Research on Differentiated Carbon Reduction Methods for Existing Communities from the Perspective of "Low-Carbon Justice"

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Full Text

Preamble

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Abstract

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endowments and demands among communities, leaving old communities trapped in renovation dilemmas due to fund shortages, while emerging communities enjoy technological dividends, thus exacerbating the "green gap" . Based on justice theory and zero-carbon community standards, this study puts forward a theoretical framework of "Low-Carbon Justice" , and constructs an evaluation indicator system containing 20 factors. The AHP-fuzzy comprehensive evaluation method is adopted to determine the weights and grades of indicators, and a strategy implementation sequence is established combined with the IPA model, on the basis of which a classification system for low-carbon communities is further proposed to realize the design of differentiated renewal paths. Taking Liangzhu Cultural Village in Hangzhou as an empirical object, this study verifies that it is an energy-saving renovation community through multi-dimensional investigation and quantitative evaluation (public perception of low-carbon potential: 85.86 points / Grade), and puts forward targeted renovation strategies for buildings and natural environment. The results show that the differentiated renewal framework can effectively bridge the low-carbon capacity gap between communities, and provide a theoretical basis and practical paradigm for policy formulation.

Keywords

Low-Carbon Justice; Community Renewal; Social Space; Evaluation Method; Classified Policy Implementation

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1.1. Background

Against the global backdrop of climate change response, achieving carbon neutrality has become a core goal of urban development in all countries, and promoting the low-carbon transformation of urban renewal has emerged as a critical pathway. This challenge is particularly prominent in developing countries undergoing rapid urbanization. As one of the countries with the fastest urbanization process in the world, China has entered a stage of stock renewal in urban development in recent years, and its practice of promoting community low-carbon transformation under the "Dual Carbon" goals is confronted with major challenges: a large number of extensively constructed infrastructures have resulted in a significant carbon lock-in effect, the principal mechanism for the renewal and renovation of existing

buildings remains imperfect, and community-level governance capacity needs to be improved. As a key emission source (accounting for 40% of global greenhouse gas emissions)[1], the emission reduction performance of the construction industry directly affects the achievement of climate targets[2]. Global comparisons reveal structural injustice in carbon emissions: developed countries have achieved the decoupling of GDP from carbon emissions, while the two indicators remain strongly positively correlated during the industrialization process of developing countries[3].

From a micro-scale perspective, meanwhile, the remarkable differences in resource endowments, development stages and group characteristics among communities lead to the risk of injustice easily triggered by homogeneous renewal strategies: vulnerable communities can hardly afford renovation costs due to a lack of funds and technology, while advantaged groups enjoy the dividends of technological spillover, exacerbating the gap between the rich and the poor[4-6]. From 2010 to 2021, China' s residential building area increased by 42.7% to 56.5 billion square meters[7], and the reality of continuously rising energy consumption highlights the urgency of transformation. The 14th Five-Year Plan has listed urban renewal as a national strategy, requiring the coordination of environmental, economic and social dimensions[8] However, under the traditional perspective of renewal, the top-down urban renewal model deprives residents of their right to speak, causing some urban renewal projects to neglect vulnerable groups and even give rise to social segregation and the "island" effect. Therefore, a fair and reasonable distribution mechanism must emphasize the identity and participation of community groups, and highlight local characteristics and residents' cultural sense of belonging in renewal planning schemes.

Differences in historical cumulative carbon emission responsibilities require adherence to the principle of "common but differentiated responsibilities"[9]. There is an urgent need to construct a justice-oriented differentiated renewal pathway to achieve the synergy between social equity and low-carbon goals [10], and in particular to prevent the cost of the "green gap" from being transferred to vulnerable groups[6,10,11].

Low-carbon transformation and community renewal pose new challenges to the realization of spatial justice. Carbon emission reduction is a consistent action program committed to by all countries worldwide to mitigate climate change.

Carbon emission reduction involves more than just energy transformation; cities, as end-users of energy, are key to

carbon emission reduction. Communities in cities are the basic social spatial units. They are not only the principal entities bearing the responsibility for carbon emission reduction, the main objects and starting points for carbon emission reduction, but also the beneficiaries of improved environmental quality[12]. Their particularity is reflected in three dimensions: first, systematicness, requiring the coordination of building renovation, energy system renewal and lifestyle transformation; second, structural differences, with old communities and emerging communities showing a significant gradient in carbon emission intensity, renovation potential and residents ' affordability; third, complex justice relations, requiring the balance of the equivalence of rights and responsibilities between the distribution of emission reduction responsibilities and the sharing of environmental benefits[13,14].

The traditional "one-size-fits-all"model ignores the above characteristics, leading to policy failure. There is an urgent need to construct a theoretical framework of community low-carbon justice, identify differentiated renewal pathways

through a scientific evaluation system, ensure that the transformation process does not exacerbate social injustice, and ultimately achieve the mutual promotion of spatial justice and low-carbon development.

1.2. Literature Review

The Theory of Justice in Spatial Reproduction

As early as the 19th century, Engels criticized the injustice manifested in workers ' housing in Britain from the perspective of class struggle in his works[15]. Influenced by him, utopian socialists Owen and Wallace put forward utopian concepts such as "workers' village" and "garden city" respectively[16]. Neo-Marxists in the 1960s, represented by Lefebvre, continued the critique of capital movement, explicitly proposed the basic concepts of "social space" and "spatial justice" [17], and pointed out the importance of examining justice issues in daily life.

In the wake of post-war reconstruction and large-scale slum clearance in the West, the "anti-gentrification" movement emerged in the field of planning practice[18], and issues related to environmental justice were also highlighted[19]. With the outbreak of the oil crisis in the 1980s, concepts such as "energy justice" [20] and "sustainability justice" [21] became hot research topics in sociology, architecture and urban planning disciplines.

At present, prominent injustices exist in the practice of spatial renewal: the traditional top-down model deprives residents of their right to speak, and consumerism-led renovation encroaches on daily living spaces, resulting in the systematic neglect of the needs of vulnerable groups[4,5,22]. This is embodied in three dilemmas:First, the commercial value of low-cost old residential spaces is excessively exploited, and consumerism-dominated community renewal occupies too much daily living space of residents, catering to social groups with consumption propensity while segregating low-income and low-consumption groups; Second, residents remain passive and inactive in the top-down-led renewal mechanism and process of residential areas, leading to the disconnection between renewal schemes and the lifestyle of indigenous residents and the emergence of informal spatial practices[23]; Third, the homogenized renovated space loses its original cultural deposits and spirit of place, weakening residents ' sense of identity and belonging[24].

Justice in spatial practice should break through the two-dimensional framework of traditional social contract and resource distribution, and emphasize the interaction among spatial production, power allocation and identity construction. Its core value in low-carbon renewal lies in breaking the one-dimensional logic of "efficiency first" in the traditional transformation model, and ensuring the fair sharing of ecological governance achievements through a multi-dimensional interest balance mechanism.

The internal correlation between community low-carbon transformation and spatial justice is essentially reflected in the spatial fairness of resource allocation, cost sharing and right enjoyment. Spatial justice guarantees that different groups equally access resources, opportunities and development rights in geographical space. As a profound social transformation, low-carbon transformation reshapes the distribution pattern of urban spatial resources through such measures as energy structure adjustment (e.g., layout of renewable energy facilities)[25], infrastructure upgrading (e.g.,

low-carbon transportation network), and building renovation (e.g., green building promotion) [26].

On the one hand, the current carbon emission reduction target has become the core driving force for global sustainable social transformation. Without justice considerations, "low-carbon gentrification" may occur[18] —that is, high-cost low-carbon renovation raises the living cost of communities, forcing low-income groups to move out, or some communities fail to enjoy the dividends of low-carbon facilities due to technical thresholds, which in turn exacerbates social differentiation. On the other hand, risks caused by climate change (e.g., extreme high temperatures) have a more significant impact on vulnerable communities [27], while low-carbon renovation (e.g., sunshade system optimization, energy-saving doors and windows replacement) is an important path to enhance community climate resilience. Injustices in spatial practice are characterized by complexity, systematicness and concealment, so relevant justice-oriented solutions are in urgent need of research and discussion.

