ASGREB), and a framework of indicators related to carbon emission control in existing public buildings was developed based on ASGREB-202X. The study provides a summary of scopes covered, weights of indicators, suggested effective measures, and the guidance path of low-carbon retrofitting for existing public buildings, which is the first such attempt from the architectural perspective in this field.

2. Methodology

The main purpose of this paper is to study the relevant indicators of CO_2 emission control for existing public building retrofits with different GBRSs. First, through literature survey, the characteristics of each GBRS were clarified. In order to make the comparison informative and based on the relevance and timeliness, the study selects the latest version of each GBRS: LEED v4.1 O + M, BREEAM INDR 2015, GM 2021, and ASGREB -202X. The following comparative analysis of CO_2-related indicators in the GBRS included three factors: the scopes, related indicators, and features of measures. On this basis, the scopes of indicators related to carbon emission control of existing buildings are summarized with quantified weights. Additionally, the measures of low-carbon retrofitting are inducted from the related indicators in the four GBRSs. Following with the qualitative and quantitative analysis of the measures, a low-carbon retrofitting path of existing public buildings is proposed with recommendations for the design stage. The study schema of this paper is shown in Figure 1.

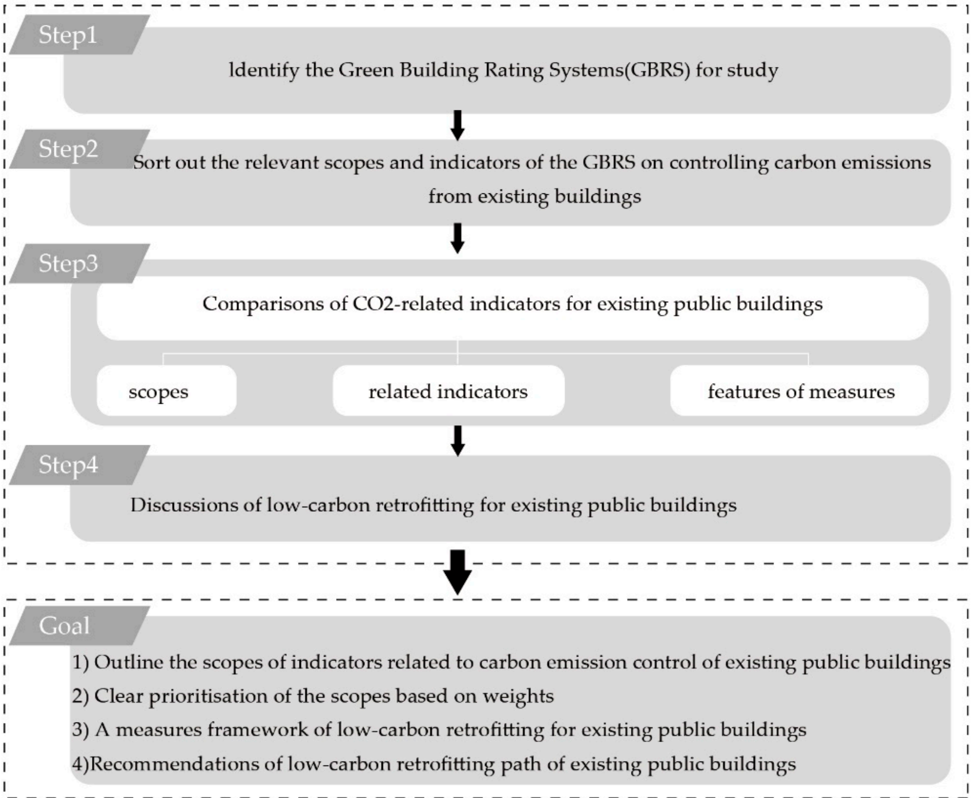

Figure 1. The study schema.

2.1. Object Determination: The Green Retrofit of Existing Public Buildings

Facing a large building stock and the gradual slowdown of new construction development, the potential for green retrofitting of existing buildings to reduce carbon emissions is becoming increasingly important. Retrofit is the "change" of elements or components of a building [39]. Meanwhile, the "retrofit" also refers to other terms in literature, such as refurbishment, rehabilitation, renovation, improvements, adaptation, repairs, and renewal on existing buildings [40,41]. Further, green retrofit is defined as "the upgrading of the building fabric, systems or controls to improve the energy performance of the property" [42]. In China, it refers to the activities of maintenance, renewal, and reinforcement of existing buildings with the objectives of guaranteeing building safety, saving energy resources, improving human living environment, enhancing usage functions, and so on [43]. The U.S. Green Building Council (USGBC) defines green retrofit as "any kind of upgrade at an existing building that is wholly or partially occupied to improve energy and environmental performance, reduce water use, and improve the comfort and quality of the space in terms of natural light, air quality, and noise, which all strategies should be financially beneficial to the owner" [44]. From the definitions, it could be seen that green retrofit could improve energy performance and achieve low carbonization of existing buildings.

There are various subdivisions of existing building-related retrofitting standards, which can be divided into residential buildings and public buildings, in terms of building types. It is essential to identify existing public buildings as research subjects at the beginning of the study. The reasons for this are as follows: the built environment requirements for residential and public buildings are different, and their retrofitting considerations have their own special characteristics. All the targeted GBRSs have specific distinctions and different requirements between existing residential and public buildings. Meanwhile, although studies have been conducted on existing public buildings, they are limited in comparison to residential ones [35–38]. Additionally, the carbon emission problem of existing public buildings is also prominent. Because of the highest energy consumption intensity of public buildings, the carbon emission intensity per unit of building area in China is also the highest, and the carbon emission intensity in 2020 is 45.7 $kgCO_2/m^2$ (Figure 2). With the steady growth of the total energy consumption and intensity of public buildings, the total carbon emission of this part is still on the rise [45], which shows that it is necessary to control the carbon emissions of existing public buildings.

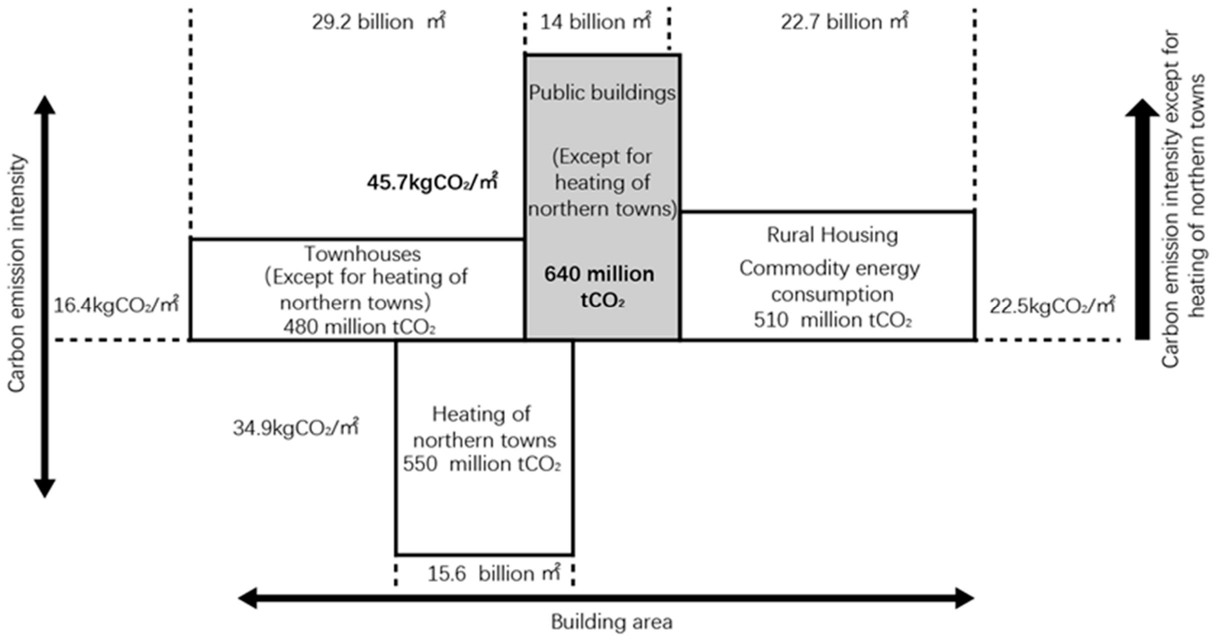

Figure 2. CO_2 emissions associated with building operations in China (2020).

2.2. Literature Surveys of Selected Assessment Systems

GBRSs adapt to the global sustainability trend and country's development [46,47]. The four countries, the U.K., the U.S., Singapore, and China, have similarities in their the national policies to respond to carbon neutrality, responding to the United Nations 2030 Sustainable Development Goals and their own economic development requirements, for which the time point for achieving carbon peaking is around 2030 and for achieving carbon neutrality around 2060 (Table 1). As the world's first green building evaluation standard, BREEAM from Britain has a moderate structure and a moderate number of standard projects, ensuring the operability and scientificity of the standard. Many GBRSs around the world are currently being developed and applied based on the experience of BREEAM, LEED, and GM, for instance [2,48]. LEED from the U.S. is currently one of the most widely used and influential green building identification and certification systems and has become a model for countries to learn from [49]. Singapore offers good lessons for

China's urbanization, demonstrating that urban development is not a barrier to improving environmental quality and that economic growth and effective policy guidelines have a positive and significant impact on reducing carbon emissions [50]. It is imminent to implement the strategy of energy conservation and emission reduction facing the massive building stock in China. Therefore, based on their development relationships and similarities, global recognition, and reference value, this paper selects the GBRSs of BREEAM, LEED, and GM to conduct a comparative study on the part of existing public building retrofitting with China's ASGREB. The scoring mechanism of LEED, BREEAM, GM, and ASGREB is similar, where LEED, GM, and ASGREB are scoring systems with no weights, but weights can be calculated by the percentage of scores, and BREEAM itself is a weighting system that calculates the final score percentage weighted by the score rate of each domain. These four criteria are convergent in the algorithm of scores; as a result, the comparison of different GBRSs can be achieved. The data treatment method of each GBRS is shown in Figure 3.

Table 1. National policies to respond to carbon neutrality.

