Urban-Act
Integrated Urban Climate Action
for Low-Carbon & Resilient Cities

# A Low-Carbon and Resilient Indicator Framework for Xi'an's Detailed Spatial Planning

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The Urban-Act project is implemented on behalf of the International Climate Initiative (IKI) of the Federal Government of Germany. Within the Federal Government, the IKI is anchored in the Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN).

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# Abstract

## I. Research Objectives

To advance Xi'an's development as a pilot city for low-carbon resilience and to meet the contemporary requirements for territorial spatial planning, this project establishes a robust technical framework focused on carbon reduction and resilience-building. By aligning with Xi'an's ongoing urban initiatives, the study ensures that low-carbon indicators are seamlessly cascaded and coordinated across various planning hierarchies, with practical applications demonstrated through pilot programs in representative urban blocks. The research focuses on four areas:

**(1) Clarifying the Transmission Mechanisms and Strategic Priorities of Low-Carbon Resilience within Territorial Spatial Planning**

Building upon existing territorial spatial plans and specialized resilience frameworks, this component defines how high-level "Dual Carbon" goals and dual-use (routine-emergency) resilience objectives are systematically cascaded from master plans down to the detailed planning level. By identifying key regulatory requirements at each tier, the study establishes a clear hierarchy for implementation, ultimately designating priority carbon-control indicators and target regulatory units at the sub-district (block) level.

**(2) Profiling and Uncovering the Baseline Low-Carbon and Resilience Characteristics of Diverse Unit Typologies in Xi'an**

This component establishes a localized carbon accounting framework tailored to the specific urban and environmental context of Xi'an. By developing calculation models for building emissions, transportation emissions, municipal infrastructure emissions, carbon sequestration (sinks), and decarbonization potential, the study provides a comprehensive diagnostic profile of emission patterns. These models, validated through site-specific field surveys, identify the unique baseline characteristics of various planning units across the city.

**(3) Developing Key Regulatory and Differentiated Indicator Systems across Unit Typologies**

To address the distinct regulatory objectives of industrial, residential, regeneration, and ecological units, the study constructs a context-specific indicator framework. Grounded in a rigorous correlation analysis between spatial planning parameters and carbon emissions, this system ensures full alignment with international best practices, domestic technical codes, and resilience guidelines, delivering a bespoke suite of metrics tailored to diverse urban fabrics.

**(4) Formulating Carbon Mitigation and Resilience Strategies for Diverse Unit Typologies**

By identifying key spatial elements for targeted regulation and the specific synergies required for different unit types, the project establishes a comprehensive strategic toolkit. From a low-carbon resilience perspective, this includes optimized spatial layouts, sustainable building practices, renewable energy systems, high-efficiency public service facilities, and green, low-carbon mobility solutions—all integrated into a cohesive strategy suite for unit-level implementation.

## II. Technical Roadmap

The research methodology culminated in a systematized set of Low-Carbon Resilience Guidelines designed to facilitate detailed territorial spatial planning at the block (unit) level. The roadmap integrated: An analysis of the transmission mechanisms and strategic priorities of low-carbon resilience within the spatial planning hierarchy; A baseline analysis of low-carbon resilience characteristics across diversified urban units in Xi'an; The construction of a context-specific key regulatory indicator system. This comprehensive approach provides the technical foundation for translating high-level sustainability goals into actionable, block-level urban design and regulatory requirements.

## III. Main Conclusions

**(I) Transmission Mechanisms for "Dual-Carbon" and Resilience Objectives**

**(1) Carbon Mitigation:** At the Master Plan level, the framework prioritizes the decomposition of carbon intensity and total emission targets from the regional scale down to functional zones. At the Detailed Planning level, the focus shifts to achieving tailored carbon intensity targets for specific land parcels through high-precision quantitative metrics.

**(2) Resilience Integration:** The study incorporates dual-use (routine-emergency) functionality into the territorial spatial planning hierarchy. Detailed planning is designated as the primary instrument for land-use regulation and functional guidance, cascading master plan indicators to specific sites while defining the siting, scale, and cross-functional adaptability of resilient infrastructure.

**(II) Baseline Characteristics and Key Spatial Parameters**

The study established a localized Carbon Emission and Sequestration Factor Repository for Xi'an to profile the low-carbon resilience of industrial, residential, regeneration, and ecological units. Statistical modeling was utilized to isolate the spatial parameters most critical to resilience, identifying office sub-units within industrial zones and regeneration units as the highest priority for carbon regulation. Key findings include:

**(1) Industrial Units:** The Jingwei Industrial Park exhibits the highest carbon intensity, primarily driven by industry and warehousing. Both office-based innovation parks share similar carbon emission profiles. The primary lever for carbon mitigation and resilience in this sector is the decarbonization of the industrial energy mix.

**(2) Residential Units:** Mitigation priorities vary by neighborhood typology. The core dimension of carbon mitigation and resilience involves optimizing residential land-use allocation.