Carbon Emission Differentiation in the Social Space of Communities

In the urban carbon metabolic network, the carbon emission pressure of non-industry-dominated cities mainly stems from the effect of population agglomeration. As the basic spatial unit, communities have become the key carrier for regulating carbon flows[10,12]. The existing community carbon emission accounting methods mainly include life cycle assessment, carbon emission coefficient assessment, consumer lifestyle approach, and input-output analysis[28]. The first three methods reveal the specific environmental performance of carbon emissions, take the whole life cycle of products or services into account in a broader scope, and improve the transparency and fairness of carbon emission accounting to a certain extent. For example, Song et al.[29] accounted for carbon emissions in the community operation stage and disaggregated the total community carbon emissions into household carbon emissions and public area carbon emissions; Roh et al. [30] calculated the carbon emissions of apartment complexes covering the construction, operation and end-of-life stages; Li et al. [31] accounted for carbon emissions in the construction and implementation phase of residential quarters, involving site leveling, foundation construction and other links. However, these methods mostly target the absolute carbon emissions at the macro level, involving many links, a wide range of fields and long cycles, and are not easy to understand. Although the input-output analysis method is conducive to evaluating and analyzing the internal correlation of community carbon emissions from the perspectives of residents'

lifestyles and consumption behaviors, it presupposes that communities enjoy equitable access to the technical and policy services required for low-carbon transformation, ignoring the differentiation among communities[32]. On the whole, existing carbon emission accounting methods focus on the accuracy of statistical absolute values[29,31], but are time-consuming, complex, and unable to highlight the differences in the history, current situation and future potential of carbon emission reduction among communities. At present, several studies have verified the rationality of simplifying carbon emission calculation through the substitution of approximate indicators; for instance, Balcer, T. et al.[33,34] provided a new path for measuring the differences in community carbon emissions.

The essence of low-carbon communities is embodied in the coordinated achievement of three goals—energy reduction, emission optimization and carbon sink expansion—within the threshold of environmental carrying capacity, through the construction of a green building system, innovation of governance models and guidance of lifestyle, so as to

gradually approach carbon neutrality[35,36]. There are diverse sources and accounting models of community carbon emissions, and different communities show carbon emission differences in historical and spatial dimensions due to social and physical factors[34]. For example, old communities have high and hard-to-reduce historical carbon emissions due to non-energy-saving buildings and residents ' economic conditions[13]; spatial morphology significantly affects the efficiency of carbon metabolism, and empirical evidence confirms that floor area ratio and jobs-housing balance index are negatively correlated with transportation energy consumption, and compact communities can reduce per capita carbon footprint[37]; the gradient of governance capacity exacerbates injustice, as high-income communities have easier access to green technologies, while vulnerable communities face the dual dilemma of fund shortage and lack of participation[6,38]. These differences undermine the justice of low-carbon renewal: in terms of resource allocation, high-emission old communities find it difficult to obtain resources due to high renewal costs and unsatisfactory expected returns, while low-carbon advantageous communities are easy to get support, widening the development gap; in cost sharing, high-emission communities bear high renewal costs, and most of the economic and social costs are borne by vulnerable residents[38]; in terms of rights and interests enjoyment, the lagging renewal of high-emission communities deprives residents of the environmental, economic and other low-carbon dividends, violating the principle of equal access to development achievements[27]. Therefore, it is necessary to explore a differentiated compensation mechanism to ensure renewal justice and coordinated development.

Realization of Justice in Low-Carbon Community Renewal

Design schemes are policy documents guiding community renewal and play an important leading role in planning. In accordance with macro carbon emission reduction goals, community renewal schemes should adopt optimal strategies to effectively guide community transformation. Although a series of justice-oriented solutions for low-carbon community renewal have been formed globally, there are still systematic defects in their application during the scheme design stage, making it difficult to fully achieve justice goals throughout the entire renewal cycle.

While Katherine et al.[39] emphasized procedural justice, they confined residents' participation to publicity after the scheme was determined, which lags behind the co-creation needs in the early stage of design. This leads to the institutional exclusion of the demands of vulnerable groups, and the participation mechanism mostly relies on elite

representatives, lacking an inclusive negotiation structure. Although the principle of co-production of energy systems proposed by Maarten[40] creates space and benefits for renewable energy infrastructure, the benefit distribution lacks differentiated justice standards, and there are institutional gaps in the redistribution of spatial resources, as well as the sharing of transformation costs and risks.

Most policies only generally advocate "inclusive sharing" and fail to establish a refined distribution framework based on justice theory. For example, the research by Adams et al.[41]overemphasizes technical efficiency and neglects the systematic impact assessment of the socio-spatial environment, which is likely to form "environmental injustice of green transformation" in ecologically sensitive areas and vulnerable communities. In addition, although Benjamin et al. [42] identified multi-dimensional injustices, they failed to balance community development needs and potential problems. Moreover, scheme design often relies on the discourse of technical experts and downplays local knowledge

and cultural memory, resulting in the dilution of community cultural identity.

To realize justice-oriented low-carbon community renewal, the specific conditions of the community's social space must be fully considered in the formulation of renewal policies, and appropriate response strategies should be formulated. This is mainly reflected in the fact that the formulation of goals, strategies and paths embodies differentiated fairness among communities. In terms of goal setting, the formulation of community carbon emission reduction goals needs to fully reflect the fairness of the allocation of carbon emission reduction quotas among various communities and groups[22], and this process should also be open to all community stakeholders, easy to discuss, understand and accept. Given the complexity of the factors influencing community carbon emissions, LMDI or STIRPAT models[43,44]should be used to comprehensively and accurately analyze the contributions of various influencing factors. Through the analysis of the overall current carbon emission situation and carbon emission reduction potential of communities from both social behavior and physical space perspectives, the hierarchical and differentiated setting of carbon reduction goals for community renewal can be realized.

In terms of strategy selection, an assessment of the potential and feasibility of various low-carbon renewal strategies should be conducted based on the current situation of communities. This includes considering the transformation costs[14] and emission reduction effects[36,46] in nine aspects: carbon emissions and carbon offset[45], green buildings, green transportation, energy systems, water resource utilization, waste disposal, public green spaces, community operation and governance, and residents' low-carbon lifestyles, while fully taking into account the adoption willingness of community groups towards renewal strategies. In terms of path selection, combined with carbon reduction goals and strategy analysis, differentiated low-carbon renewal paths for communities should be formulated.

Rong et al. [37] identified the carbon emission characteristics of five types of communities with different spatial forms based on the four-dimensional spatial form measurement indicators of "location-density-accessibility-mixity".

1.3. Innovations and Aims

In general, the existing studies have the following deficiencies: 1) Against the background of low-carbon transformation, the existing spatial justice theory needs further development; 2) The existing carbon emission

accounting methods cannot well reflect the impact of low-carbon transformation on different communities or groups and their living environments; 3) The concept of justice is difficult to be integrated into the practical operation level of low-carbon community renewal. In response to this, future research needs to focus on the reasonable simplification of community carbon emission calculation methods and formulate a justice-oriented technical system for classified carbon reduction policies. Therefore, the purpose of this study is: (1) Establish a justice evaluation index system for low-carbon community renewal; (2) Construct a community classification model based on the low-carbon justice theory; (3) Propose differentiated renewal methods for low-carbon communities based on categories.

The innovation of this study lies in:

(1) Based on the background of low-carbon transformation, construct the concept of "Low-Carbon Justice" , and reveal the injustice characteristics in community renewal from the "social-spatial" perspective. (2) Use the AHP (Analytic Hierarchy Process) and FCE (Fuzzy Comprehensive Evaluation) methods to screen key indicators of low-carbon communities, construct an evaluation system, and conduct empirical tests. (3) Based on the "Low-Carbon Justice" concept, evaluation system and classification model, formulate differentiated renewal strategies for the core contradictions and needs of existing communities.

2. Methodology

This study is carried out in accordance with the logical framework of "indicator screening—model construction—case verification" (Figure 1 [Figure 1: see original paper]): First, based on literature review, expert consultation, and AHP (Analytic Hierarchy Process), the indicator database is constructed, screened and stratified, and a hierarchical evaluation index system for phased low-carbon renewal of communities is proposed. Second, the indicator weights and clustering results are determined through AHP and K-means methods, and the low-carbon renewal potential and elements of communities are evaluated and classified using FCE and IPA (Importance-Performance Analysis) methods. Finally, the communities in Liangzhu Subdistrict are taken as the case study object, and the renewal schemes are analyzed and verified according to the evaluation index system and low-carbon community classification method.

In the path of realizing justice in low-carbon community renewal, indicator screening and weighting are not merely technical operations, but the core link connecting abstract justice principles with operable standards. The essential demands of justice —including the fairness of resource allocation, the comprehensiveness of rights protection, and the pertinence of compensation mechanisms —

need to be materialized through the identification of specific

dimensions and weight configuration: Through indicator screening, core dimensions such as distributive justice (e.g., differences in resource endowments), procedural justice (e.g., residents' participation), recognition justice (e.g., community cultural characteristics), and compensatory justice (e.g., technical accessibility) can be systematically incorporated, ensuring that the needs of vulnerable communities (e.g., the renovation fund gap of old communities) and the potential of advantageous communities (e.g., the technical adaptability of emerging communities) are both

included in the evaluation framework, so as to avoid one-sided interpretation of justice from a single dimension; the weighting process highlights the priority of different justice dimensions through weight allocation; for example, under resource constraints, the weight of distributive justice is prioritized to avoid the exacerbation of the "green gap" , transforming justice from a theoretical principle into measurable and comparable specific indicators.