	Countries' Responses to the UN's 2030 Sustainable Development Goals	Carbon Neutrality Target
U.K.	Reduce UK emissions by at least 68% from 1990 levels by 2030 (peaked in 1991).	Achieving "net-zero emissions" of greenhouse gases by 2050, the goal of achieving carbon neutrality.
U.S.	Reduce greenhouse gas emissions by 50%–52% from 2005 levels by 2030 (peak in 2007).	Carbon-free electricity generation by 2035 through transition to renewable energy, 2050 carbon neutral.
Singapore	Peak carbon by 2030, reduce the net carbon emissions of local schools by two-thirds by 2030 at the latest, and make at least 20% of schools carbon neutral in the initial stage.	Halve peak carbon emissions to 33 million tons by 2050 and achieve carbon neutrality as soon as possible in the second half of this century.
China	2030 carbon peak.	2060 carbon neutral.

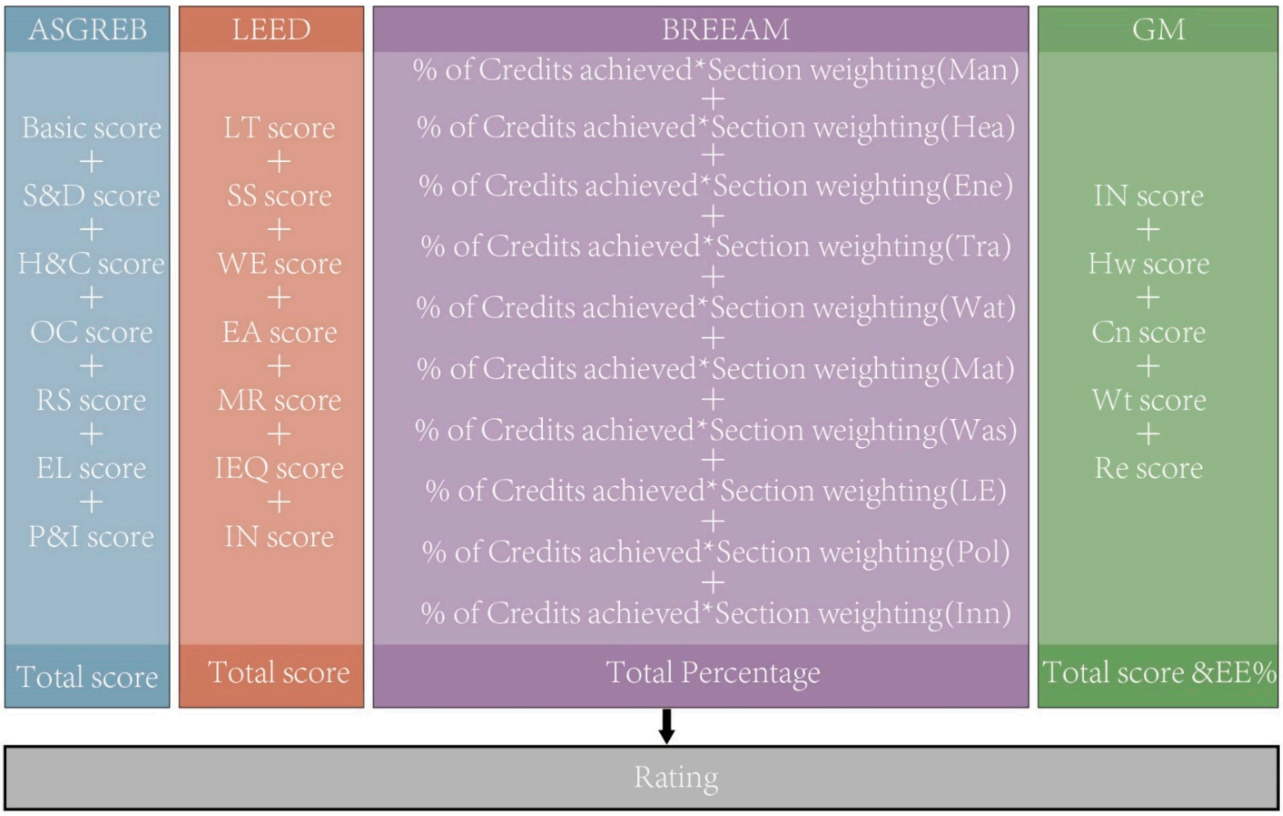

Figure 3. Data treatment method of each GBRS.

2.2.1. LEED for Operations and Maintenance Version 4.1 (LEED v4.1 O + M)

LEED v4.1 is the next-generation standard for green building design, construction, operation, and performance, and LEED for Operations and Maintenance (LEED O + M) offers a framework for existing buildings to be green-retrofitted; it fits every project from office spaces and restaurants to data centers and schools. There are seven criteria in it: Location and Transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, and Innovation [51]. The total credits should be calculated using Equation (1). Among the criteria, the five scopes related to existing building CO_2 emission control are Location and Transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, and Materials and Resources (Table 2). From the very beginning of the LEED system, a common assumption was that it would reduce the energy consumption of buildings and limit GHG emissions.

$$Q_{LEED} = Q^1_{LEED} + Q^2_{LEED} + Q^3_{LEED} + Q^4_{LEED} + Q^5_{LEED} + Q^6_{LEED} + Q^7_{LEED} \quad (1)$$

Table 2. Criteria of LEED v4.1 O + M.

Criteria		Score
• Location and transportation	Q^1_{LEED}	14
• Sustainable Sites	Q^2_{LEED}	4
• Water Efficiency	Q^3_{LEED}	15
• Energy and Atmosphere	Q^4_{LEED}	35
• Materials and Resources	Q^5_{LEED}	9
Indoor Environmental Quality	Q^6_{LEED}	22
Innovation	Q^7_{LEED}	1
Total	Q_{LEED}	100

• Scopes related to CO_2 emission.

Here, Q_{LEED} is the total score of LEED indicators, and Q^1_{LEED}–Q^7_{LEED} are scores of the seven indicators.

2.2.2. BREEAM International Nondomestic Refurbishment 2015 (BREEAM INDR 2015)

The BREEAM International Nondomestic Refurbishment 2015 scheme is applicable to nondomestic buildings undergoing refurbishment and fit-out. It includes 10 criteria: Management, Health and Wellbeing, Energy, Transport, Water, Material, Waste, Land Use and Ecology, Pollution, and Innovation (Table 3) [52]. The total credits should be calculated using Equation (2). Among the criteria, the eight scopes related to existing building CO_2 emission control are Health and Wellbeing, Energy, Transport, Water, Material, Waste, Land Use and Ecology, and Innovation.

$$Q_{BREEAM} = \sum_{i=1}^{10} \frac{W_i Q^i_{BREEAM}}{Tot_i} \quad (2)$$

Here, Q_{BREEAM} is the total credits of the BREEAM indicators; W_1–W_{10} are the weights of the ten indicators; Q^1_{BREEAM}–Q^{10}_{BREEAM} are scoring item credits of the ten indicators; and Tot_1–Tot_{10} are the total credits of the ten indicators.

2.2.3. Green Mark 2021 (GM:2021)

GM:2021 is for newly designed and existing buildings either undergoing retrofitting (including major change to the cooling system) or that have not been previously certified. It aims to drive energy efficiency and carbon reduction in mitigating the effects of climate change as well as other sustainable aspects that deliver on addressing the key sustainability drivers. The criteria are divided into two categories: energy efficiency and sustainability, where energy efficiency is the control item and sustainability is the scoring item, and consists of five parts: Intelligence, Health and Well-being, Whole-life Carbon, Maintainability, and Resilience (Table 4) [53]. The total score should be calculated using Equation (3). All the criteria are related to existing building CO_2 emission control.

$$Q_{GM} = Q^1_{GM} + Q^2_{GM} + Q^3_{GM} + Q^4_{GM} + Q^5_{GM} \quad (3)$$

Table 3. Criteria of BREEAM INDR 2015.

Criteria	Score	Weighting
Management	20	12%
• Health and wellbeing	22	15%
• Energy	34	15%
• Transport	11	9%
• Water	9	7%
• Materials	14	13.5%
• Waste	13	8.5%
• Land use and ecology	5	10%
Pollution	13	10%
Total		100%
• Innovation	10	10%

Scopes related to CO_2 emission.

Table 4. Criteria of GM:2021.

Attribute of Items	Criteria Related to CO_2 Emission	Score
Prerequisite items	• Energy Savings	Essential condition
Scoring items	• Intelligence	15
	• Health and wellbeing	15
	• Whole Life Carbon	15
	• Maintainability	15
	• Resilience	15
Total		75

Here, Q_{GM} is the total score of GM indicators and Q^1_{GM}–Q^5_{GM} are scores of the five indicators.

2.2.4. Assessment Standard for Green Retrofitting of Existing Building GB/T51141-202X (ASGREB-202X)

The latest version of the Assessment Standard for Green Retrofitting of Existing Buildings is GB/T 51141-202x; it is the next generation of GB/T 51141-2015. Compared with the 2015 version, the assessment scope of this version has been greatly changed from the original eight indicators to six indicators, and clearly proposed to reduce the carbon emission intensity per unit of floor area [54]. ASGREB-202X includes five required indicators: Safety and Durability, Health and Comfort, Occupant Convenience, Resources Saving, Environment Livability, and one bonus indicator, Promotion and Innovation (Table 5). The total credits should be calculated using Equation (4). All the criteria are related to existing building CO_2 emission control.

$$Q_{ASGREB} = (Q_0 + Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_A)/10 \quad (4)$$

Table 5. Criteria of ASGREB-202X.

Attribute of Items	Criteria Related to CO_2 Emission	Score
Prerequisite items		400
Scoring items	• Safety and Durability	100
	• Health and Comfort	100
	• Occupant Convenience	100
	• Resources Saving	200
	• Environment Livability	100
Bonus items	• Promotion Innovation	100
Total		1100

Here, Q_{ASGREB} is the total score of ASGREB indicators, and Q_0–Q_A are scores of the seven indicators.