**(3) Regeneration Units:** Electricity consumption in commercial and industrial / warehousing buildings remains a high-intensity carbon source. As these units undergo functional diversification into culture and tourism, carbon mitigation and resilience strategies must focus on Programmatic Mix Regulation and Infrastructure & Environmental Optimization.

**(4) Ecological Units:** Carbon sequestration sources vary by landscape attribute. Riverfront units rely on stratified arboreal-shrub-grass systems, while heritage sites rely on turfgrass. The core dimension for carbon sink expansion is to adjust vegetation community structures.

**(III) Strategy Framework for Unit-Level Carbon Mitigation and Resilience**

Based on the aforementioned findings, the study establishes a comprehensive strategy framework that integrates low-carbon resilient spatial layouts, sustainable building construction, renewable energy systems, high-efficiency community service facilities, green low-carbon mobility, and high-sequestration green spaces. This framework serves as the basis for proposing targeted carbon mitigation and resilience strategies tailored to the specific characteristics of each unit type. The conclusions are as follows:

**(1) Industrial Units:** Strategies prioritize industrial restructuring by regulating energy productivity and the rate of decline in carbon intensity per unit of Gross Value Added (GVA), auditing the energy efficiency of planned buildings, and expanding the deployment of renewable energy systems.

**(2) Residential Units:** A four-fold strategy is proposed, encompassing: managing land-use scale; optimizing Floor Area Ratio (FAR) and Building Coverage Ratio (BCR); enhancing the spatial enclosure of residential blocks; and strengthening rail transit infrastructure.

**(3) Regeneration Units:** The framework focuses on four key areas: balancing low-carbon objectives with commercial vitality; reducing indirect building energy consumption; prioritizing Transit-Oriented Development (TOD) to enhance rail transit facilities; and maximizing environmental and ecological co-benefits.

**(4) Ecological Units:** Resilience and sequestration are enhanced through two primary pathways: developing "pocket parks" and increasing the carbon sink capacity of riverfront green spaces; and optimizing vegetation configurations by increasing the ratio of trees, shrubs, and grasses.

The research has successfully established key regulatory and differentiated indicator systems for diverse urban units, alongside a Baseline Carbon Mitigation and Resilience Database for Xi'an's urban units. These efforts have culminated in the development of standardized, replicable, and scalable Carbon Mitigation and Resilience Operational Guidelines and Action-Oriented Factsheets, providing the robust technical foundation required for the formulation of unit-level low-carbon and resilient detailed plans.

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# 1. Overview of the Study

## 1.1 Research Objectives and Significance

The urgency of global climate change following the *Paris Agreement* has established a worldwide consensus on emissions reduction and climate mitigation. In 2020, President Xi Jinping committed China to an international mandate: peaking carbon dioxide emissions before 2030 and achieving carbon neutrality by 2060. This was further reinforced by the *CPC Central Committee's Proposals for Formulating the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035*, which emphasize a new paradigm for territorial spatial protection and the acceleration of green, low-carbon development[1]. **Consequently, researching spatial planning pathways centered on low-carbon and resilience principles has become a strategic imperative for plan formulation and delivery in this new era.**

Spatial planning serves as a critical coordinating mechanism with a profound "lock-in effect, [1]" exerting a long-term structural influence on carbon profiles and urban resilience. **By optimizing the allocation of spatial elements, low-carbon resilience planning targets emissions across energy, transport, industry, and construction. This approach enhances the capacity of cities to mitigate latent climate risks while engineering green, healthy, and sustainable urban environments[2].**

As a designated pilot city for the project of Integrated Actions for Low-Carbon and Resilient Territorial Spatial Planning under the Context of Climate Change, Xi'an must leverage its localized characteristics and existing planning outcomes to explore synergetic frameworks for decarbonization and resilience. While the intersection of urban space and carbon reduction is a premier international research frontier, significant challenges persist: (1) highly diversified urban functions lead to disparate planning priorities; and (2) the complexity of multi-level planning hierarchies often results in implementation lag and a lack of functional adaptability in indicator systems. **The formulation of precise, high-efficacy, and chronologically optimized carbon mitigation and resilience measures—alongside the construction of a low-carbon, resilient urban spatial strategy and indicator system specific to Xi'an's Detailed Territorial Spatial Planning—necessitates further rigorous and evidence-based empirical research.**

This project addresses these challenges by aligning with Xi'an's mandate to serve as a low-carbon resilience pilot. Informed by baseline assessments of the city's current development and low-carbon goals, the study focuses on representative employment (productive) and residential (living) units. By analyzing functional positioning and regulatory priorities, **the study examines the transmission mechanisms and strategic priorities of Xi'an's detailed spatial planning. The outcome is a framework comprising both universal key and differentiated indicator systems designed to identify the primary pathways for unit-level emissions reduction**.