2.1. Indicator Screening and System Stratification

The construction of the evaluation indicator system for low-carbon community renewal follows five basic principles, namely comprehensiveness, scientificity, feasibility, representativeness, and independence. The comprehensiveness principle requires indicators to cover multiple dimensions of carbon emission intensity and the entire scope of justice theory; the scientificity principle emphasizes theoretical support and method reproducibility; the feasibility principle focuses on data accessibility and operational simplicity; the representativeness principle focuses on core characteristic indicators; the independence principle ensures indicator mutual exclusivity and irreplaceability. These principles

together ensure the rigor and effectiveness of the evaluation system[47]. Based on the above principles, the construction and stratification of the evaluation system involve the following steps:

Construction of Indicator Set

In community carbon emission evaluation, justice theory can better analyze and solve problems such as uneven distribution of carbon emissions and unfair environmental burdens. The core principles of justice theory include: fair distribution —resources and burdens should be fairly distributed among social members; rights protection —ensuring that individuals' basic rights (such as the right to health and the right to the environment) are not infringed; compensation mechanism —providing compensation to groups harmed by unfair distribution; these principles provide a theoretical framework for community carbon emission evaluation.

Based on justice theory, the evaluation indicator set for differentiated community carbon emissions is divided into 4 element modules from the perspective of justice dimensions, namely distributive justice, procedural justice, recognition justice, and compensatory justice. From the perspective of this study, different dimensions of "Low-Carbon Justice" are taken as the criteria for indicator selection. Evaluation indicators that have an impact on the evaluation modules are selectively extracted from relevant literatures, and then classified and sorted out in combination with the evaluation indicators extracted from the "Guidelines for the Construction and Evaluation of Zero-Carbon Communities" . After supplementing gaps and merging similar items, a total of 29 indicators are integrated to form a preliminary evaluation factor set.

The preliminary selection of indicators integrates three sources: extracting evaluation factors used in the construction and low-carbon renewal of communities in multiple fields such as energy, architecture, and transportation in accordance with the "Guidelines for the Construction and Evaluation of Zero-Carbon Communities" ; synthesizing the research results of literatures related to the STIR-

PAT model[29,34,43,44,48], and selecting evaluation indicators that have an impact on the evaluation modules with different dimensions of "Low-Carbon Justice" as the criteria for indicator selection from the perspective of this study; conducting secondary sorting and integration of the initially integrated evaluation factor set according to the actual changes in carbon emission reduction intensity after the current community renewal and renovation, and forming the initial evaluation indicator set after adding, deleting, revising and summarizing the indicator set.

Indicator Set Screening

In this study, the preliminary evaluation indicator set containing 29 indicators was optimized and finalized through expert questionnaire consultation and expert interviews. The expert panel covered architectural technology, sociology and practical fields: 7 university teachers and postgraduate students (master' s and doctoral candidates) focusing on residential planning and design and low-carbon technologies; 4 practitioners with practical experience such as designers and project managers from design institutions; and 4 research scholars and postgraduate students with sociology-related backgrounds. These 15 experts scored the importance of the indicators in the questionnaire according to their professional expertise. The reliability of the questionnaire results was verified using the expert

authority coefficient (Cr=(Ca+Cs)/2), and the Cr value of all experts was required to exceed the acceptable threshold of 0.7. Abnormal indicators were re-examined based on the mean value of indicator importance (only items with $M > 3.5$ were retained) and the coefficient of variation (with a focus on items with $Cv > 0.25$). On the basis of the questionnaire survey, further opinions on the composition of evaluation indicators were collected via expert interviews, and the core indicator set was eventually optimized.

Statistical analysis showed that the mean importance value M of all indicators was greater than 3.5. After eliminating redundant items and merging overlapping indicators through cross-interviews, a core indicator set of 20 items was formed, with a mean score of 4.52 in the final round. It can be concluded that the indicator system is reasonable and can comprehensively reflect the key factors influencing the differentiated carbon emissions of communities.

Hierarchical Structure Division of the Indicator Set

A four-level framework of the indicator system is constructed based on the Analytic Hierarchy Process (AHP): The Target Layer is defined as the influencing factors of differentiated low-carbon renewal of communities; The Criterion Layer corresponds to the four modules: distributive justice, procedural justice, recognition justice and compensatory justice; The Sub-criterion Layer refines nine categories of characteristics: economic factors, physical factors, demographic factors, cultural factors, behavioral factors, technical factors, support mechanisms, laws and policies, and residents' participation degree; The Indicator Layer consists of the final specific observation indicators. Through step-by-step decomposition from the target layer to the indicator layer, this structure realizes the transformation from the theoretical framework into an operational tool.

2.2. 体系构建与评价分类

Indicator Weight Determination Based on AHP

The experts who participated in indicator screening were invited to conduct pairwise comparisons of the hierarchical indicator system and assign scores according to the defined scale. Due to differences in the views and preferences of individual decision-makers, the evaluation results of indicator weights may present significant discrepancies. To reduce such weight variations caused by multi-expert evaluation, 12 judgment matrices were constructed using the 1–9 scale on the basis of the analytic hierarchy process (AHP). The group decision-making method was adopted, and individual differences were integrated via the expert judgment weight P in Formula (2.1), so as to establish a more reliable weight set for the evaluation system.

Pk m

10 m 1 CI k

10 m 1 CI k

(2.1)

The sum method was used to calculate the weights. The weight vector was obtained through column normalization, row summation, and eigenvector normalization, and the consistency test was completed based on the consistency ratio. Finally, the priority of each factor relative to the target layer T was determined through composite weight calculation, with data processing implemented via Excel and SPSS.

Indicator Clustering Determination Based on K-means Algorithm

The K-means clustering method[49] is a partition-based unsupervised machine learning algorithm used to divide samples in a dataset into K non-overlapping clusters. Its core procedure is to minimize the sum of squared errors of samples within clusters, so that samples in the same cluster are as similar as possible while samples from different

clusters are as distinct as possible. The remaining data points are assigned to the vicinity of different central points to form K clusters, and the central point of each cluster is updated continuously until the points remain unchanged. The optimal K is selected by observing the cost function values (the sum of distances from each point to its cluster center) corresponding to different K values. As K increases, the cost function decreases; however, when K reaches a certain value, the decreasing amplitude drops sharply, forming an "elbow point".

The obtained indicator weight data were imported into the K-means model, and a cluster number comparison diagram was generated according to the elbow method. It can be observed from the diagram that when the cluster number equals a specific value, the loss function (i.e., the sum of squared errors) tends to be gentle, indicating that the optimal clustering effect is achieved. Under this value, the weight differences among indicator clusters are statistically significant. At this point, field difference analysis of each cluster reveals significant discrepancies in weight characteristics, reflecting the heterogeneity of weight distribution among clusters. This provides critical differentiating factors for the subsequent classified research on the characteristics of different categories. Specifically, clusters with higher weights may correspond to certain specific factors or variables with a strong overall impact, while clusters with lower weights may represent relatively secondary or universal features.

Evaluation and Grading Based on Fuzzy Comprehensive Evaluation (FCE)

The Fuzzy Comprehensive Evaluation (FCE) method is based on fuzzy mathematics and handles multi-factor decision-making problems by quantifying qualitative indicators. Given that this study takes the perception of community residents (the primary users at the urban community level) to reflect the actual effectiveness of community low-carbon transformation, the evaluation result of each indicator is mainly represented by the low-carbon renewal potential of the community, and differentiated community renewal schemes are formulated according to the carbon reduction potential.

The evaluation standard divides the results of each indicator into five grades: Grade (High potential), 90 -100; Grade (Relatively high potential), 80 -90; Grade (Medium potential), 70 -80; Grade (Relatively low potential), 60 -70; Grade (Very low potential), 0 -60. These grades correspond to five levels of transformation priority in sequence. To make the evaluation results quantitative and scientific, the evaluation grades are assigned scores, with the median of each grade adopted as the grade score.