2.3. Criteria-Based Tools Comparison and Life Cycle Assessment (LCA)

In this paper, two methods of comparative research based on evaluation criteria and full life cycle evaluation are used to construct the low-carbon retrofit path of existing public buildings. By using contents, weights, and the characteristics of its indicators, and at the same time, by analyzing the timeliness of its indicators, the design path is summarized from the perspective of the whole life cycle.

2.4. Specific Research Method: Weight Calculation (WC)

In the process of comparison, we not only made a qualitative analysis of the relevant indicators of low carbon in the evaluation system related to the green retrofitting of existing buildings, but also made a quantitative study on them.

The weight is a quantitative analysis of low-carbon-related indicators in order to clarify their proportion in the GBRS of each country. BREEAM itself is credited" and rated according to the credits ratio, and the weight of related indicators is affected by the weight of its scope. The specific calculation method is Equation (5).

$$B^{i}_{BREEAM} = P^{i}_{BREEAM}\, W^{i}_{BREEAM} / T^{i}_{BREEAM} \tag{5}$$

Here, B^{i}_{BREEAM} is the weight of indicators related to low-carbon design in category i of BREEAM INDR 2015; P^{i}_{BREEAM} is the maximum score of indicators related to CO_2 emission control of category i; T^{i}_{BREEAM} is the total score of criteria in category i; and W^{i}_{BREEAM} is the weight of every criterion.

LEED, GM, and ASGREB are scoring systems without a weighting system, so the weight of low-carbon-related indicators can be calculated by dividing its credits by the total credits of the standard. The weight of the indicators related to CO_2 emission control was calculated using Equation (6) in LEED v4.1 O + M.

$$B^{i}_{LEED} = P^{i}_{LEED} / T_{LEED} \tag{6}$$

Here, B^{i}_{LEED} is the weight of indicators related to the low-carbon design in category i of LEED v4.1 O + M; P^{i}_{LEED} is the maximum score of indicators related to CO_2 emission control of category i; and T_{LEED} is the total score of indicators in LEED v4.1 O + M.

The weight of the indicators related to CO_2 emission control was calculated using Equation (7) in GM:2020.

$$B^{i}_{GM} = P^{i}_{GM} / T_{GM} \tag{7}$$

Here, B^{i}_{GM} is the weight of indicators related to the low-carbon design in category i of GM:2020; P^{i}_{GM} is the maximum score of indicators related to CO_2 emission control of category i; and T_{GM} is the total score of indicators in GM:2020.

The weight of the indicators related to CO_2 emission control was calculated using Equation (8) in ASGREB-202X.

$$B^{i}_{ASGREB} = P^{i}_{ASGREB}/(T_{ASGREB} - 400) \tag{8}$$

Here, B^{i}_{ASGREB} is the weight of indicators related to the low-carbon design in category i of ASGREB-2019; P^{i}_{ASGB} is the maximum score of indicators related to CO_2 emission control of category i; and T_{ASGREB} is the total score of indicators without division in ASGREB-202X.

3. Results

Through comparative analysis, the CO_2-related indicators in the four GBRSs are listed and compared in terms of scope, weight, induction, and measure features.

3.1. Analysis of Scopes of Related Indicators

Through the analysis of categories involved in low-carbon retrofitting of existing public buildings in four systems, scopes of related indicators are summarized. ASGREB mainly involves "S&D (Safety and durability)", "H&C (Health and comfort)", "OC (Occupant convenience)", "RS (Resources saving)", "EL (Environment livable)", and "P&I (Promotion and innovation)", for a total of six scopes. LEED O + M mainly involves "LT (LOCATION AND TRANSPORTATION)", "SS (SUSTAINABLE SITES)", "WE (WATER EFFICIENCY)", "EA (ENERGY and ATMOSPHERE)", and "MR (MATERIALS and RESOURCES)", for a total of five scopes. BREEAM Nondomestic Refurbishment mainly involves eight scopes: "Hea (Health and wellbeing)", "Ene (Energy)", "Tra (Transport)", "Wat (Water)", "Mat (Materials)", "Wst (Waste)", "Pol (Pollution)", and "Inn (Innovation)". Green Mark mainly involves "EE (Energy Savings) ", "In (Intelligence)", "Hw (Health and Well-being)", "Cn (Whole Carbon)", "Mt (Maintainability)", and "Re (Resilience)", for a total of six scopes. Among them, "S&D", "RS", and "EL" in ASGREB; "MR" in LEED; "Mat" and "Wst" in BREEAM; and "Cn", "Re", and "Mt" in GM can be summarized as Material scope. "RS" in ASGREB; "SS" and "WE" in LEED; "Wat" in BREEAM; and "Re" in GM can be summarized as Water scope. "H&C", "RS", and "P&I" in ASGREB; "EA" in LEED; "Hea" and "Ene" in BREEAM; and "EE" in GM can be summarized as Energy scope. "OC" and "EL" in ASGREB; "LT" and "SS" in LEED; "Tra" and "LE" in BREEAM; and "Hw" and "Re" in GM can be summarized as Site scope. "OC", "RS", and "P&I" in ASGREB; "WE" and "EA" in LEED; "Hea", "Ene", and "Wat" in BREEAM; and "In" and "Cn" in GM can be summarized as Management scope. "EL" and "P&I" in ASGREB; "EA", "SS", and "MR" in LEED; "Ene", "Wst", "LE", and "Wat" in BREEAM; and "Cn", "Wat", and "Re" in GM can be summarized as Innovation scope (Figure 4).

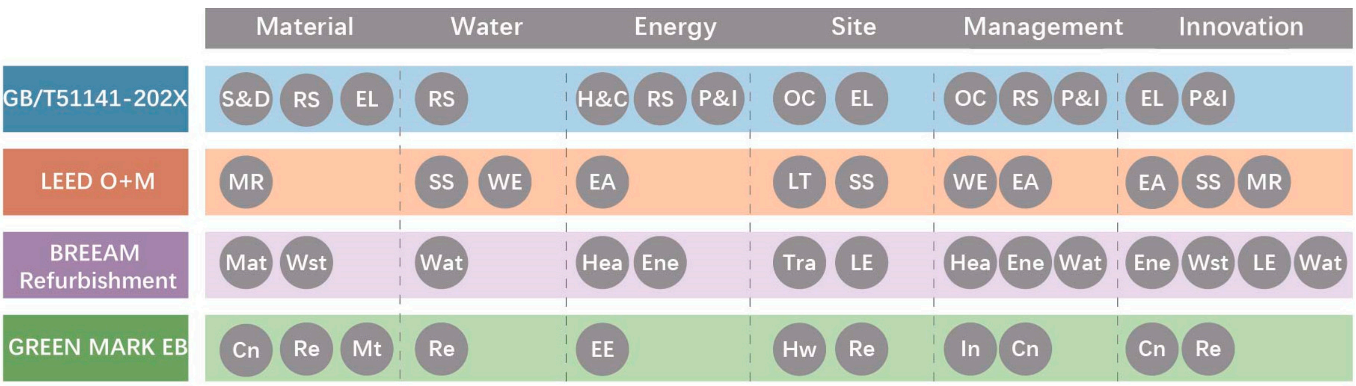

Figure 4. Scopes of related indicators.

3.2. Analysis of Scope Weights of Related Indicators

The scope analysis has clarified fields that need to be involved in the low-carbon retrofit of existing public buildings but does not give priority in the scope. The focus of each scope could be considered by analyzing scope weights.

In terms of indicators related to carbon emission control in the retrofitting of existing public buildings within the scope of Material, ASGREB mainly includes "4.2.1" (15 credits), "4.2.2" (10 credits), "4.2.7" (6 credits), "4.2.8" (10 credits), "4.2.9" (12 credits), "4.2.10" (14 credits), "7.2.12" (13 credits), "7.2.14"(10 credits), "7.2.16" (10 credits), "7.2.17" (8 credits), and "8.2.1 " (4 credits), which is 112 in total. According to Formula (8), the Material scope weight (ASGREB) is 16%. LEEDv4.1 O + M mainly includes MR (9 credits). The total LEED credits are 100. According to (6), it can be known that the Material scope weight (LEED) is 9%. BREEAM Nondomestic Refurbishment 2015 mainly includes "Mat 01" (5 credits), "Mat 03" (4 credits), "Mat 05" (1 credit), "Mat 06" (1 credit), "Wst01" (3 credits), "Wst02" (2 credit), and "Wst03" (1 credit). According to Formula (5), the Material scope weight (BREEAM) is 14.9%. Green Mark mainly includes "CN2" (5 credits), "CN3.2" (2 credits), "RE2.2" (3 credits), and "Mt" (15 credits), which is 25 in total. The total GM credits are 75. According to Formula (7), the Material scope weight (GM) is 13.3% (Table 6).

Table 6. Material scope CO_2-related indicators analysis.

GBRS	Indicators	Credits	Indicators	Credits	GBRS	Indicators	Credits
ASGREB	4.2.1	15	4.2.10	14	LEED	Waste performance	8
	4.2.2	10	7.2.12	13			
	4.2.7	6	7.2.14	10			
	4.2.8	10	7.2.16	10			
	4.2.9	12	7.2.17	8		Purchasing	1
			8.2.1	4			
GBRS	**Indicators**	**credits**	**GBRS**		**Indicators**		**credits**
BREEAM	Mat 01	5	GM		CN2 Construction		5
	Mat 03	4					
	Mat 05	1			CN3.2 Decoration Products		2
	Mat 06	1					
	Wst 01	3			RE2.2 Circularity		3
	Wst 02	2			Maintainability		15

In terms of indicators related to carbon emission control in the retrofitting of existing public buildings within the scope of Water, ASGREB mainly includes "II Water Saving and Water Resource Utilization" under "Resource Conservation" (60 credits); according to Formula (8 credits), the Water scope weight (ASGREB) is 8.6%. LEEDv4.1 O + M mainly includes "Rainwater Management" (1 credit) in "SS" and "Water Performance" (15 credits) in "WE". The total LEED credits are 100. According to Formula (6), it can be seen that the Water scope weight (LEED) is 16%. BREEAM Nondomestic Refurbishment 2015 mainly includes "Wat 01 "(6 credits) and "Wat 04" (1 credit); from Formula (5), it can be known that the Water scope weight (BREEAM) is 5.7%. Green Mark mainly includes "RE 1.1 b" (1 credit). The total GM credits are 75. According to Formula (7), the Water cope weight (GM) is 1.3% (Table 7).