Ultimately, this study establishes a technical system that synchronizes low-carbon resilience indicators across all planning hierarchies to regulate specific urban construction activities. Through pilot demonstrations, **the project provides the foundational technical support necessary for a city-wide roll-out of resilient development in Xi'an**. **Furthermore, by promoting the coupling of technical resilience solutions with spatial planning systems, this study offers significant demonstration value and scalable best-practice precedents for achieving national decarbonization and resilience goals.**

## 1.2 Research Scope

**(1) Transmission Mechanisms and Strategic Priorities of Low-Carbon Resilience in Territorial Spatial Planning.** Based on existing territorial spatial plans and specialized resilience frameworks, this task defines how high-level "Dual Carbon" goals and dual-use (routine-emergency) resilience objectives are integrated across the master and detailed planning tiers. The study identifies priority carbon-control indicators, designates key regulatory units at the block level, and defines the core resilience-enhancement dimensions tailored to specific urban functions.

**(2) Baseline Analysis of Low-Carbon Resilience Characteristics across Diversified Urban Units in Xi'an.** This component involves the construction of a unit-level carbon accounting framework tailored to Xi'an's local urban fabric. It establishes sophisticated quantification models for emissions from buildings, transportation, and municipal infrastructure, alongside assessments of carbon sequestration and mitigation potential. By integrating field survey data, the research characterizes emission profiles and identifies critical baseline issues for each planning unit typology.

**(3) Key Regulatory and Differentiated Indicator Systems across Unit Typologies.** To address the distinct regulatory objectives of industrial, residential, regeneration, and ecological units, the study constructs a context-specific indicator framework. Grounded in a rigorous correlation analysis between spatial planning parameters and carbon emissions, this system ensures full alignment with international best practices, domestic technical codes, and resilience guidelines, delivering a bespoke suite of metrics tailored to diverse urban fabrics.

**(4) Formulating Unit-Level Carbon Mitigation and Resilience Strategies.** By identifying key spatial elements for targeted regulation and the specific synergies required for different unit types, the project establishes a comprehensive strategic toolkit. From a low-carbon resilience perspective, this includes optimized spatial layouts, sustainable building practices, renewable energy systems, high-efficiency public service facilities, and green, low-carbon mobility solutions—all integrated into a cohesive strategy suite for unit-level implementation.

## 1.3 Research Methodology

**(1) Carbon Emission Quantification Models Based on the Xi'an Database.** Drawing upon Xi'an's current energy consumption and socio-economic datasets, and considering the technical complexities of localized accounting, this study utilizes the IPCC Emission Factor Method to establish a bespoke quantification framework. The model integrates carbon emissions from the building, transportation, and infrastructure sectors, alongside carbon sequestration (sinks) [4][3]. A bottom-up approach is employed to estimate $CO_2$ emissions and sequestration at the block level (detailed planning level). These findings are subsequently triangulated against the top-down disaggregation of city-wide (master plan) data. This rigorous cross-validation ensures the precision and integrity of the Xi'an Carbon Mitigation and Resilience Dataset.

**1) Building-Sector Carbon Emissions**

The accounting boundary for the building sector encompasses emissions from electricity and natural gas consumption. By analyzing per capita energy indices, the study developed a localized consumption coefficient library categorized by building typology. Primary variables include total floor area, energy intensity (consumption per unit area), and building-specific emission factors.

Calculation Model for Building Electricity Emissions ($C_E$):

$$C_E = \sum_{i=1}^{n} S_i \times \partial_i \times k_1 \qquad (1\text{-}1)$$

Where: $S_i$: Total floor area for building typology $i$; $\partial_i$: Electricity consumption coefficient per unit area for building typology $i$ in Xi'an; $k_1$: Carbon emission factor for the Shaanxi Provincial Power Grid[3].

Calculation Model for Building Natural Gas Emissions ($C_s$):

$$C_s = \sum_{i=1}^{n} S_i \times \beta_i \times k_2 \qquad (1\text{-}2)$$

Where: $S_i$: Total floor area for building typology $i$; $\beta_i$: Natural gas consumption coefficient per unit area for building typology $i$ in Xi'an; $k_2$: Carbon emission factor for natural gas[4].

**2) Transportation Carbon Emissions**

Of the two primary quantification methodologies—the fuel-based approach and the activity-based (distance-driven) approach—this study adopts the latter. Emissions are modeled based on the commuting patterns and travel behavior of Xi'an residents. Key variables include Vehicle Kilometers Traveled (VKT) by mode, vehicle stock, modal split (travel structure), and mode-specific emission factors.

Calculation Model for Commuting Emissions ($E_T$):

$$E_T = \sum L_i \times e_i \times P \qquad (1\text{-}3)$$

Where: $E_T$ Total transportation carbon emissions; $L_i$: Vehicle Kilometers Traveled $i$; $e_i$: Carbon emission factor corresponding to commuting mode i; P: Total travel volume (trips or vehicle-trips)[5].

**3) Infrastructure-Sector (Municipal) Emissions**

Infrastructure-sector emissions typically comprise GHGs generated during the operation and maintenance of urban utilities, including energy use, wastewater treatment, and waste management. Due to current data limitations, these emissions are excluded from the accounting boundary at this stage.