In this study, the hierarchical structure of the evaluation objects is relatively complex, so the fuzzy comprehensive evaluation is conducted step by step according to the hierarchy. First, the factor set = 1 , 2 , 3 ⋯ composed of carbon emission factors of low-carbon renovation is established, and the five-dimensional comment set =

1 , 2 , 3 ⋯ is defined corresponding to the potential grades. A fuzzy relation matrix R is constructed based on

public questionnaire data, where the element denotes the membership degree of to . Combined with the

indicator weight vector = 1 , 2 , 3 ⋯ , the result vector is generated via the fuzzy synthesis operation in Formula (2.2), aggregated layer by layer from the indicator layer to the criterion layer and finally to the target layer. The quantitative grading is ultimately realized through the comprehensive evaluation formula = ∗ .

r11 Y X * R x1 , x2 , x3 ⋯xn * 21 ⋯ rn1

···r1m ···r2 m y , y , y ···y ······ ···rnm

(2.2)

Prioritization of Indicator Elements Based on IPA Method

Importance-Performance Analysis (IPA) is a commonly used tool for strategic planning and decision-making. By evaluating the importance and feasibility of various factors, it helps researchers identify key improvement areas and provides clear strategic directions accordingly.

The core of IPA lies in constructing a two-dimensional coordinate system: the horizontal axis represents the importance of factors, and the vertical axis represents their feasibility (i.e., potential degree). According to the distribution of factors in the quadrants: The zone of high importance–high feasibility adopts a maintenance strategy; The zone of high importance–low feasibility implements a key improvement strategy. This method provides a priority decision-making basis for various renovation strategies and renewal paths to improve justice in differentiated low-carbon communities, and optimizes the efficiency of resource allocation.

2.3. Case Study of Liangzhu Subdistrict

Against the backdrop of China' s "Dual Carbon" strategy, low-carbon community construction has become a core unit of urban sustainable transformation. As a pioneering province practicing the Two Mountains Concept, Zhejiang has established a practical system covering local standards (e.g., the Evaluation Standard for Green Ecological Urban Districts approved in 2024) and diverse pilot projects. Relying on its strengths in the digital economy and ecological

background, Hangzhou has promoted the implementation of intelligent energy management and sponge city technologies through the Hangzhou Three-Year Action Plan for Carbon Peaking (2023–2025), forming differentiated pathways for low-carbon planning of new communities and energy-saving renovation of old communities. However, problems such as unbalanced regional development, insufficient adaptability of technical scenarios, and scattered resident participation in low-carbon practices are common phenomena in China ' s low-carbon community construction.

This study takes the communities in Liangzhu Subdistrict, Yuhang District, Hangzhou as the empirical object. By analyzing the resource allocation logic and social participation mechanism of the Liangzhu Subdistrict case, it extracts a justice-oriented renewal scheme suitable for low-carbon communities, providing theoretical support and practical reference for spatially equitable transformation under the "Dual Carbon" goals. Liangzhu Subdistrict is located in the

central part of Yuhang District, Hangzhou, Zhejiang Province, covering 24 communities and 20 administrative villages (Figure 2 [Figure 2: see original paper]), with a total area of 101.69 square kilometers. It boasts a long history and culture as well as complex social realities. Its communities present three typical characteristics: Old communities in the urban-rural fringe are confronted with low building energy efficiency, high renovation difficulty, and strong transportation dependence; Industrial transformation communities have economic and facility advantages but are restricted by floating population management and intelligent means; Emerging communities feature good building performance but lag in energy consumption management mechanisms (see Appendix A for the main contradictions in low-carbon renewal of each community in Liangzhu Subdistrict). The more than 20 years of construction of Liangzhu Cultural Village epitomizes the development trajectory of urban communities in China. Under the new-era goals of carbon peaking and carbon neutrality, its future development direction and renewal demands are also typically representative –focusing on fairness and justice in the transformation of the stock urban social space.

This study conducts an investigation and analysis of the low-carbon community construction of Liangzhu Cultural Village, centering on its built environment and applicable groups. On-site observations, questionnaire surveys, and semi-structured interviews were carried out on the current usage and low-carbon renewal of internal community buildings, public facilities, green spaces, parks, etc. Data were collected on the behavioral characteristics of different groups and their perception of low-carbon renewal potential. The questionnaire covered the basic information of respondents and a five-level rating of low-carbon renewal potential. A total of 100 questionnaires were distributed online and offline, with 86 valid questionnaires recovered (effective response rate: 95.6%). In the survey, the gender ratio of residents in Liangzhu Cultural Village was roughly balanced, with a slightly higher proportion of males. In terms of age distribution, respondents were mainly concentrated in the 20–40 and 40–60 age groups, with a certain proportion of adolescents and the elderly, though smaller than the two main age groups.

Local tourists accounted for the largest proportion in the survey data, followed by surrounding residents and out-of-town tourists, indicating that both tourists and residents have a high degree of use and participation in Liangzhu Cultural Village. This reflects the complexity of its population structure and the typicality of its carbon emission profile. Reliability testing was conducted on the 20 indicators of the 86 valid samples via the online SPSSPRO analysis platform. The results showed that the Cronbach ' s α coefficient was 0.903, higher than 0.9,

indicating high data reliability. Validity verification was performed using the KMO and Bartlett tests: the KMO value was 0.856 (greater than 0.8), and the Bartlett sphericity test was passed, confirming good data validity. The overall

research data are suitable for further analysis.

3.1. Evaluation Indicator System Based on "Low-Carbon Justice"

Indicator Composition and System Division

After repeated integration and sorting of indicators, a four-level evaluation structure —Target Layer -Criterion Layer -Sub-criterion Layer -Indicator Layer —is established based on the Analytic Hierarchy Process (AHP) (Figure 3 [Figure 3: see original paper]). Grounded in justice theory, the system takes the influencing factor T of differentiated low-carbon community renewal as the target layer "Low-Carbon Justice" , and adopts its classic four-dimensional framework (distributive, procedural, recognition, and compensatory justice) as the criterion layer X, which secures the theoretical foundation and academic depth of the evaluation. These four dimensions are interrelated and mutually supportive: they concern not only the distributive justice of carbon emission outcomes (who benefits and who bears the costs), but also the procedural justice underlying such outcomes (procedural and recognition justice), and provide remedial

mechanisms for correcting injustices (compensatory justice). Going beyond traditional single-dimensional environmental or economic evaluation, the system integrates social and governance dimensions as core components, forming a complete justice-oriented evaluation framework.

Furthermore, the four theoretical dimensions are concretized and operationalized into nine characteristic sub-criterion layers Y, namely economic factors, physical factors, demographic factors, cultural factors, behavioral factors, technical factors, support mechanisms, laws and policies, and residents 'participation degree. After multiple rounds of indicator screening and revision by expert evaluation, 20 quantifiable and qualitatively judgeable indicators corresponding to the sub-criterion layers are finally determined as the indicator layer Z, including per capita income, per capita living area, and residential mode, forming a logically rigorous evaluation system (the name and description of each indicator are shown in Appendix B; indicator numbers are used uniformly hereinafter).

The preliminary indicator set is selected from recent literature on "community low-carbon measurement and evaluation" and relevant laws and regulations for low-carbon community construction, and the final indicator set is formed through scientific quantification and evaluation by the expert group. The underlying logical mechanism lies in the following four aspects:

First, digging from "surface differences"to "root causes": Experts are not satisfied with measuring the outcome difference of "per capita carbon emissions" , but trace how such differences are jointly caused by a series of antecedent factors such as economic capacity, spatial location, information access, participation rights, and cultural habits. The indicator system constructs a complete causal chain from "causes" to "process" , "outcomes" and "remedies" .

Second, focusing on "leverage points" rather than "appearances" : The indicators selected by experts are usually "leverage points" that can be intervened and changed. For example, "Per Capita Income and Consumption Level (Z1)" and "Per Capita Living Area (Z2)" are economic levers; "Participation Degree and Channels of All Groups in Decision-making (Z20)"is a governance lever; "Support Mechanism for Low-carbon Transformation (Z17)" is a capacity-building lever. Measuring these indicators helps to better design and optimize policies, so as to effectively and fairly narrow carbon emission differences.

Third, emphasizing "justice perception" to ensure sustainability: Experts are well aware that technological renewal is unsustainable without social acceptance. Therefore, a large number of subjective perceptions of residents (such as sense of fairness and perception of influence) are incorporated into the indicators. Even if objective data seem fair, residents' subjective sense of injustice will trigger resistance and frustrate emission reduction efforts. Indicators in the dimensions of procedural justice and recognition justice are designed to safeguard residents' "justice perception" , so as to provide stable social support for low-carbon renewal.

Fourth, reflecting the governance wisdom of "differentiation": The ultimate goal is "differentiated low-carbon renewal", which means no "one-size-fits-all"solution. The indicator system acts as a diagnostic tool, helping managers identify the specific dimensions of injustice in different communities —

whether distributive, procedural, or

recognition problems. On this basis, precise and targeted differentiated measures can be adopted to finally achieve the synergy and win-win results of efficient emission reduction and social justice.