In terms of indicators related to carbon emission control in the retrofitting of existing public buildings within the scope of Energy, ASGREB mainly includes "5.2.9" (6 credits), "5.2.12" (6 credits), "Resource Conservation", "I Energy Conservation and Energy Utilization" (80 credits), and "9.2.1" (30 credits), which is 122 in total. According to Formula (8), the Energy scope weight (ASGREB) is 17.4%. LEEDv4.1 O + M mainly includes "Energy Efficiency" (16.5 credits) and "Grid Harmonization" (1 credit) in "EA". The total LEED credits are 100. According to Formula (6), the Energy scope weight (LEED) is 17.5%. BREEAM Nondomestic Refurbishment 2015 mainly includes "Daylighting" (3 credits) in "Hea 01", "Ene 01" (19 credits), "Passive design" in "Ene 04" (2 credits), "Ene 05" (3 credits), "Ene 06

"(3 credits), "Ene 08" (2 credits), and "Ene 09" (1 credit); it can be seen from Formula (5) that the Energy scope weight (BREEAM) is 18.1%. Green Mark mainly includes "EE", which can be classified into the energy scope; it is a prerequisite basis for judging building energy consumption but is not scored (Table 8).

Table 7. Water scope CO_2-related indicators analysis.

GBRS	Indicators	Credits	GBRS	Indicators	Credits
ASGREB	RSII	60	LEED	Rainwater Management Water Performance	1 15
GBRS	**Indicators**	**credits**	**GBRS**	**Indicators**	**credits**
BREEAM	Mat 01	5	GM	RE 1.1 b Resources (ii)	1

Table 8. Energy scope CO_2-related indicators analysis.

GBRS	Indicators	Credits	GBRS		Indicators		Credits
ASGREB	5.2.9 5.2.12 RS I 9.2.1	6 6 80 30	LEED		Energy Efficiency Grid Harmonization		16.5 1
GBRS	**Indicators**	**credits**			**GBRS**	**Indicators**	**credits**
BREEAM	Hea 01 Ene 01 Ene 04	3 19 2	Ene 05 Ene 06 Ene 08 Ene 09	3 3 2 1	GM	EE	N/A

In terms of the indicators related to carbon emission control in the retrofitting of existing public buildings within the scope of Site, ASGREB mainly includes "I Travel and Barrier-Free" (12 credits), "8.2.3" (16 credits), and "8.2.9" (10 credits), which is 38 in total. According to Formula (8), it can be seen that the Site scope weight (ASGREB) is 5.4%. LEEDv4.1 O + M mainly includes "Heat Island Reduction" (1 credit) in "SS" and "Transportation Performance" (14 credits) in "LT". The total LEED credits are 100. According to Formula (6), the Site scope weight (LEED) is 15%. BREEAM Nondomestic Refurbishment 2015 mainly includes "Tra" (11 credits) and "LE 04" (1 credit). From Formula (5), it can be known that the Site scope weight (BREEAM) is 11%. Green Mark mainly includes "HW1.1" (2 credits) in "Hw", "RE1.2" (3 credits), and "RE3.1" (3 credits) in "Re", which is 8 in total. The total GM credits are 75. According to Formula (7), the site scope weight (GM) is 10.7% (Table 9).

Table 9. Site scope CO_2-related indicators analysis.

GBRS	Indicators	Credits	GBRS	Indicators	Credits
ASGREB	OCI 8.2.3 8.2.9	12 16 10	LEED	Heat Island Reduction Transportation Performance	1 14
GBRS	**Indicators**	**credits**	**GBRS**	**Indicators**	**credits**
BREEAM	Tra LE 04	11 1	GM	HW1.1 RE1.2 RE3.1	2 3 3

In terms of the indicators related to carbon emission control in the retrofitting of existing public buildings within the scope of Management, ASGREB mainly includes "III

Smart Operation" (29 credits) under the "Convenience of Life", "6.2.10" (6 credits), "6.2.13" (3 credits), and "9.2.4" (15 credits), which is 53 in total. According to Formula (8), the Management scope weight (ASGREB) is 7.6%. LEEDv4.1 O + M mainly includes "WE" and "Energy Performance" in "EA", which includes energy metering; they are related to Management but are not scored. BREEAM Nondomestic Refurbishment 2015 mainly includes "Internal and external lighting" in "Hea 01" (1 credit), "Ene 02" (1 credit), "Ene 03" (1 credit), "Wat 02" (1 credit), and "Wat 03" (2 credits); according to Formula (5), the Management scope weight (BREEAM) is 3.9%. Green Mark mainly includes "In" (15), "CN1.2" (5 credits), "CN3.1" (3 credits), and "CN3.3" (3 credits) in "Cn", which is 25 in total. The total GM credits are 75. According to Formula (7), the Management scope weight (GM) is 33.3% (Table 10).

Table 10. Management scope CO_2-related indicators analysis.

GBRS	Indicators	Credits	GBRS	Indicators	Credits
ASGREB	OC III	29	LEED	WE	N/A
	6.2.10	6			
	6.2.13	3		Energy Performance	
	9.2.4	15			
GBRS	**Indicators**	**credits**	**GBRS**	**Indicators**	**credits**
BREEAM	Ene 01	1	GM	In	15
	Ene 02	1			
	Ene 03	1		CN1.2	5
	Wat 02	1		CN3.1	3
	Wat 03	2		CN3.3	3

In terms of the indicators related to carbon emission control in the retrofitting of existing public buildings within the scope of Innovation, ASGREB mainly includes "7.2.16" (10 credits), "8.2.1" (9 credits), "9.2.5" (10 credits), and "9.2.9" (20 credits), which is 49 in total. According to Formula (8), it can be seen that the Innovation scope weight (ASGREB) is 7%. LEEDv4.1 O + M mainly includes "Rainwater Management" (1 credit), "Site Management" (1 credit) in "SS", "Energy Performance" (16.5 credits) in "EA", "Waste Performance" (8 credits), and "Purchasing" (1 credit) in "MR". The total LEED credits are 100. According to Formula (6), the Innovation scope weight (LEED) is 27.5%. BREEAM Nondomestic Refurbishment 2015 mainly includes "Ene 01" (2 credits), "Ene 04" (4 credits), "Mat 01" (5 credits), "Mat 06" (1 credit), "Wst 01" (3 credits), "Wst 02" (1 credit), "Wst03" (1 credit), "LE 02" (1 credit), and "LE 04" (1 credit); by Formula (5), it can be seen that the Innovation scope weight (BREEAM) is 15.7%. Green Mark mainly includes "CN1.1" (1 credit), "CN2.3" (3 credits), and "RE2.2" (3 credits), which is 7 in total. The total GM credits are 75. According to Formula (7), the Innovation scope weight (GM) is 9.3% (Table 11).

Table 11. Innovation scope CO_2-related indicators analysis.

GBRS	Indicators	Credits	GBRS	Indicators	Credits
ASGREB	7.2.16	10	LEED	Rainwater Management	1
	8.2.1	9		Site Management	1
	9.2.5	10		Energy Performance	16.5
	9.2.9	20		Waste Performance	8
				Purchasing	1

GBRS	Indicators	credits	Indicators	credits	GBRS	Indicators	credits
BREEAM	Ene 01	2	Wst01	3	GM	CN1.1	1
	Ene 04	4	Wst02	1		CN2.3	3
	Mat 01	5	Wst03	1			
	Mat 06	1	LE 02	1		RE2.2	3
			LE 04	1			

A comparison of the six scope weights is shown in Figure 5, with an average weight of 18.3% in the Materials scope, 7.9% in the Water scope, 17.7% in the Energy scope, 10.5% in the Site scope, 14.9% in the Management scope, and 14.9% in Innovation scope. Comparing its weights, it can be seen that $B^{Material}_{Average} > B^{Energy}_{Avera} > B^{Innovation}_{Average} = B^{Management}_{Average} > B^{Site}_{Average} > B^{Water}_{Average}$. Therefore, the Material and Energy scope should be taken into consideration when considering the retrofitting of existing public buildings.

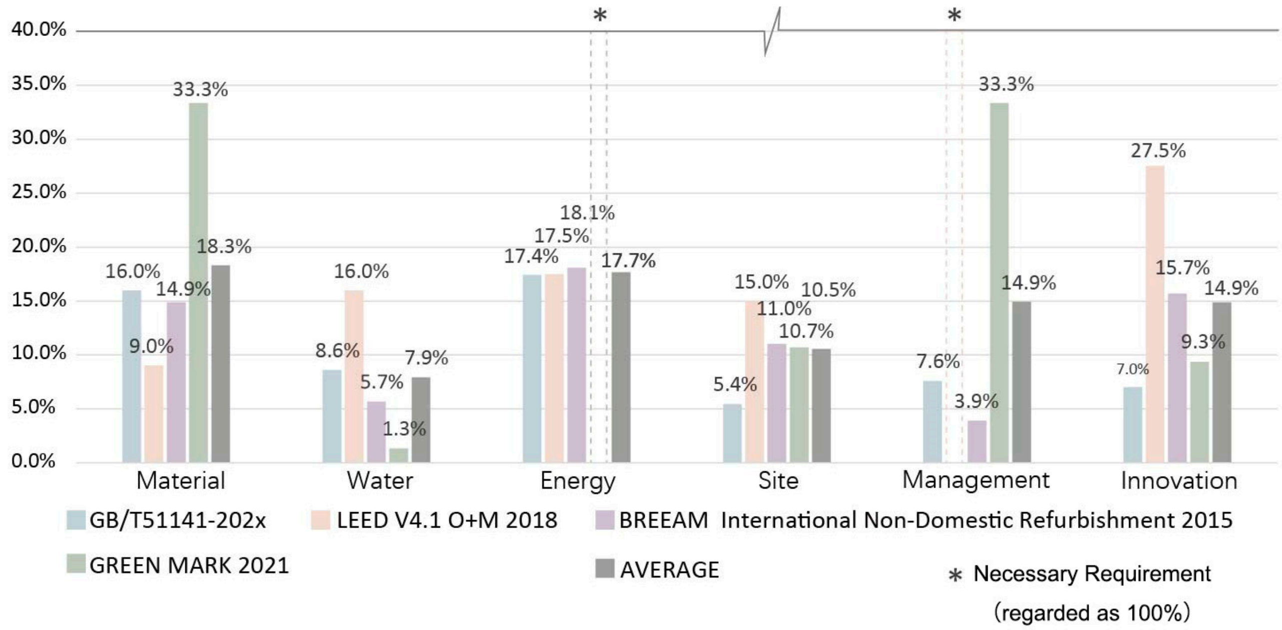

Figure 5. Analysis of scope weights.