**4) Green Space Carbon Sequestration (Sinks)**

To ensure methodological feasibility at the detailed planning level, this study utilizes an integrated approach combining Photosynthetic Assimilation with area-based modeling. Grounded in Xi'an's Urban Greening Technical Guidelines, carbon sequestration coefficients were developed for localized green space types, including stratified arboreal-shrub-herbaceous systems, shrub-herbaceous, lawn, and grassland categories. The calculation formula is as follows:

$$C = \sum_{j=1}^{n} T_j \times S_j \times D \qquad (1\text{-}4)$$

Where: $S_j$ Daily carbon fixation rate for green space types $j$ in Xi'an; $S_j$: Total area of green space types $j$; D: Number of active sequestration days per annum[6].

**5) Mitigation Potential**

Block-level carbon mitigation potential is evaluated across two vectors: Photovoltaic (PV) generation capacity and Solar Thermal potential.

The calculation model for Photovoltaic (PV) generation potential is: PV Generation Potential = [(Building Rooftop Area × Rooftop Installable Area Ratio / Incidence Angle Adjustment (cos 26°)) + (Installable Area Ratio of Open-Space Areas × Total Block Area)] × PV Panel Power Density (150 W/m²) × Annual PV Generation per Watt in Xi'an (1.029 kWh/W)[9].

The calculation model for Solar Thermal potential is: Solar Thermal Potential = **(Annual Domestic Hot Water Demand per Capita (2,190 L/person·year) × Total Occupant Population) / Annual Hot Water Yield per Square Meter (91,980 L/m²·year) × Annual Energy Offset per Square Meter (417 kWh/m²·year)[7].

**(2) Literature Review and Policy Synthesis.** This study employs a comprehensive review of domestic and international scholarship regarding low-carbon and resilient urbanism. By synthesizing academic literature with the Territorial Spatial Planning Climate Risk Assessment Technical Report and the Xi'an Resilient City Special Planning, the project established its overarching technical roadmap. This process involved a meta-analysis of existing detailed planning frameworks to identify critical gaps in current domestic research, which served as the analytical point of departure for this study. This method ensures a comprehensive baseline for contextualizing findings and generating evidence-based results.

**(3) Empirical Fieldwork.** The study adopts a site-specific empirical approach to data collection across ten representative pilot blocks in Xi'an. Utilizing a combination of on-site observations, stakeholder interviews, and questionnaire-based surveys, the research captured localized baseline data on resident behavior and urban spatial configurations. These ground-truth datasets provide the essential inputs required for subsequent model calibration and the validation of unit-level carbon profiles.

**(4) Spatial Analysis.** The study utilizes the ArcGIS 10.6 platform to integrate high-resolution geospatial data with multi-dimensional attribute information. By synthesizing spatial objects with their corresponding datasets, this GIS framework facilitates the extraction of complex spatial patterns and deeper morphological insights[8]. Central to this methodology is the development of a Baseline Carbon Mitigation and Resilience Database for Xi'an's Urban Units, which aggregates building layouts, road networks, demographic distributions, and public service layouts to serve as the quantitative baseline for all subsequent carbon accounting.

**(5) Quantitative Statistical Inference.** This research integrates multi-source datasets—including building morphology, human trajectory patterns, and industrial profiles—with measured energy consumption data and primary fieldwork results. These inputs were utilized to simulate carbon emission intensity and establish resilience assessment scenarios based on Xi'an's existing spatial configurations. Following a multivariate descriptive analysis (utilizing bar and pie charts to map baseline distributions), the data underwent rigorous processing via SPSS and Excel. Advanced inferential modeling, including Pearson Correlation Analysis and Ordinary Least Squares (OLS) Regression, was applied to isolate critical spatial variables and extract latent structural and behavioral characteristics from the urban dataset.

## 1.4 Technical Roadmap

The research technical roadmap is illustrated in the figure below.

To date, the study has completed the core components of the research, including: the analysis of transmission mechanisms and strategic priorities for low-carbon resilience within Territorial Spatial Planning (TSP); the baseline analysis of low-carbon resilience characteristics across diversified urban units in Xi'an; and the establishment of key regulatory and differentiated indicator systems across unit typologies. A preliminary Strategy Framework for Unit-Level Carbon Mitigation and Resilience has been established. Subsequent phases will focus on refining these strategies to provide robust technical support for the formulation of unit-level low-carbon and resilient detailed plans.