Indicator Weight Assignment Analysis

Based on the four-level indicator evaluation system, the original experts were invited to compare the indicator weights. The consistency test showed that the consistency ratio (CR) of all comprehensive judgment matrices was less than 0.1, meeting the consistency requirement. The final weight analysis (Table 1) indicated that X1 (43.94%) > X2 (30.57%) > X3 (15.43%) > X4 (10.06%), which means that in the process of low-carbon renewal of urban communities, distributive justice is regarded as the primary consideration for achieving social fairness and justice, and they largely determine the differences in carbon emission intensity among different communities.

The core position of X1 is reflected in the dominant impact of Z1, Z2, and Z3 in Y1 on community carbon differences.

In particular, the comprehensive weight of Z1 (0.1654) is more than twice that of other indicators (the comprehensive weight of Z8, which ranks second, is 0.0837). These indicators are crucial in the formulation of low-carbon renewal schemes, especially in the links such as setting carbon reduction goals, selecting carbon reduction strategies, and formulating transformation implementation paths, which should be fully considered.Second, X2 accounts for about one-third of the entire justice theory framework. Attention should be paid to Z8, Z9, Z11, and Z13. Through community self-identification, the rights and obligations of various groups, especially vulnerable groups and marginalized groups, are identified to avoid injustices that may be caused by community low-carbon transformation.

Compared with X1 and X2, X3 and X4 account for a lower weight in the entire system (about one-quarter). Among X3, the weight of indicator Z15 is relatively high, ranking third among the 20 indicators in terms of importance; in addition, Z16 and Z17 are also in the upper-middle position, highlighting the role of technical factors in balancing community differences. As a relatively macro element in the justice theory, X4 mainly targets relevant departments such as the government. Although it has the lowest weight, the legal foundation of its policy framework has normative value for safeguarding social fairness.

Target Level

Weight

Criterion Level

Weight

Sub-Criterion Level

Composite

Indicator

Weight

Level

Weight

Weight

Composite Weight

Analysis of Indicator Weight Clustering Results

Based on the weight data of the 20 indicators, K-means algorithm was adopted for clustering analysis[50]. The optimal cluster number was determined to be 5 according to the elbow rule (silhouette coefficient = 0.639). The clustering results showed that five categories of weight characteristics were significantly different (Figure 4 [Figure 4: see original paper]): Category 1 was a single outlier with extremely high weight (0.165, n=1); Category 2 had the highest average weight (0.075 ± 0.006); Category 3 was the second (0.05 ± 0.002); Category 4 (0.036 ± 0.003) and Category 5 (0.024 ± 0.004) showed a gradient decrease. Analysis of variance confirmed that the differences between categories were statistically significant (P=0.000).

The indicators were divided into a five-level system according to their weight values. The only most important indicator was Z1, whose weight was significantly higher than other indicators, serving as the key factor determining the differences in carbon emissions among communities. The core mechanism is that high-income groups dominate community carbon emission differences through high carbon-intensive consumption patterns. The important indicators included four items: Z8, Z15, Z3 and Z2, which should be comprehensively considered before and during the formulation of differentiated low-carbon renewal schemes to determine the prioritized status of each community, especially focusing on the differentiated impacts of age structure on energy use patterns. The secondary indicators covered four items including Z11 and Z18, which have emission reduction potential under specific circumstances. The remaining 11 indicators were divided into 6 general indicators and 5 auxiliary indicators. Although their weights were relatively low, they were still indispensable elements to be considered for community transformation and the

realization of low-carbon justice. Integrated with justice theory, the differentiated realization of community low-carbon transformation is a systematic project combining all the above influencing indicators and factors. Combined with the clustering results, the top-ranked indicators (Z1, Z8, Z15, Z3 and Z2) were extracted as the classification reference. Integrated with national guidelines, expert suggestions and residents ' demands, as well as the main factors and demands of differentiated carbon emissions among communities, they were summarized into six aspects: per capita income and consumption level, population structure, per capita living area, renewable energy substitution and resource recycling, utilization frequency of private cars and public transport, and low-carbon management. Among them, low-carbon institutions include two related but separable dimensions: institutional and cultural.

3.2. Evaluation and Analysis of Low-Carbon Construction in Liangzhu Cultural Village Community

(1) Comprehensive Low-Carbon Potential Score and Classification Based on Fuzzy Comprehensive Evaluation

Method

Based on the Fuzzy Comprehensive Evaluation (FCE) method, the final comprehensive low-carbon potential index is 85.86, which falls within the range of 80–90 points according to the grading standard (Grade), indicating that the community has considerable carbon reduction potential (Table 2). Among the 20 evaluation indicators, 9 indicators are higher than the comprehensive score, and 11 indicators are lower than the comprehensive score. The dimensional test shows that: the score of Dimension X1 is 87.24, in which Z4 and Z5 present remarkable potential while Z2 has

shortcomings, demonstrating that the low-carbon construction of Liangzhu Cultural Village has great potential in achieving distributive justice, but limited potential in per capita living area; the score of Dimension X2 is 83.65, with high potential in Z13 and weak performance in indicators such as Z9; the score of Dimension X3 is 84.64, slightly lower than the comprehensive score, and all three indicators are lower than the comprehensive score, indicating that the public' s perception of carbon reduction potential in this dimension is low, requiring optimization of the timing of resource allocation; the score of Dimension X4 is 88.37, and Z18 reaches the Grade standard, reflecting that the community has a high perception of demand for procedural justice elements in low-carbon renewal construction, and resources should be mobilized to further improve and optimize relevant policies.

The results of this quantitative evaluation reveal that the public has a high perception of the potential of various indicators for low-carbon renewal in Liangzhu Cultural Village Community, which means that from the perspective of low-carbon transformation potential, sufficient resources still need to be mobilized to promote the process of carbon reduction renovation in the village. On the other hand, the carbon reduction potential of the village remains at Grade with an overall high potential level. In particular, indicators with potential higher than the comprehensive score should be focused on and prioritized in the follow-up renewal and renovation.

Criteria layer

Weight

Score

Sub-criteria layer

Score

Weight

Indicator

Comprehensi

Comprehensi

rating

ve score

ve rating

Indicator

Weight

Score

(2) Low-Carbon Community Classification Based on Principal Components and Potential Values Based on the theory of sustainable development, the low-carbon community classification system constructed in this study follows five core principles[46]: scientificity, grounded in carbon emission

influencing factors and emission reduction potential; systematicness, coordinating the multi-dimensional correlations among spatial form, functional structure, social and economic factors[37]; differentiation, identifying the essential characteristics of communities to guide targeted resource allocation; hierarchy, integrating the multi-level framework of policy-making and residents' daily life; and dynamism, adapting to technological evolution and changes in social demands. By integrating policy orientation, expert opinions and residents' demands, and focusing on seven key dimensions (per capita income and consumption level, population structure, living area, renewable energy substitution rate, transportation mode, community awareness and low-carbon management) according to the indicator clustering results[47], existing communities

classified

seven

differentiated

types:

green

consumption-oriented,

population

optimization-oriented, energy substitution-oriented, green travel-oriented, energy-saving renovation-oriented, institutional innovation-oriented and cultural influence-oriented communities, which lays a theoretical foundation for the precise implementation of differentiated renewal strategies. (3) Targeted Problems and Demands of Community Low-Carbon Renewal Based on the IPA Model Combined with the evaluation results of low-carbon construction in Liangzhu Cultural Village, this study adopts the IPA (Importance-Performance Analysis) model to analyze perceived importance (I) and current potential (P). The standardized value of the composite weight of each indicator is taken as perceived importance (I), and the potential evaluation score is taken as current performance (P), so as to construct a four-quadrant coordinate system (the IPA model is shown in Figure 5 [Figure 5: see original paper], and the specific indicator data are detailed in Table 2 and Table 3). Through calculation, the mean value of the standardized composite weights of the 20 evaluation indicators is 0.0500, and the corresponding mean value of the processed potential evaluation scores is 4.0785. Therefore, the coordinate of the intersection point of the four quadrants in the IPA matrix is (0.0500, 4.0785).

According to the analysis results of the IPA model, the improvement strategies and priorities of the evaluation factors have been clarified (Table 3). Among them, 9 factors including Z1, Z3, Z18, Z13, Z4, Z7, Z10, Z5 and Z19 are located in Quadrants and (improvement zone), indicating that they have high carbon reduction potential but lag in construction and should be prioritized for improvement; 11 factors including Z8, Z2, Z15, Z11, Z9, Z17, Z16, Z6, Z14, Z20 and Z12 are located in Quadrants

and

(maintenance zone), with low potential and suitable for

maintaining the current status. IPA quadrant

Indicator number

Importance standardized value (I)

Performance

Decision and priority order

Performance standardized value (P)

Improve

Maintain

(4) Classification of Low-Carbon Community Construction for Communities in Liangzhu Subdistrict Combined with the current principal components of low-carbon renovation and carbon reduction potential values of each community in Liangzhu Subdistrict, the classification of low-carbon community construction is carried out (see communities in Liangzhu Subdistrict focus on energy-saving renovation and management systems, which also reflects various resistances faced by current energy-saving renovation, such as insufficient evaluation of renovation funds, high difficulty in renovating old communities, complex internal population structure of communities, large divergence of opinions among groups, etc.