3.3. Inductive Analysis of Indicators Related to Low-Carbon Retrofitting

The scope of low-carbon retrofit of existing buildings is clear, and measures for each scope should be summarized (Figure 6).

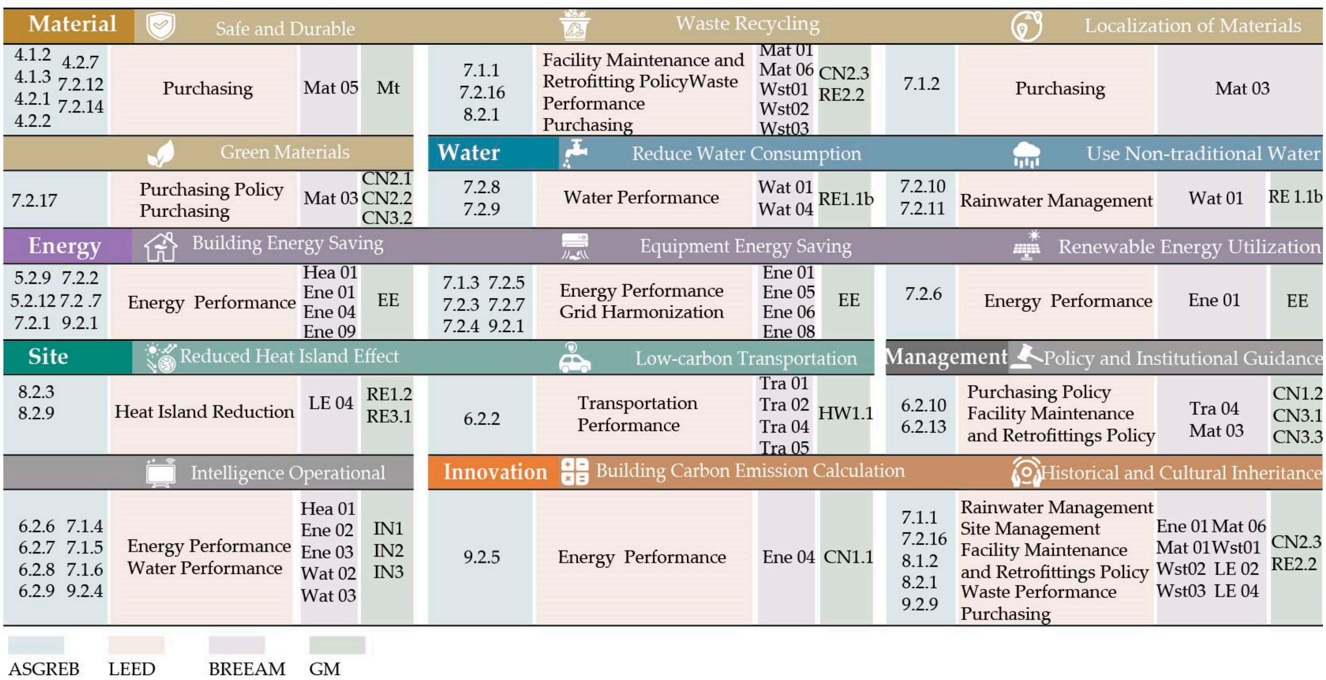

Figure 6. Measures in the GBRS.

In the Material scope, indicators 4.1.2, 4.1.3, 4.2.1, 4.2.2, 4.2.7, 7.2.12, and 7.2.14 in ASGREB; Purchasing of MR in LEED; Mat 05 in BREEAM; and Mt in Green Mark can be summed up as "Safe and Durable". Indicators 7.1.1, 7.2.16, and 8.2.1 in ASGREB; Facility Maintenance and Retrofitting Policy, Waste Performance, and Purchasing of MR in LEED; Mat 01, Mat 06, Wst01, Wst02, and Wst03 in BREEAM; and CN2.3 and RE2.2 in Green Mark can be summarized as "Waste Recycling". Indicators 7.1.2 in ASGREB; Purchasing of MR in LEED; and Mat 03 in BREEAM can be summarized as "Localization of Materials". Indicators 7.2.17 in ASGREB; Purchasing Policy and Purchasing of MR in LEED; Mat 03 in BREEAM; and CN2.1, CN2.2, and CN3.2 in Green Mark can be summarized as "Green Materials".

In the Water scope, 7.2.8 and 7.2.9 in ASGREB; Water Performance of WE in LEED; Wat 01 and Wat 04 in BREEAM; and RE1.1b Resource (ii) in Green Mark can be summarized as "Reduce Water Consumption". Indicators 7.2.10 and 7.2.11 in ASGREB; Rainwater Management of SS in LEED; Wat 01 in BREEAM; and RE 1.1b Resources (ii) in Green Mark can be summarized as "Use Non-traditional Water".

In the Energy scope, 5.2.9, 5.2.12, 7.2.1, 7.2.2, 7.2.7, and 9.2.1 in ASGREB; Energy Performance of EA in LEED; Daylighting of Hea 01, Ene 01, Ene 04, and Ene 09 in BREEAM; and EE in Green Mark can be summed up as "Building Energy Saving. Indicators 7.1.3, 7.2.3, 7.2.4, 7.2.5, 7.2.7, and 9.2.1 in ASGREB; Energy Performance and Grid Harmonization of EA in LEED; Ene 01, Ene 05, Ene 06, and Ene 08 in BREEAM; and EE in Green Mark can be summarized as "Equipment Energy Saving". Indicators 7.2.6 in ASGREB; Energy Performance of EA in LEED (referring to the use of renewable energy can improve credits); Ene 01 in BREEAM (plus the subitem mentions the utilization of renewable energy); and EE (any shortfall in performance can be made up by using on-site renewable energy) in Green Mark can be summarized as "Renewable Energy Utilization".

In the Site scope, 8.2.3 and 8.2.9 in ASGREB; Heat Island Reduction of SS in LEED; and LE 04 in BREEAM; and RE1.2 and RE3.1 in Green Mark can be summarized as "Reduced Heat Island Effect". Indicators 6.2.2 in ASGREB; Transportation Performance of LT in LEED; Tra 01, Tra 02, Tra 04, and Tra 05 in BREEAM; and HW1.1 in the Green Mark can be summarized as "Low-carbon Transportation".

In the Management scope, 6.2.10 and 6.2.13 in ASGREB; Purchasing Policy, Facility Maintenance, and Retrofittings Policy of MR in LEED; Tra 04 and Mat 03 in BREEAM; and CN1.2, CN3.1, and CN3.3 in Green Mark can be summarized as "Policy and Institutional Guidance". Indicators 6.2.6, 6.2.7, 6.2.8, 6.2.9, 7.1.4, 7.1.5, 7.1.6, and 9.2.4 in ASGREB; Energy Performance of EA in LEED (referring to energy metering); Water Performance (referring to water metering) of WE in LEED; Hea 01, Ene 02, Ene 03, Wat 02, and Wat 03 in BREEAM; and IN1, IN2, and IN3 in Green Mark can be summarized as "Intelligence Operational".

In the Innovation scope, 9.2.5 in ASGREB; Energy Performance of EA (including carbon emission fractions) in LEED; Ene 04 in BREEAM; and CN1.1 in Green Mark can be summarized as "Building Carbon Emission Calculation". Indicators 7.1.1, 7.2.16, 8.1.2, 8.2.1, and 9.2.9 in ASGREB; Rainwater Management, Site Management of SS, Facility Maintenance and Retrofittings Policy, Waste Performance, and Purchasing of MR in LEED; Ene 01, Mat 01, Mat 06, Wst01, Wst02, Wst03, LE 02, and LE 04 in BREEAM; and CN2.3 and RE2.2 in Green Mark can be summarized as "Historical and Cultural Inheritance".

3.4. Analysis of Features of the Measures

3.4.1. Life Cycle Analysis

According to the GBRSs, the implementation stages of different indicators are different, and the low-carbon design of each stage should be comprehensively considered. From the perspective of the six scopes, the four specifications are highly consistent in the four scopes of Material, Water, Energy, and Innovation, covering the design, construction, use, and demolition stages. In Site, all four standards cover the design and construction phase, with LEED adding the operational phase. In Management, LEED, BREEAM, and GM all cover the design, construction, and operation phases, while ASGREB covers the full life cycle (Figure 7).

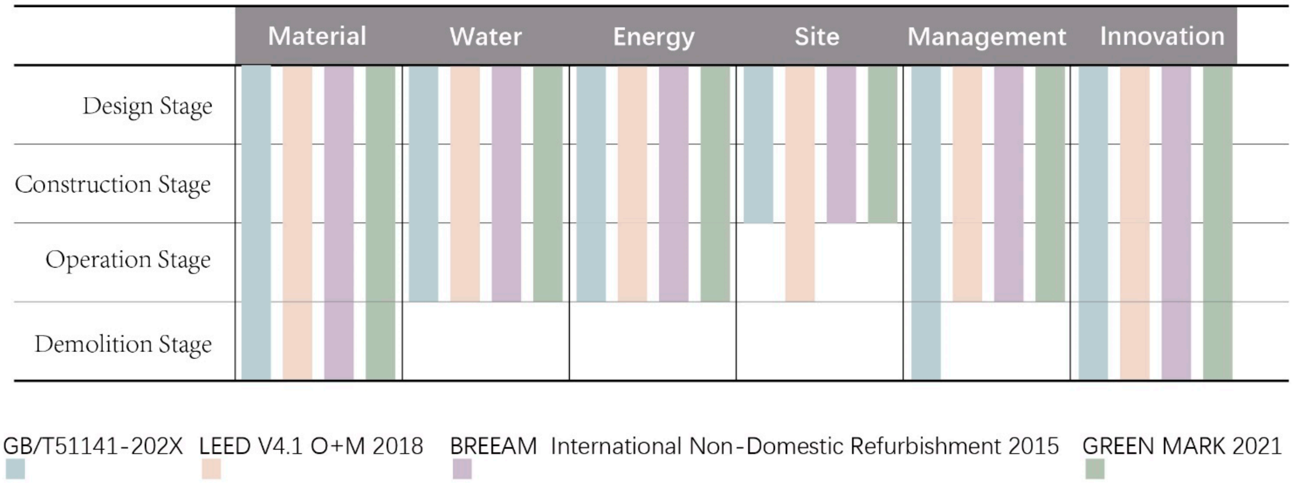

Figure 7. Implementation involving different stages.