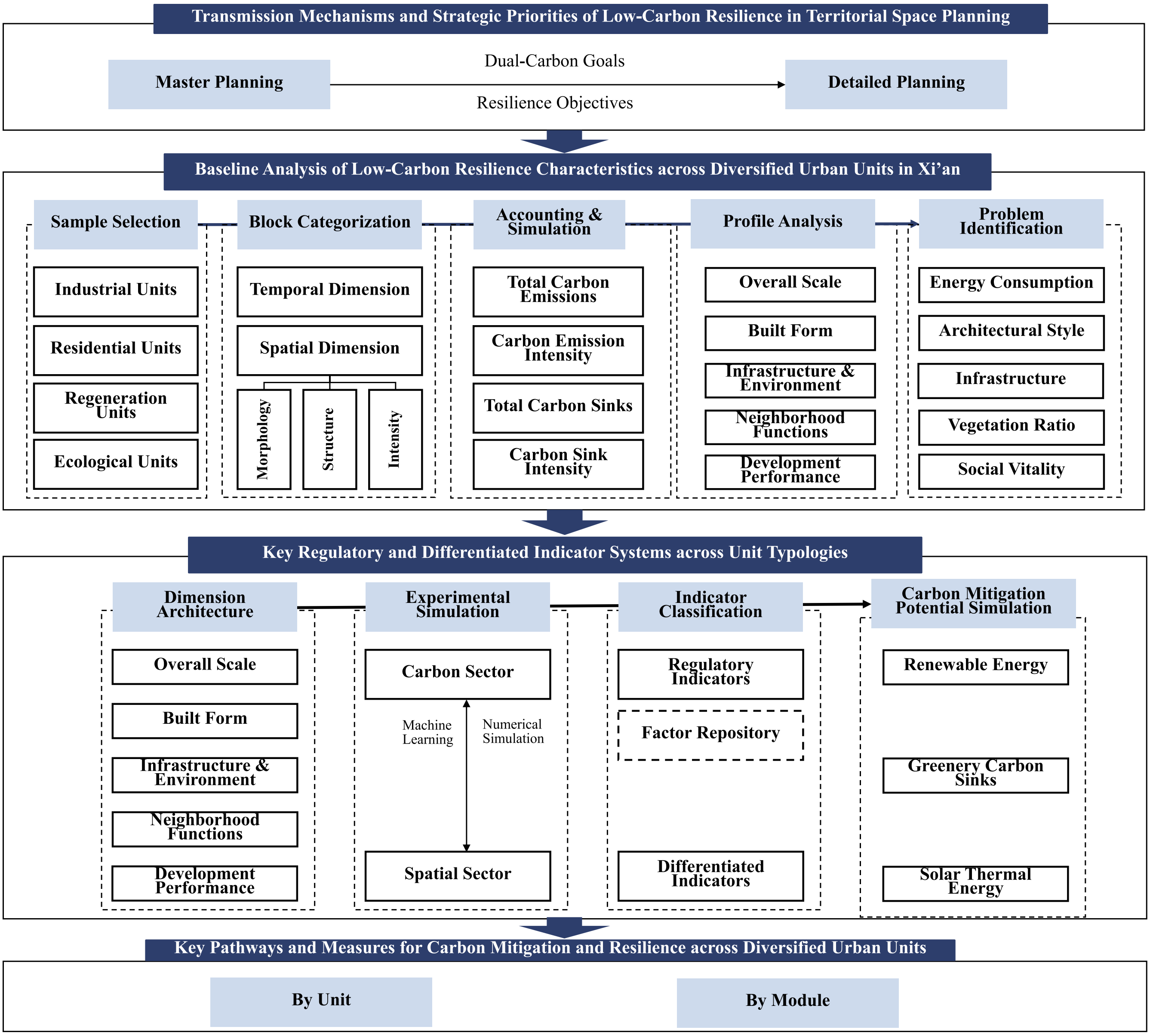



Figure 1-1: Technical Roadmap
Source: Prepared by author

# 2. Literature Review of Domestic and International Research and Practice

## 2.1 Theoretical Foundations of Low-carbon Cities and Resilient Cities

### 2.1.1 Concept and Characteristics of Low-carbon Cities

To address the global climate crisis and fulfill the strategic mandate of achieving carbon neutrality by 2060, the principles of sustainable development—centered on energy conservation and emissions reduction—have gained unprecedented prominence. In this context, the transition toward low-carbon economies, technologies, and societies has become a focal point of academic and policy discourse. As the primary spatial nexus for socio-economic activity, the **Low-Carbon City** represents the physical manifestation of these principles and serves as a critical strategic lever for advancing low-carbon economic development.

**A low-carbon city is defined as an urban environment that adopts the low-carbon economy as its primary development model and orientation, where residents integrate sustainable lifestyles into their core ideologies and behaviors, and where urban governance utilizes the low-carbon society as its construction paradigm and blueprint[2].** The construction of low-carbon cities in China is characterized by four distinct pillars: planning guidance, innovation-driven development, diversified pathways, and technological support. In terms of **planning**: Guided by the *Implementation Plan for Peaking Carbon Emissions in Urban and Rural Development Sector* issued by the MOHURD and the NDRC, China prioritizes green development through large-scale urban regeneration and rural construction initiatives to enhance the quality of sustainable growth[9]. In terms of **paradigm**: Through the implementation of pilot policies—covering 81 cities as of 2017—China has fostered a "test-bed" approach, encouraging institutional innovation tailored to local conditions across the country. In terms of **pathways**: Regions pursue decarbonization through varied strategic entry points according to their specific local conditions, including the low-carbon transformation of energy systems, economies, and social structures, to achieve the overarching goal of sustainable development. In terms of **methods**: The synergy between urban planning and construction is maintained through focused basic research, frontier technology advancements, and the industrial application of engineering demonstrations, ensuring that low-carbon cities are supported by a robust technical foundation.