Specifically, the same community may fall into multiple low-carbon renewal categories. For example, Xinqiao Community belongs to the energy substitution type, green travel type and energy-saving renovation type at the same time, indicating that there are important connections among the main contradictions of low-carbon renewal. The application of new energy technologies in communities helps reduce building energy consumption, and the promotion of new energy vehicles also contributes to green travel. All aspects need collaborative promotion and governance to achieve efficient transformation. This does not mean that goals such as green consumption and population optimization are unimportant, but that there are more urgent and appropriate strategies at present. Based on the analysis of the current situation of low-carbon construction of communities in Liangzhu Subdistrict, the low-carbon community renovation and renewal should focus on three levels at this stage: optimization of governance system, key breakthrough of infrastructure, and in-depth participation of residents.

Classification of Low-Carbon Communities

Communities in Liangzhu Subdistrict

Green Consumption

Wannianqiao Community, Guanjiatang Community, Yuniao Community, Boyuan Community, Wujiashu

Oriented Communities

Community

Population Optimization Oriented Communities

Wannianqiao Community, Mingya Community, Qinqin Jiayuan Community, Guanjiatang Community, Beixiu Community, Juxian Community, Tongyun Community, Wujiashu Community, Xitangyayuan Community, Changqiao Community

Energy Substitution

Xinqiao Community, Yuniao Community, Yuexiu Community, Boyuan Community, Changyun Community,

Oriented Communities

Xinxi Community

Green Travel Oriented

Xinqiao Community, Liangzhu Cultural Village Community, Tongyun Community, Yuniao Community,

Communities

Changyun Community, Changqiao Community

Energy Saving

Xinqiao Community, Shijiawan Community, Mingya Community, Qinqinjiayuan Community, Zonglvwan

Renovation Oriented

Community, Chongfu Community, Jinbodu Community, Liangzhu Cultural Village Community, Yijucheng

Communities

Community, Beixiu Community, Beichen Community, Juxian Community, Wujiashu Community

System Innovation

Yuze Community, Wannianqiao Community, Mingya Community, Qinqinjiayuan Community, Zonglvwan

Oriented Communities

Community, Chongfu Community, Jinjiadu Community, Yijucheng Community, Beixiu Community, Beichen

Community, Juxian Community, Tongyun Community, Yuexiu Community, Boyuan Community, Xitang Yayuan Community, Changyun Community, Xinxi Community Cultural Influence Oriented Communities

Shijiawan Community, Zonglvwan Community, Liangzhu Cultural Community, Beichen Community

4.Discussion

4.1. Implementing the Concept of Justice into Low-Carbon Community Practice

The spatial turn of justice theory began in the 1960s, and its connotation has been continuously expanded with the development of the times[51]. Spatial justice is characterized by sociality, historicity and spatiality[52], and has derived branch concepts such as environmental justice[10], climate justice[45] and energy justice[22] in low-carbon community renewal. These conceptual differences stem from the types of resource distribution and the nature of injustice concerned: spatial justice reveals the spatial contingent mechanism behind power relations and social inequality[53]; energy justice focuses on the critical framework for the distribution of costs and benefits in energy systems[4]; and environmental justice emphasizes the contradiction between impoverished groups and environmental health[5].

Despite their different focuses, existing studies mainly revolve around distributive justice, procedural justice and recognition justice. Among them, distributive justice concerns the balanced distribution of resources (e.g., public space, carbon emission rights) and costs in the transformation; procedural justice and recognition justice, as its prerequisites[51,54], require guaranteeing the right to information and participation of vulnerable groups. The traditional top-down renewal model exacerbates social segregation by depriving residents of their right to speak[24,55-57], so low-carbon renewal needs to construct a fair distribution mechanism by strengthening community identity and cultural belonging.

The particularity of low-carbon justice lies in integrating carbon emission reduction into the spatial resource allocation system. However, the existing refined carbon emission accounting system constitutes a technical barrier for communities, and standardized strategies ignore community heterogeneity, intensifying the implicit deprivation of vulnerable groups[27]. Injustices in the low-carbon community transformation present three characteristics: Complexity stems from the multi-dimensional interweaving of emission reduction fields, covering 8 types of activities including household life, building operation and community environment[58,59], while the current carbon emission statistics have blurred boundaries and fail to reflect community differences; Systematicness requires the coordination of physical space renovation and behavioral pattern transformation[46,47], and the overall planning of internal and external community elements as well as the non-linear correlation between history, present and future; Potentiality is reflected in the difficulty of identifying injustices under the interdisciplinary background. Refined carbon emission calculation hinders residents' participation instead, and ignoring community differences easily leads to implicit injustices[28,48].

This requires the construction of a collaborative mechanism of "three-stage justice" in low-carbon community construction: establishing a whole-process participation path for residents at the level of procedural justice, respecting community cultural genes at the level of recognition justice, and realizing the fair allocation of carbon emission

responsibilities and ecological rights at the level of distributive justice[24,55–57], so as to ultimately achieve the in-depth construction of spatial justice in the process of carbon neutrality.

Meanwhile, community carbon emissions come from multiple sources, including buildings and public facilities, transportation, waste disposal and carbon sinks. Energy consumption of buildings and public facilities, residents ' travel, purchased electricity and heat production all lead to carbon emissions. Traditional carbon emission accounting requires collecting data from these sources through different technologies and methods, which is difficult in data collection, and the conventional top-down management can hardly mobilize residents' enthusiasm and participation.

The current low-carbon community certification systems have significant defects under the framework of low-carbon justice[60–62]: the high-cost certification models of LEED-ND and DGNB intensify distributive injustice and exclude vulnerable communities; BREEAM lacks procedural justice, resulting in the virtualization of residents' participation; the green space ratio in CASBEE, as a rigid standard, ignores regional differences.

The theoretical context and existing evaluations of current research on the justice of low-carbon community renewal have three limitations (cited from small-scale papers): First, methodologically, qualitative research accounts for 75%, with a lack of quantitative tools. Only 5 studies involve quantitative carbon emission calculation, mostly targeting single emission reduction measures (e.g., building energy conservation, renewable energy), and there is no comprehensive evaluation framework covering the whole process of "goal-strategy-path" (cited); Second, dimensionally, although core dimensions such as distributive justice, procedural justice and recognition justice have been identified, they have not been transformed into operable indicators, and the differences in community social space are ignored, making it difficult for evaluation results to guide differentiated practices[63]; Third, applicationally, most studies focus on ex-post effect evaluation, lacking forward-looking guidance for the planning and design stage, and justice goals often degenerate into remedial amendments[64]].

The research by Charoenkit and Kumar[65] emphasizes that an ideal evaluation system needs to "simplify carbon emission calculation" and "consider community heterogeneity" , but does not involve technical details such as specific indicator screening and weight determination. This study constructs a four-level evaluation system (target layer -criterion layer -sub-criterion layer -indicator layer) in a targeted manner, materializes the theory of "low-carbon justice" through 20 core indicators, and emphasizes the direct connection between evaluation results and community classification as well as strategy formulation.

4.2. Selection and Action Paths of Low-Carbon Community Renewal

The implementation subjects of low-carbon community renewal consist of multiple stakeholders, including the government, community autonomous organizations, market enterprises, professional institutions, and residents[36], and their complementary roles are the foundation for achieving systematic renewal. The evolution of domestic and foreign policies shows that there are three types of dominant models in global practice: the government-led model focuses on public facilities and long-term benefits, the social unit-led model tends to prioritize high-yield projects, and the resident autonomous model focuses on daily life pain points but is limited in efficiency (Table 5).

Therefore, it is necessary to conduct differentiated classification according to the current situation and potential of community low-carbon renewal, and establish an implementation path of "responsibility subject division - task gradient sorting - visual list" to implement the concept of justice. A collaborative governance framework is constructed based on the matching of community characteristics and subject functions. First, responsibility subjects are divided according to carbon emission characteristics, tasks are sorted by renovation urgency, and visual operation specifications are established[38]. At the same time, community classification has the characteristics of dynamic evolution, and a community may change its dominant type in the process of renovation.