3.4.2. Necessary and Recommended Ones

The fifteen indicators are analyzed and summarized from the four GBRSs; each standard includes control items and scoring items, among which the control items are mandatory to meet the standards and are green technologies that must be followed in the low-carbon retrofitting of existing buildings. A total of 11 of these 15 standards can be regarded as necessary measures for the low-carbon retrofitting of existing buildings, namely, Safe and Durable, Waste Recycling, Localization of Materials, Green Materials, Reduce Water Consumption, Buildings Energy Saving, Equipment Energy Saving, Low-carbon Transportation, Intelligent Operation, Building Carbon Emissions Calculation, and Historical and Cultural Inheritance. The remaining four measures are recommended measures, namely, Use Non-Traditional Water, Renewable Energy Utilization, Reduce Heat Island Effect, and Policy and Institutional Guidance. The distribution of low-carbon-related control items of each standard is shown in Figure 8 below, among which three national standards involve Equipment Energy Saving in the necessary items; two national standards involve Waste Recycling, Green Materials, Reduce Water Consumption, Buildings Energy Saving, Intelligent Operation, and Historical and Cultural Inheritance in the necessary items; and one national standard involves Safe and Durable, Localization of Materials, Low-carbon Transportation, and Building Carbon Emissions Calculation in the necessary items. The analysis of the proportion of the control items of each standard shows that the number of low-carbon-related necessary items in LEED is the largest, accounting for 60%, followed by ASGREB, accounting for 47%; BREEAM and GM are 13% and 7%.

3.4.3. Context Correlation Analysis

The measures aimed at low carbon in the rating system for the retrofitting of existing buildings in various countries are full of contextual considerations. In this paper, six measures that are closely related to the context have been extracted. They are Waste Recycling, Localization of Materials, Buildings Energy Saving, Reduce Heat Island Effect, Low-carbon Transportation, and Historical and Cultural Inheritance. From the perspective of the relationship with the context, three measures can directly reflect the context (strongly context-related measures); they are Waste Recycling, Localization of Materials, and Historical and Cultural Inheritance. The other three measures, which are Buildings Energy Saving, Reduce Heat Island Effect, and Low-carbon Transportation, need to take into account local conditions during the implementation process in order to better inherit the cultural context (Figure 9).

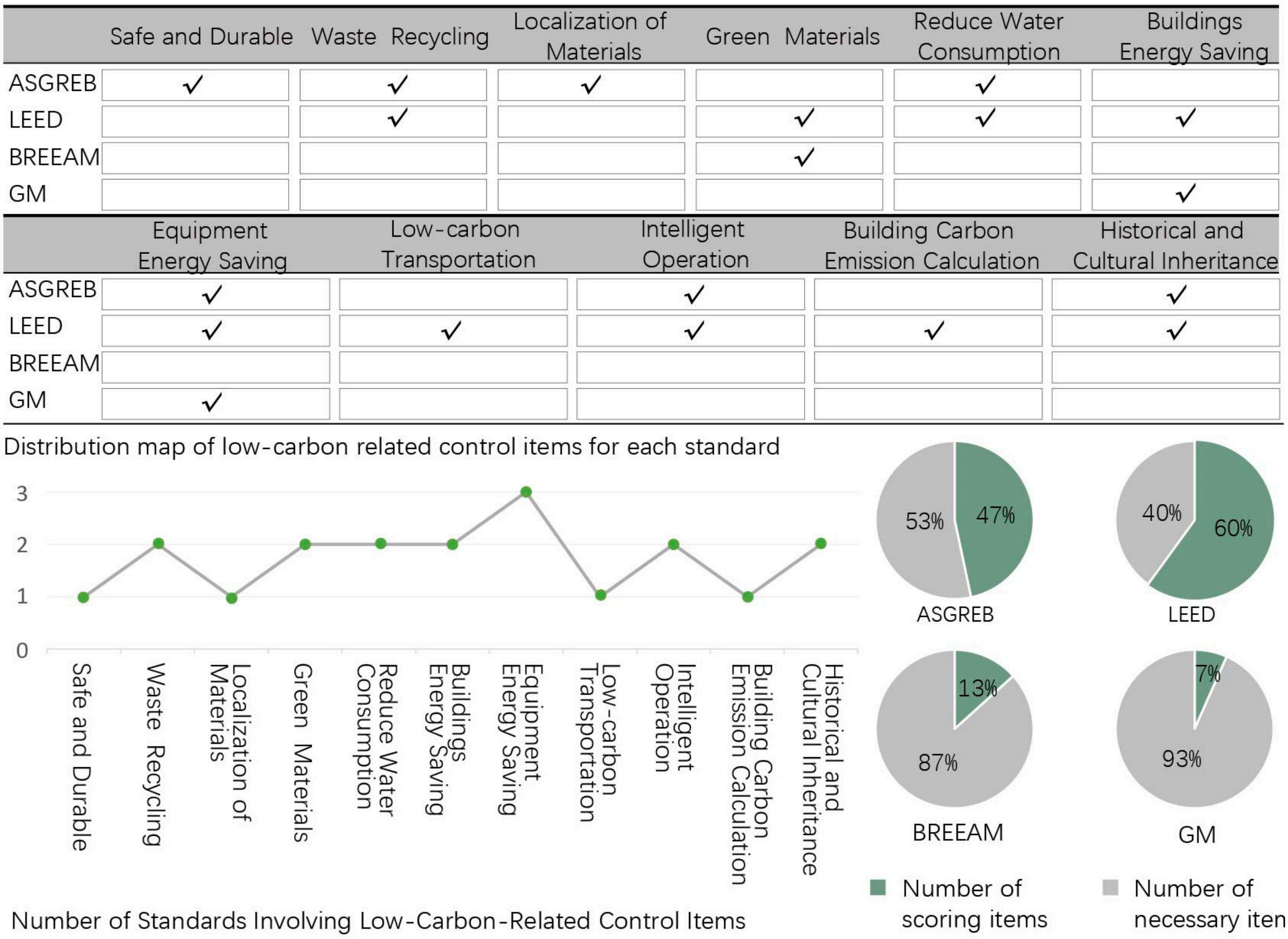

Figure 8. Analysis of necessary and recommended items.

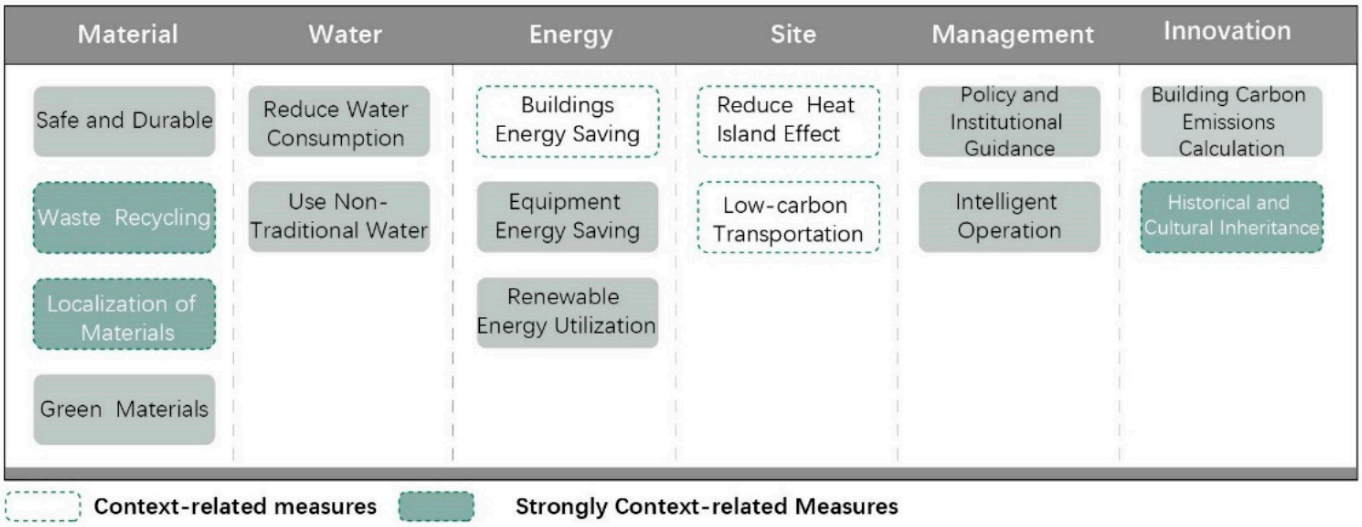

Figure 9. Context-related items of measures.

In terms of the weighting of the scores of the indicators related to the context, the Materials and Innovation scopes involved the highest average weighting of the culture indicators, with 8% and 9.4%, respectively. The weights and percentages of the four GBRSs in the Material and Innovation Scopes are shown below (Figure 10). In the scope of Materials, the weight related to context in ASGREB is 2%, accounting for 12% of the index credits in this scope. LEED was 9%, accounting for 100% of the index credits in this scope; BREEAM was 12.9%, accounting for 87% of the index credits in this scope; GM was 8%, accounting for 24% of the index credits in this scope. In the scope of innovation, the weight related to context in ASGREB is 5.6%, accounting for 80% of the index credits in this scope, and LEED is 11%, accounting for 40% of the index credits in this scope. BREEAM is 13.1%, accounting for 83% of the index credits in this scope, and GM is 8%, accounting for 86% of the index credits in this scope.