### 2.1.2 Concept and Characteristics of Resilient Cities

The concept of "resilience" was pioneered by ecologist C.S. Holling to characterize the capacity of an ecosystem to absorb perturbations while maintaining a stable state[12][10]. Within the urban context, a Resilient City is defined as one capable of withstanding, recovering from, and adapting to diverse shocks and stresses while maintaining essential functions, structures, and identities[11]. Contemporary resilience theory has evolved into a multi-dimensional framework, encompassing resilient development for disaster prevention and the enhancement of urban governance through integrated planning and construction guidelines.

The Making Cities Resilient 2030 (MCR2030) initiative[12] identifies three fundamental properties of systemic resilience: ① Robustness (Self-Control): The ability of a system to withstand external changes while maintaining its functional and structural integrity. ② Self-Organization: The maintenance of dynamic equilibrium through strong internal synergies and interactions between systemic components. ③ Adaptive Capacity: The ability of a system to facilitate learning and self-evolution in response to change. These core attributes of engineering and systemic resilience have recently expanded to include spatial, ecological, and governance resilience. Ecological Resilience pertains to the diversity and functional interactivity of urban environmental elements. It posits that a heterogeneous network of infrastructure, greenbelts, woodlands, and wetlands can provide cross-functional redundancies when responding to climate change or sudden crises[13], thereby enabling the self-regulatory capacity of the urban ecosystem. Spatial Resilience focuses on spatial security and structural robustness. China's *Guidelines for the Evaluation of Safe and Resilient Cities* distinguishes spatial resilience from traditional engineering resilience by establishing clear technical criteria and regulatory benchmarks[14]. Urban Safety Resilience is defined by three cyclical characteristics: Response, Recovery, and Adaptation. These represent not only the operational behavioral patterns of a resilient city during emergencies but also the dynamic process of integrated emergency management[15].

### 2.1.3 Correlation Analysis Between Low-Carbon and Resilient Cities

Low-carbon cities prioritize urban spatial interventions centered on energy conservation and emissions reduction to curb GHG emission trajectories and address the global climate crisis. Resilient cities focus on enhancing urban robustness, adaptability, and recovery through planning, technical, and policy instruments integrated across the urban development and management lifecycle. While these two concepts are divergent in their primary operational focus, they are fundamentally complementary and intrinsically linked.

**Common Strategic Objectives:** Both frameworks are conceptualized to facilitate urban sustainability, serving as a unified planning response to environmental challenges. **Sequential Synergy:** The relationship is progressively reinforcing; low-carbon planning promotes high-quality, sustainable growth, which in turn strengthens urban resilience against natural disasters, climate volatility, and economic fluctuations. **Spatial Integration:** Through comprehensive spatial coordination, low-carbon and resilience objectives are unified during the implementation of detailed planning and site-specific production activities. **Technological Convergence:** Significant interdisciplinary technical overlaps exist between the two fields, with energy efficiency technologies frequently providing the foundation for decentralized, resilient infrastructure systems.

## 2.2 Research Progress in Low-Carbon and Resilient Urban Planning

### 2.2.1 Domestic Research Progress on Low-Carbon and Resilient Cities

Policy Context: China's low-carbon agenda began in 2009 with the establishment of the Action Target for Controlling Greenhouse Gas Emissions by 2020. In 2010, the National Development and Reform Commission (NDRC) issued the *Notice on Launching Pilot Projects for Low-Carbon Provinces and Cities*, marking the official implementation of the national low-carbon pilot policy.

In 2021, against the backdrop of new socio-economic development paradigms, the State Council re-issued the *Notice on Launching Pilot Projects for Low-Carbon Provinces and Cities*. In 2022, the Ministry of Housing and Urban-Rural Development (MOHURD) and the NDRC jointly released the *Implementation Plan for Peaking Carbon Emissions in Urban and Rural Development Sector*, directing urban planning, construction, and management toward national carbon-peaking objectives. **Measurement and Classification:** Yu et al. (2020) [18][16] utilized the Tapio Decoupling Model to calculate decoupling elasticity coefficients, categorizing pilot cities into a three-tier typology: Mature, Growing, and Nascent. Wang et al.[17] established an evaluation index system for urban low-carbon development quality grounded in sustainable development theories covering social, economic, environmental, spatial planning, and energy utilization dimensions. Ying[18] evaluated the urban low-carbon energy transition and its associated spatial spillover effects resulting from pilot policies using Difference-in-Differences (DID) and Spatial DID modeling. **Evaluation Frameworks:** Using the Pressure-State-Response (PSR) model, Zhu et al.[21] assessed development quality across six key sectors: carbon emissions, energy intensity, construction, industry, transport, and waste management. Regional studies, such as Duan et al.'s[19] analysis of Shanxi Province, focused on the economic-social-energy-environment nexus, while Lou et al. [20] developed an eight-dimension system based on LCC certification benchmarks, covering metrics from urban mobility to resource circularity. Kong et al.[21] specifically analyzed the Yangtze River Delta, measuring 41 cities based on emission volumes, socio-economic drivers, and the efficacy of low-carbon technical interventions. Further specialization includes Liu Qingao et al.'s[22] evaluation of industrial parks via a five-dimension framework (industry, resource efficiency, synergy, infrastructure, and governance), and Liu Zhihua et al.'s[23] dual-focus approach on low-carbon economics and high-quality growth, balancing ecological integrity with commercial value. A comprehensive review of these evaluation systems is summarized in Table 2-1.