Based on this, a closed-loop mechanism of "monitoring - evaluation - decision-making - implementation" is established: integrating multi-source data through a digital twin platform to track community characteristics in real time; setting a quantitative threshold collaborative decision-making model to gradually adjust implementation strategies; and ensuring the fairness and justice of transformation in accordance with the three priority rules of data objectivity, resident participation, and policy mandatory. Existing communities are classified into a low-carbon classification system according to their different key contradictions and needs, including the seven types of communities obtained through the combination of qualitative and quantitative analysis mentioned above: green consumption-oriented, population optimization-oriented, energy substitution-oriented, green travel-oriented, energy-saving renovation-oriented, institutional innovation-oriented, and cultural influence-oriented communities.

Differentiated paths are implemented for the seven types of communities[47,66]:

Green consumption-oriented communities restructure consumption patterns through distributed energy to reduce electricity prices and low-carbon funds; Population optimization-oriented communities regulate density gradients based on ecological thresholds, and promote shared housing and green skills training; Energy substitution-oriented communities rely on community microgrids and group purchasing to reduce the cost of clean technologies; Green travel-oriented communities strengthen multi-modal transportation and carbon inclusive mechanisms, and optimize the layout of charging facilities; Energy-saving renovation-oriented communities adopt passive technologies to upgrade envelope structures, dynamically monitor energy consumption, and share equipment resources; Institutional innovation-oriented communities implement the decomposition of carbon emission goals and community carbon neutrality bonds, and establish a government-community collaborative decision-making

mechanism; Cultural influence-oriented

communities reshape community values through low-carbon courses and behavioral points. (see Appendix C for the implementation subjects and action lists of renovation for various types of low-carbon communities) Stakeholder type Government agencies

Social entities

Resident

Core attribute

Key influencing factors

Policy enforcement power, resource allocation

Administrative hierarchy, fiscal budget, policy

capacity

continuity

Technology enterprises

Technological barriers, business model maturity

Market competition landscape, policy incentives

Real estate development

Capital strength, technological integration

Market scale, green finance support, policy

enterprises

capability

Non-profit organizations

Professional authority, resource networks

Community self-governance

mobilization capacity, financial autonomy

constraints Donor trust, partnerships with government and enterprises Community cohesion, public affairs

autonom

organizations Residents

participation Diverse demands, action capability

Economic level, educational background, organizational level

The evaluation results of low-carbon renewal in Liangzhu Cultural Village show that its comprehensive low-carbon potential index reaches 85.86 (Grade), classifying it as an energy-saving renovation-oriented community. Among the dimensions, distributive justice (X1, 87.24) and procedural justice (X4, 88.37) perform prominently, while recognition justice (X2, 83.65) and compensatory justice (X3, 84.64) leave room for improvement. This confirms the community's advantages in resource allocation and policy implementation, as well as deficiencies in responding to group demands and differentiated compensation. The practice of Liangzhu Cultural Village verifies the feasibility of the differentiated renewal path under the "low-carbon justice" framework. By combining the AHP-fuzzy comprehensive evaluation and IPA model, the core contradictions of the community (such as building energy efficiency and governance coordination) are accurately identified and matched with corresponding strategies, providing a paradigm reference of "problem diagnosis -classified implementation -dynamic optimization" for low-carbon community renewal in China. The case reflects common problems in China ' s community low-carbon transition: insufficient funding and technical adaptability in the renovation of old communities, difficulties in opinion integration caused by complex population structures (e.g., floating population and aging), and the mismatch between residents' low-carbon participation and governance efficiency.

In terms of low-carbon renewal strategies, measures focusing on economic feasibility (e.g., cost-sharing for renewable energy substitution), convenience of resident participation (e.g., carbon inclusive incentives and visual energy consumption monitoring), and policy coordination (e.g., whole-life cycle management of green buildings) are more feasible for Liangzhu Cultural Village. This is consistent with the practical logic of prioritizing indicators such as Z1 (per capita income), Z13 (transportation mode), and Z18 (policy guarantee) in the Liangzhu case. The realization of fairness relies on a collaborative mechanism of "four-dimensional justice" : in distributive justice, targeted resource inclination is used to bridge the "green gap" between old and emerging communities; in procedural justice, a deliberation platform for full resident participation is established; in recognition justice, the community ' s cultural genes (e.g., ecological protection demands in Liangzhu Cultural Village) are respected; in compensatory justice, a differentiated sharing system for renovation costs is formulated.

Compared with justice-oriented community construction abroad, Chinese characteristics are reflected in three aspects: first, in governance subjects, a ternary structure of "government policy-driven –community autonomy coordination –market technology support" can be formed, which is different from the foreign models focusing on resident autonomy or market leadership, such as the linkage between Hangzhou ' s carbon peaking policy and the community intelligent platform in the Liangzhu case; second, in value orientation, social harmony and collective interests are highlighted, emphasizing the concretization of "common but differentiated responsibilities" at the community level, such as low-carbon empowerment rather than exclusion for the floating population; third, in the implementation path, attention is paid to the integration of whole-life cycle management and intelligent tools (e.g., dynamic energy consumption monitoring systems), which is

different from the foreign focus on a single dimension (e.g., spatial justice or energy justice) and more suitable for the complex governance needs of high-density communities in China.

4.3. Research Limitations and Prospects

(1) Lack of a direct carbon emission accounting system: This study innovatively decouples community low-carbon potential assessment from carbon emission calculation, yet the evaluation of carbon emissions mostly relies on indirect deduction and subjective perception, which limits the persuasiveness and practical guidance of the existing conclusions. It is suggested that targeted carbon emission accounting be carried out in follow-up studies to verify the scientificity of the evaluation system. (2) Subjective bias in the evaluation indicator system: The selection of evaluation indicators and weight assignment in existing studies mostly depend on expert questionnaire consultation and judgment. Although expert experience can reflect industrial consensus, the subjectivity in this process may reduce the universality of the evaluation model, making it difficult to support low-carbon renewal design decisions for cross-regional and cross-type communities.

Insufficient sample size and diversity of case empirical research: The current evaluation system has only been applied in Liangzhu Cultural Village Community, lacking cross-comparison and verification with achievements of other types of communities. It is suggested to increase research and practice on other types of communities to enhance the universality of the study.

(4) Limited population representativeness of questionnaire surveys: Field surveys are affected by temporal and spatial conditions (e.g., rest days) and the structure of respondents. It is necessary to extend the survey period, increase the sample size and frequency to improve data reliability. (5) Disconnection between static evaluation and dynamic verification: This study only evaluates the static status of the current community, without integrating the dynamic changes of community development into the

analysis framework. It is necessary to supplement dynamic monitoring and verification of the implementation process of community low-carbon renewal.

5. Conclusions

In response to the social injustice issues in community low-carbon renewal, this study constructs an evaluation system with 20 factors based on the complexity of community systems, justice theory and zero-carbon standards, and uses the AHP-fuzzy comprehensive evaluation method to determine weights and grades. By characterizing the differences in carbon emission impacts and classifying communities, combined with the IPA model, a dynamic mechanism and strategy sequence are established to achieve precise matching of resources and demands as well as fair scheme design, improving the accuracy, dynamics and fairness of renewal. The main conclusions of the study are as follows: (1) Existing justice-oriented solutions have deficiencies such as delayed participation and extensive distribution. To realize "low-carbon justice", the concept of justice needs to be integrated into the whole process of renewal design,

targeting the core characteristics and demands of communities to ensure differentiated fairness in low-carbon transformation. (2) A four-dimensional criterion layer including distributive, recognition, compensatory and procedural justice is constructed, deriving 9 sub-criteria such as economic, physical and demographic factors and 20 specific indicators, forming a hierarchical indicator system for low-carbon communities. Among them, Y1 (economic factors, weight 0.6975), represented by Z1 (per capita income and consumption level of residents, composite weight 0.1654), significantly enhances the importance of X1 (distributive justice) to 0.4394; while X4 (procedural justice) accounts for the lowest weight in low-carbon justice, only 0.1006. (3) Using K-means clustering combined with indicator weights, seven differentiated renewal types of communities

identified,

namely

green

consumption-oriented,

population

optimization-oriented,

energy

substitution-oriented, green travel-oriented, energy-saving renovation-oriented, institutional innovation-oriented and cultural influence-oriented communities. A classified simplified calculation method is formulated, and an implementation path of "responsibility subject division - task gradient sorting - visual list" is established. (4) Based on low-carbon justice, an evaluation model centered on carbon reduction potential is established, integrating grade assessment and IPA analysis. The comprehensive score of low-carbon potential of Liangzhu Cultural Village Community is quantified as 85.86 (Grade

), belonging to the energy-saving

renovation-oriented type. The renewal measures mainly focus on four aspects: building renovation, natural environment, public facilities and intelligent management. The evaluation results of the Liangzhu case point out the neglect of community heterogeneity in China ' s community low-carbon renewal, providing support for the goal of differentiated policy implementation to achieve social justice.