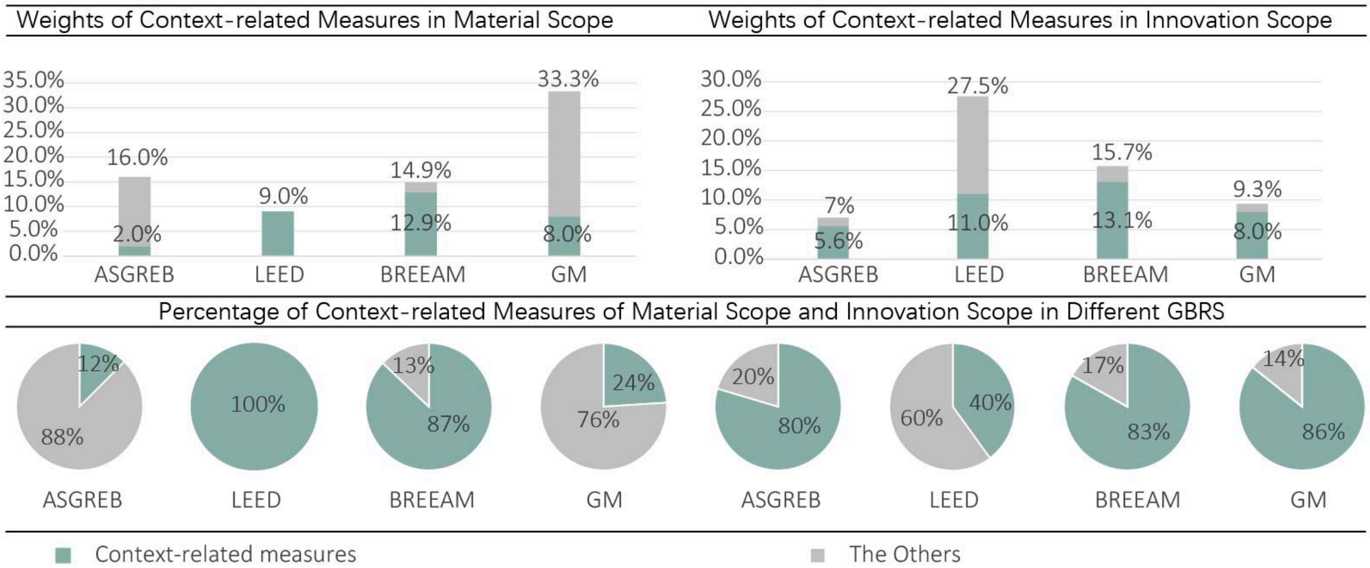

Figure 10. Analysis of context-related items.

Through the reuse of waste materials, some materials of old buildings are preserved. These materials have historical imprints and textures, and their colors are also the continuation of historical memory. Therefore, Waste Recycling is conducive to the continuation of context. The use of localized building materials is conducive to promoting regional culture, highlighting regional characteristics, and helping to change the situation of "one thousand cities". Therefore, Localization of Materials is conducive to the continuation of context. By designing the building body, passive means are used to create atriums, patios, and other spatial forms that are not only conducive to energy saving, but are also cultural symbols of the old buildings and the embodiment of the cultural lineage; therefore, Buildings Energy Saving is conducive to the continuation of context. Measures to reduce the heat island effect include adjusting the local microclimate by setting up greenery. The choice of greenery will affect the expression of the context. Adopting local greenery can create a landscape atmosphere that echoes the local culture and is conducive to the inheritance of the context. Therefore, Reduce Heat Island Effect is conducive to the continuation of context. The planning and design of low-carbon transportation is closely related to the site itself. Respecting the historical conditions of the site is a respect for the cultural context. Therefore, Low-carbon Transportation is conducive to the continuation of context. The inheritance of history and culture is an intuitive expression of the inheritance of the context. Therefore, Historical and Cultural Inheritance is conducive to the continuation of context.

3.4.4. Qualitative and Quantitative Analysis

A total of 11 of these 15 indicators involve quantitative calculation, namely, Waste Recycling, Localization of Materials, Green Materials, Reduce Water Consumption, Use Non-Traditional Water, Buildings Energy Saving, Equipment Energy Saving, Renewable Energy Utilization, Reduce Heat Island Effect, Low-carbon Transportation, and Building Carbon Emissions Calculation. Among them, LEED gives the calculation methods of low-carbon transportation (9), (10), and (11), and building carbon emissions (12) and (13);

BREEAM gives 1–3 points depending on the amount of CO_2 reduction percentage; and GM propose using the Embodied Carbon Calculator to Calculate the embodied carbon of the development. In terms of the quantity of indicators, the indicators that need to be calculated quantitatively account for 73% of the total, and other qualitative indicators account for 27% (Figure 11).

$$\text{adjusted GHG emissions} = (\text{GHG emissions} * \text{outside temperature adjustment factor} * \text{operating hours adjustment factor})/365\ \text{days} \quad (9)$$

$$\text{GHG emissions per occupant} = \text{adjusted GHG emissions}/\text{weighted occupancy} \quad (10)$$

$$\text{GHG emissions per floor area} = \text{adjusted GHG emissions}/\text{gross floor area} \quad (11)$$

$$CO_2e\ \text{for route (lbs.)} = (CO_2e\ \text{lbs./mile}) * \text{distance traveled in miles} \quad (12)$$

$$CO_2e\ \text{for individual occupant (lbs.)} = (\textstyle\sum CO_2e\ \text{for route})/\text{routes} \quad (13)$$

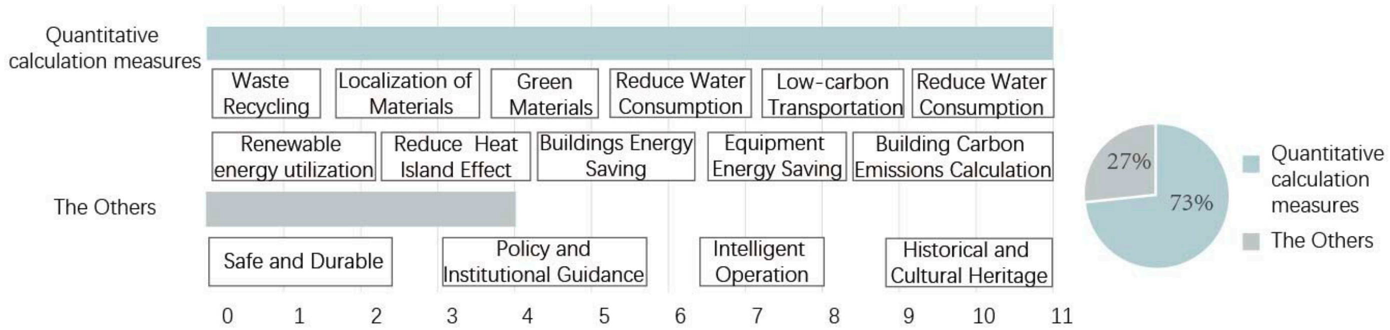

Figure 11. Analysis of qualitative and quantitative items.

4. Discussion

In this paper, for the first time, low carbon is discussed as a concept in the context of retrofitting existing public buildings, and indicators are summarized from the perspective of GBRSs to build a framework for low-carbon retrofitting of existing public buildings to guide design. Based on the above six scopes and 15 measures, a low-carbon retrofitting path for existing buildings can be constructed (Figure 12). For the material scope, the selection and optimization of materials need to be considered, including the factors Safe and Durable, Waste Recycling, Localization of Materials, and Green Materials. For the energy scope, new energy utilization and energy saving measures should be considered, including Buildings Energy Saving, Equipment Energy Saving, and Renewable Energy Utilization. For water and site scopes, site and landscape design need to be considered, including Reduce Heat Island Effect, Low-carbon Transportation, and water conservation. For the management scope, an intelligent operation management system should be considered, including Policy and Institutional Guidance and Intelligent Operation. In the scope of innovation, carbon reduction-oriented design should be considered, and attention should be paid to the calculation of project carbon emissions. In addition, low-carbon design that integrates cultural heritage should be actively considered. Low carbon itself includes the part of context, which should be considered more in the design.