Table 2-1: Summary of Low-Carbon City Evaluation Frameworks
Source: Compiled by author according to relevant documents

| Year | Author | Evaluation Dimension |
|---|---|---|
| 2017 | Zhu Jing et al. | Carbon emissions, energy consumption, construction, industry, transportation, waste disposal |
| 2018, | Duan Yonghui et al. | Economy, society, energy, environment |
| 2019, | Lou et al. | Carbon and environment, economy, society, living, urban mobility, solid waste, water resources, energy |
| 2023, | Kong Minwei | Carbon emissions, socio-economic factors related to carbon emissions, low-carbon technologies and policies |
| 2024, | Liu Qingao | Low-carbon industry, energy and resource utilization, pollution and carbon reduction, low-carbon infrastructure, long-term management |
| 2024, | Liu Zhihua | Low-carbon economy and high-quality development |

Theoretical Introduction (1991–2005): During this initial phase, resilience was introduced into China's planning discourse as a pivotal theoretical construct, with research primarily focused on the conceptual definitions and theoretical foundations of the term. Evolutionary Frameworks (2006–2015): The subsequent decade saw the interpretation of core resilience attributes—including redundancy, adaptability, and vulnerability—alongside the incremental exploration of evaluation systems centered on disaster mitigation and climate change[24].

In recent years, the construction of resilient cities in China has been accelerated and promoted with increasing momentum. The national standard, *Guidelines for the Evaluation of Safe and Resilient Cities* (GB/T 40947—2021), was implemented on May 1, 2022. By clarifying the fundamental concepts, evaluation criteria, and technical benchmarks for safe and resilient cities, it provides the essential standardized support for advancing resilience construction and conducting comparative performance assessments across China[25].

In 2021, the General Office of the Beijing Municipal People's Government issued the *Notice on the Guiding Opinions on Accelerating the Construction of Resilient Cities*. The objectives specified within these guidelines mandate that by 2025, a comprehensive resilience indicator and standard system will be established, alongside the completion of 50 resilient communities, neighborhoods, and pilot projects to form scalable and replicable best practices for resilient urban development. By 2035, significant progress is expected in the construction of resilient cities, characterized by a substantial enhancement in catastrophic disaster mitigation capacity, adaptive strength, and rapid recovery speeds. In March 2024, the *Beijing Special Spatial Plan for Resilient Cities (2022–2035)* was promulgated. This policy document outlines a strategy to enhance overall systemic resilience throughout the entire urban development and management lifecycle. Its primary objective is the establishment of a capital spatial governance system defined by reliability, functional flexibility, rapid recovery, and systemic cohesion[26].

### 2.2.2 International Research Progress on Low-Carbon and Resilient Cities

International research on low-carbon cities predates domestic efforts. In 1947, Copenhagen introduced the Proposal for the Planning of the Capital Region (the "Finger Plan"), which emphasized the need to prevent unrestricted urban sprawl and improve the urban environment through satellite towns and green corridors to reduce carbon dioxide emissions. In 2003, the United Kingdom officially introduced the concept of the "Low-Carbon Economy" for the first time in its *Energy White Paper* (Department of Trade and Industry). In 2008, Japanese Prime Minister Yasuo Fukuda proposed the "Comprehensive Low-Carbon Society Model" and pledged to reduce Japan's national carbon dioxide emissions by 60%–80% by 2050. Academic Advancements: In 2008, Ewing established an analytical framework for the interaction between urban morphology and residential carbon emissions, demonstrating that multiple elements of urban spatial form are intrinsically linked to carbon outputs. In 2019, Kim et al. utilized the Gyeongui Line Forest Park in Seoul, South Korea, as a case study, discovering that the park's completion had a quantifiable cooling and energy-reduction effect on buildings within a 300-meter radius[27]. In 2020, Ma et al. employed a Random Forest predictive model to analyze urban building energy consumption in New York City, revealing that building story count is a primary indicator for evaluating urban carbon emissions[28].

During the initial phase of domestic research in the 1990s, C.S. Holling spearheaded the Resilience Alliance (often associated with the broader community of environmental scientists) to catalyze the application of resilience theory within international environmental and development projects. During this period, the academic community was focused on internalizing the concept of resilience and establishing theoretical frameworks across social-ecological systems, climate adaptation, and ecosystem management[29][30]. In 2002, the International Council for Local Environmental Initiatives (ICLEI) introduced the Resilient Cities agenda, sparking a surge in the development of assessment metrics. Consequently, resilience theory has evolved into a critical instrument for addressing climate change, infrastructure protection, natural disasters, and pandemic risks.