Data Availability Statement: Data are contained within the article.

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Abbreviations

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Appendices Appendix A. Main contradictions in low - carbon renewal of communities in Liangzhu Subdistrict district Main Communities in Liangzhu Subdistrict Yuze Community Xinqiao Community Wannianqiao Community Shijiawan Community Mingya Community Qinqinjiayuan Community Zonglvwan Community Chongfu Community Jinbodu Community

Main Contradictions in Low - Carbon Renovation Differentiation between commercial housing and resettlement housing communities; Lack of community management integration mechanism; Insufficiency in systematic energy management Low building energy efficiency, high renovation difficulty; Lagging infrastructure restricts resource utilization; Insufficient public transportation construction Dense migrant population, high management difficulty; Competition between industrial land and low - carbon space Slow progress in building energy - saving renovation; Unbalanced coverage of environmental protection publicity Slow progress in building energy - saving renovation; Prominent situation of separated households and tenants, dense rental population; Insufficient funds for low - carbon renovation Slow progress in building energy - saving renovation; Population aging, incomplete low - carbon management system Factors such as fund coordination and divergent residents' opinions affect the progress of low - carbon renovation; Insufficient residents' low - carbon responsibility awareness Low energy efficiency of old facilities; Limitations in the application of smart governance platforms; Unbalanced structure of residents' participation Insufficient low - carbon renovation after the demolition of guaranteed housing; Lack of intelligent management means; Insufficient residents' participation in low - carbon management

Guanjiatang

Industrial transformation affects the collective economy of the village; High proportion of floating population, high

Community

management difficulty

Liangzhu Cultural

Ineffective waste classification; Resistance in promoting low - carbon transportation; Slow progress in building

Village Community

energy - saving renovation

Yijucheng Community Beixiu Community Beichen Community Juxian Community Tongyun Community

Lack of integration of community management mode into low - carbon renewal; Aging infrastructure, lack of maintenance Low energy efficiency of early buildings; Large population size, complex structure, high management difficulty; Insufficient intelligent management means Insufficient low - carbon construction of infrastructure; Community governance system to be improved; Insufficient integration of low - carbon concepts in newly built communities Special challenges brought by the characteristics of talent communities; Incomplete low - carbon supporting facilities in community planning and construction Governance problems brought by the characteristics of mixed - type communities; Lagging public transportation

supporting facilities; Resistance in energy - saving renovation of multi - property buildings Low - carbon planning of commercial Subdistricts to be optimized; Poor connection of slow - moving systems;

Yuniao Community

Contradictions between governance coordination and commercial operation Difficulties in coordinating the interests of multiple subjects in the composite function area; Insufficient supporting

Yuexiu Community

facilities for new energy; Single function of the smart platform Un unified management standards for energy consumption of diverse business forms; Low energy efficiency of

Boyuan Community

public buildings; Defects in community participation mechanisms Contradictions between industrial transformation and low - carbon goals; Difficulties in renovating infrastructure at

Wujiaku Community

farmers' living points; Lack of low - carbon management for floating populations

Xitangyayuan

Superposition of aging and floating populations; Lack of control in community commercial low - carbon

Community

management; Disruption of resource recycling systems

Changyun Community Changqiao Community

Dilemma in three - dimensional space energy management; Carbon management derived from transportation hubs; Out - of - control energy consumption management at the commercial - residential interface Structural contradictions in the renovation of industrial heritage; Governance troubles in industrial - agricultural mixed areas; High carbonization of logistics transportation Low coverage rate of smart electricity meters; Insufficient construction of new energy infrastructure; Insufficient

Xinxi Community

innovation in low - carbon systems

Appendix B. Optimized and integrated evaluation indicator set for community-specific carbon emission intensity differentiation Number

Evaluation Indicator

Preliminary Description of the Evaluation Indicator

Per Capita Income and Consumption

The increase in the level of per capita disposable income promotes the growth of residents'

Level

living demands, and the consumption level and patterns also become diversified accordingly.

Per Capita Living Area

Correlated with population density, it affects the carbon emission intensity per unit area.

Private Car Ownership Rate and

The number of private cars owned per capita by residents and the proportion of new energy

Proportion of New Energy Vehicles

vehicles.

Mixed - use Degree of Surrounding Functions Compliance

Green

The diversity and accessibility of service facilities around the community.

The energy - consuming degree designed by the layout, density, height, etc. of the building

Buildings in the Community

space.

Green Area and Types in the

The construction situation of public green spaces, three - dimensional greening, and

Community

community greenways in the community.

Sharing Utilization Level of Public

The density of basic public facilities in the community and their contribution to reducing the

Facilities

internal energy consumption of residences. The proportion and structure type of the population in different age groups in the

Age Structure

Residential Mode

The location, development status, regional characteristics, etc. of the community.

Education Attainment

The average education level of the community population.

Community Folk Cultural Activities

The inherent living habits and traditions left over from the history of some communities.

Popular

Science

community.

Education

Publicity Private Car Travel Rate and Public Transport Sharing Rate

The function of integrating popular science education into the community environment.

The travel distance and travel mode per capita of community residents.

Implementation Degree of Waste

The energy consumption reduction in waste treatment in the community and the

Classification

improvement of waste resource and economic value.

Supply of Renewable Energy and Resource Recycling Rate

The proportion of clean energy used in the community and the reuse rate of resources.

Coverage Rate of Technical Means Support Mechanism for Low carbon Transformation

The popularization rate of technologies such as carbon capture, carbon storage, and carbon utilization in the community.

The policy incentives for circular economy and sharing economy in the community.

Life - cycle Management of Green

The construction situation of the community building carbon emission update monitoring

Buildings

system.

Carbon Emission Incentive and

The preferential policies given by the community to families or individuals that meet the

Accountability Mechanism

energy - consumption standards.

Participation Degree and Channels of All Groups in Decision - making

The decision - making participation wishes and methods of representatives of all groups in the community for the update methods of representatives of all groups in the community for the update plan.

Appendix C. Implementation entities and action directory for the classified renovation of low - carbon communities Community

Key Fields

Consumption Habits

Green

Population Density

Age Structure

Population

Clean Energy

Substitution

7. Carry out community - based low - carbon consumption

publicity and green consumption education

5. Guide the integration of floating populations into the

community

1. Comprehensively consider the layout of subways and bus

stations to ensure community coverage

5. Open new energy utilization lectures and training courses

Transport

6. Provide affordable housing and renovation subsidies

Promotion

2. Design compact communities (reduce commuting needs)

elderly group

low - rise residences)

4. Create renewable energy demonstration projects

Public

1. Reasonably plan the population size (layout of high - rise and

Technology

Green Travel

carbon industries in the community

talents Floating

Social Entities

3. Concentrate resources to attract young families and support the

Population

Government

3. Establish community - level resource recycling and

systems to reduce costs

Awareness

Community

4. Build community - based photovoltaic and energy storage

System

Implementation Entities

2. Use clean energy

Industry

Low-Carbon

Energy

green daily necessities

remanufacturing centers

Guarantee

Optimization

1. Purchase energy - saving equipment, electric vehicles, and

Green Consumption

Action Directory

Infrastructure

4. Manage bicycle lanes and sidewalks, and build community

slow - moving traffic

5. Equip community charging facilities

vehicles

Policies

6. Implement public transport fare subsidies and restrict private

car travel Low-carbon Awareness

Building Renovation

8. Organize community market activities to shorten non -

commuting travel distances

Saving

Green Space

Renovation

2. Optimize the electromechanical system and replace high -

energy - consuming old equipment

5. Integrate multi - dimensional functions such as shady

walkways, rain gardens, and farms

6. Renew the water supply system and other municipal

Public

infrastructure

Facilities

7. Integrate shared public infrastructure such as photovoltaics and

energy storage stations

Smart Management

8. Monitor and manage green building energy consumption data

Government

relevant regulations

Management

2. Develop carbon incentives and subsidy policies

Innovation

Community Self-

Governance

5. Introduce professional institutions to guide community low -

Collaboration

carbon management

Awareness

2. Collect residents' low - carbon willingness opinions and

formulate community green covenants

Cultural

3. Publicize low - carbon culture through multiple online and

Influence

offline channels within the community

Tripartite

Low- Carbon

3. Monitor and record community carbon emission data

unified democratic decision - making

1. Formulate community low - carbon renovation standards and

System

1. Upgrade the building envelope structure

on demand Energy-

5. Subsidy policies for replacing fuel vehicles with electric

Regulatory

Cultural

4. Build a community low - carbon cultural center, and share

Publicity

updated achievements with residents

5. Organize green market and other low - carbon activities to

promote residents' participation

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.