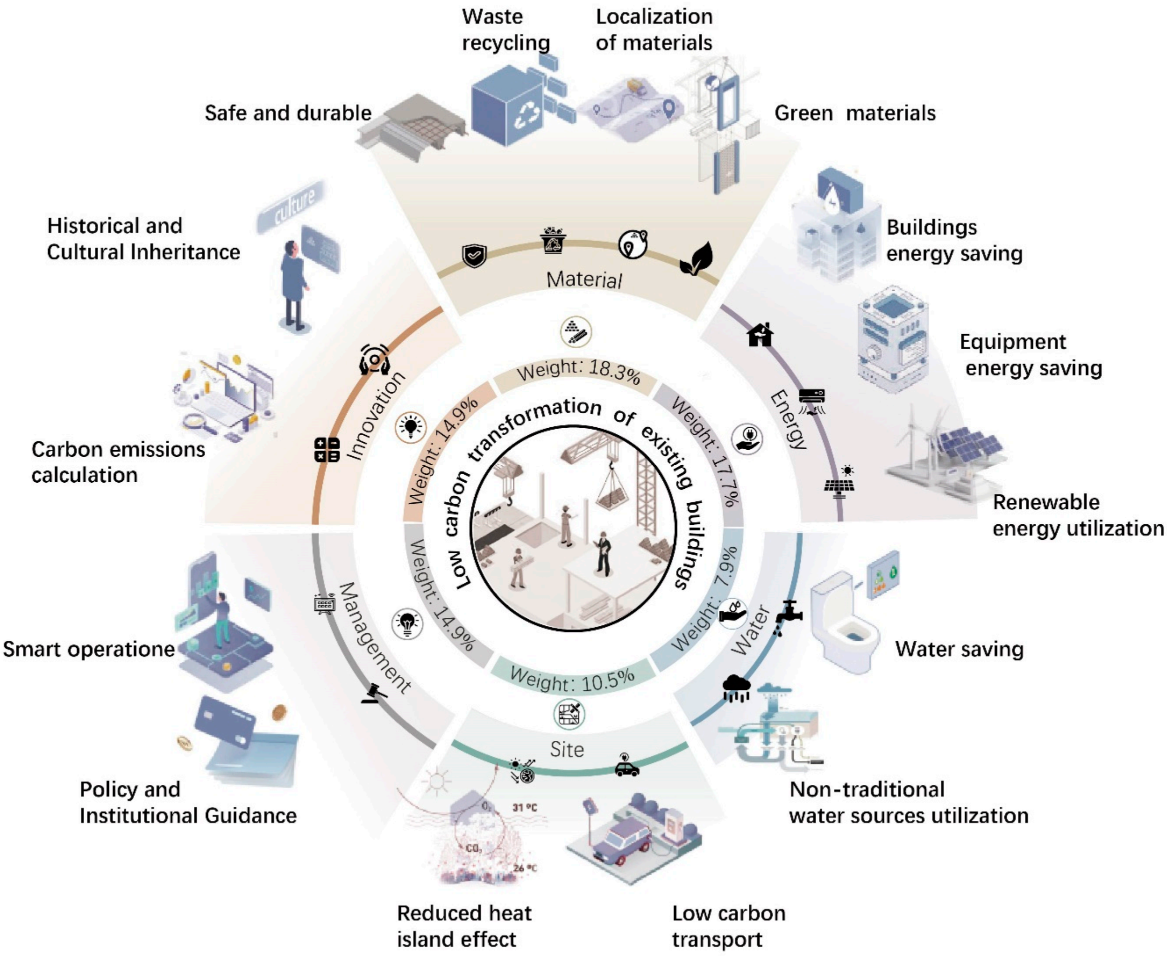

Figure 12. The low-carbon retrofitting path for existing buildings.

4.1. Material Selection and Optimization

Compared with new buildings, the safety of existing buildings is not considered from the beginning of construction, and with the age and dilapidation, it is more important to give priority to safety when retrofitting them [55]. Therefore, the safety of materials should be considered in the selection of materials, including the load-bearing capacity, strength, maintainability, and the impact on the old materials. In addition, from the perspective of cultural heritage, new materials can take two forms; one is different from the original form, and the other is similar to the original form; the former is conducive to highlighting the special characteristics of the original building materials, and the latter is conducive to maintaining consistency with the original style. The degree of retrofitting of existing buildings varies, and for noncultural preservation buildings, most of them are facing demolition and retrofitting, involving the replacement of various materials. From the perspective of cultural heritage and low carbon, the use of old materials should be given priority in the retrofitting, and local preservation or re-creation can be considered according to the specific conditions of the materials so that the old materials can realize their own recycling, not only to reduce the carbon emission in the production of new materials but also to reproduce the old texture and form with different shapes and to fulfill low carbon and cultural heritage at the same time. When using new materials, priority should be given to local materials, and building materials produced within 500 km are preferred in order to reduce carbon emissions during transportation, while local context should be tapped and materials that meet regional characteristics or local culture should be selected; in addition, we should also consider the low carbon of the building materials themselves and choose green building materials with a low-carbon production process.

4.2. New Energy Utilization and Energy Saving

Energy consumption is the main source of carbon emissions in the process of building use, and the energy consumption of existing buildings is generally high due to the low age standard [10], and controlling energy consumption is a necessary measure for the low-carbon retrofit of existing buildings. The retrofit design of the building itself will affect the energy consumption, and passive retrofit measures adapted to local conditions should be considered, fully taking into account ventilation, lighting, and climate conditions; incorporating traditional energy-saving concepts; drawing on its spatial form, local details, and layout; and improving the performance of the building itself [53]. The energy consumption of the equipment itself should not be neglected. Equipment that meets energy-saving standards should be selected, and special attention should be paid to the efficiency of its supporting transmission and distribution systems, such as pumps and fans, whose energy consumption account for 30% and more of the energy consumption of the entire HVAC system. The use of renewable energy can reduce carbon emissions without reducing energy use; it should be used in conjunction with the actual situation of the site, such as wind, solar, water, and other clean energy.

4.3. Intelligent Operation Management

Intelligent methods can improve management efficiency, and energy submetering and equipment zoning control can be used to achieve fine management of energy. Energy submetering is good for managers to accurately control the actual energy consumption of the project from the perspective of data feedback so as to reduce energy consumption and carbon emissions in an oriented manner, and equipment zoning control is good for using energy according to demand and avoiding unnecessary waste. In addition, BIM technology can be used for the whole life cycle management of the project to improve the quality and efficiency of the whole project and avoid additional carbon emissions due to inefficiency [56]. In addition, user behavior can be guided to be low-carbon through the construction of data platform, the release of corresponding policies, and the provision of regular green education and publicity, such as encouraging users to purchase energy produced by renewable energy or other economic forms to motivate users to save energy, water, and materials by offsetting rent [53].

4.4. Carbon Reduction-Oriented Design

The quantification of carbon emissions is a direct consideration of the carbon-reduction effect, and the low-carbon retrofit of existing public buildings should be based on carbon reduction effect-oriented design. The above four GBRSs all require carbon emission calculation to different degrees, among which LEED proposes a carbon emission calculation formula, BREEAM mentions carbon-neutral consideration, GM explicitly mentions whole life cycle carbon emission of buildings, and ASGREB proposes to reduce carbon emission intensity per unit of building area, where the calculation approach could refer to the national standard GB/T 51366-2019 [57]. Carbon emissions can be predicted by energy consumption simulation in the design stage of retrofitting to verify the rationality of the design and make targeted modifications.

4.5. Actively Considered Low-Carbon Design That Integrates Local Context

Local context is an important connotation of low carbon, and the relevance of local context and low carbon has been explained in the previous analysis. Currently, "existing context" and "low carbon" are both hot topics of discussion, and it is necessary to combine them. In addition to the abovementioned indicators that are strongly related to the local context, other measures should be actively explored to take both into account, such as retrofitting the old equipment itself as a basis for new energy use and using the old equipment itself as an architectural space. Shanghai Nancheng Power Plant has retrofitted its fly ash separator into a base for wind power generation, preserving the material and making a contribution to low carbon while preserving the memory [58]. Shanghai Yang

Shupu Power Plant Site Park has freed up the net pond space in a cafe, retrofitted the ash bin space in an art gallery, and renovated the pump pit space in an art space [59]. This equipment was originally engaged in production, not human activity space, and turning them into architectural space satisfies the requirement of land conservation. The saved land can be used for greening, strengthening the carbon sink effect, and also continuing the cultural lineage in terms of spatial forms.

4.6. Site and Landscape Design

The design of the site should focus on reducing the heat island effect to improve the microclimate of the site, from the perspective of site shading, high reflectivity of road paving and roofing, planting, etc. It can also be combined with the practice of sponge city to collect rainwater and reuse it for landscape water and create a good microclimate with wind direction. To show the context, the shading of the site can be directly adopted from the existing components or expressed in the form of new materials; the roads and roofs can be made of materials similar to the texture and color of the original site. In addition, native plants with regional characteristics can be selected to create landscape nodes together with water bodies and old components [59]. Plants can be used in the form of drip irrigation and other forms of water replenishment to save water resources. As the main carrier of carbon sink, plants should be expanded from multiple dimensions as much as possible, and the form of three-dimensional greening can be considered to give full play to its carbon sequestration [52]. If the site belongs to a large area scattering a number of existing buildings with high cultural value, it can be made into a cultural area. The vitality of the entire area can be stimulated through site space design with a series of large and small landscape nodes, connected by a roaming path. Furthermore, low-carbon travel should be guided to reduce carbon emissions generated by motor vehicle travel. To further promote low-carbon travel, charging piles can be arranged at suitable locations, and barrier-free design can be considered to meet the requirements of different people, while respecting the site conditions and on the basis of not damaging the hydrology, historical conditions, and greenery of the site. In addition, users' travel habits should be considered, and bicycle parking points should be reasonably arranged to provide diversified options for low-carbon transportation, while the accessibility of public transportation should be improved, and the use of private motor vehicles should be reduced

5. Conclusions

Based on the comparative analysis of GBRS, this study obtains the relevant contents of low-carbon retrofitting of existing public buildings. The main findings are as follows:

1. The related CO_2 emission control indicators of retrofitting existing public buildings are clarified based on the comparison of GBRS firstly, covering six scopes: materials, energy, management, innovation, site, and water.
2. The material (weight: 18.3%) and energy (weight: 17.7%) ranges should be considered first in the low-carbon retrofit of existing public buildings. Among the remaining scopes, according to their average weights, the scopes that should be considered, in order, are: management (weight: 14.9%), innovation weight (weight: 14.9%), site (weight: 10.5%), and water (weight: 7.9%).
3. A total of 15 measures for the retrofitting of existing public buildings are summarized in the six scopes. Of these, 11 measures are required and 4 are recommended.
4. Context is the essential part that needs to be paid attention to in the low-carbon retrofitting of existing public buildings. More than 80% of the points in the low-carbon-related part of the indicator are related to the local context, which is reflected in both materials and innovation scopes.
5. It is analyzed that the low-carbon retrofitting of existing public buildings needs quantitative calculation, which accounts for 73% of the total index.
6. This study proposes a low-carbon retrofit path for existing public buildings, which should pay more attention to six measures: material selection and optimization,

new energy utilization and energy saving, intelligent operation management, carbon reduction-oriented design, actively considered low-carbon design that integrates cultural heritage, and site and landscape design.

Low carbon has rarely been discussed as a necessary design concept in the past, nor has it been developed into a systematic design approach. This study provides theoretical and methodological guidance for the low-carbon retrofitting of existing public buildings. The research results are mainly derived from the comparative analysis of the relevant indicators of the four GBRS, mainly related to the carbon emission reduction of building energy consumption and material consumption. In this paper, we mainly discuss the low-carbon indicators mentioned in GBRS, and there is a lack of model validation. In future research, we will demonstrate the rationality and validity of our framework path in the design of specific projects.

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