In recent years, the global adoption of resilience concepts—aimed at fostering more inclusive, safe, and sustainable cities—has gained significant traction and transitioned into practice, representing a core trend in urban security and development[31]. For example, the United States has prioritized National Resilience, emphasizing the construction of a secure and resilient nation with robust capacities for prevention, protection, response, and recovery. New York City released the *A Stronger, More Resilient New York* plan, which encompasses strategic planning across programmatic pillars including infrastructure and architecture, economic recovery, community preparedness and response, environmental restoration, and neighborhood reconstruction[32]. Japan has established the overarching goal of building a "Strong and Resilient National Land, Economy, and Society[33]." Similarly, the EU's overarching plan—the ESDP (European Spatial Development Perspective)—utilizes integrated spatial planning to facilitate the collaborative development of European metropolitan regions[34].

A systematic review of global literature reveals that recent low-carbon research is **increasingly policy-responsive and demand-driven**, shifting **from qualitative descriptions toward quantitative modeling and dynamic analysis**. Resilience research is increasingly characterized by its integration into public policy and social governance, with a growing emphasis on the territorial spatial development of resilient systems. Building upon these theoretical foundations and tailored to the local context of Xi'an, this study investigates the correlations between urban morphology, architectural form, and carbon emission intensity. By advancing existing methodologies, this research implements a high-precision, customized measurement of spatial variables to isolate their specific impacts on carbon intensity.

## 2.3 Case Studies in Low-Carbon and Resilient Urban Planning

### 2.3.1 Case Analysis of Domestic and International Low-Carbon Urban Planning

**(1) Singapore: A Low-Carbon City Defined by Human-Nature Symbiosis**

Despite being a high-density city with severe land constraints, Singapore maintains a remarkable green coverage rate of 46.5%. As a paradigmatic model for green urbanism, its planning and development offer several transferable best practices[38].

**Policy Leadership.** Following COP26, the Singaporean government launched the "Clean and Green Singapore" campaign and promulgated the "Green Singapore 2050" strategy. These initiatives prioritize the adoption of green roofs and vertical gardens to expand vegetative cover and enhance urban carbon sink potential. The government also implemented the "Active, Beautiful, Clean Waters" (ABC Waters) Programme, which reimagines traditional drainage and supply infrastructure as vibrant blue-green spaces. This initiative effectively mitigates the urban heat island (UHI) effect, facilitates sustainable stormwater management, and enriches urban biodiversity.

**Urban Design.** Singapore embeds low-carbon principles directly into its urban design, fostering innovation in residential development paradigms and green building technologies. For example, the "club sandwich" model of layered, high-density development integrates extensive sky-rise greenery into residential environments, creating optimal spaces for recreational utility and social cohesion. By enhancing the environmental performance of green buildings, the city mitigates ambient heat stress and improves the microclimate, fulfilling the strategic vision of a "City in Nature." Furthermore, the adoption of alternative landscaping techniques facilitates managed rewilding, allowing vegetation to grow spontaneously within public spaces to eventually integrate into the city-wide ecological network.

**Public Participation.** In 2021, the government launched the "Singapore Green Plan 2030," a nationwide movement designed to foster civic agency and incentivize proactive public contribution toward the goal of becoming a global leader in sustainable urbanism. The Green Plan 2030 mandates a 50% increase in land allocation for nature parks and integrates active travel networks (slow-traffic planning) into the urban fabric to ensure seamless multimodal connectivity.

Figure 2-1: Singapore's Strategic Framework for Low-Carbon Urban Development
Source: Journal of Tongji University: Social Science Edition, 2022, 33(3):70-80

**(2) Shanghai: A Low-Carbon Community Model Driven by Smart-Digital Co-Creation**

Shanghai serves as a national pioneer in low-carbon urban development. As a paradigmatic demonstration case for green urbanism, its planning and construction provide several transferable strategic insights[39].

**Low-Carbon Human Settlements.** Shanghai adopts the "Neighborhood-Community" scale as the fundamental spatial unit for implementing low-carbon strategies. During the 14th Five-Year Plan period, the city aims to establish high-quality low-carbon development pilot zones to foster a societal transition toward sustainable lifestyles. This framework utilizes the development of low-carbon communities and pilot zones as strategic entry points. By cultivating granular low-carbon modules and establishing an accreditation system for Low-Carbon Demonstration Units, Shanghai facilitates a modular expansion strategy to scale up green development city-wide.

**Smart-Digital Co-Creation.** Operating at the same neighborhood scale, Shanghai integrates Digital Twin and Smart City technologies to build a comprehensive low-carbon digital platform. This system integrates performance dashboards, data aggregation, dynamic analytics, and policy recommendations. Utilizing diverse tools such as spatial mapping, 3D parametric models, and trend analytics, the platform provides a visual representation of low-carbon outcomes and their spatial distribution. This facilitates integrated lifecycle management across the planning, construction, and operational phases of low-carbon urban development.

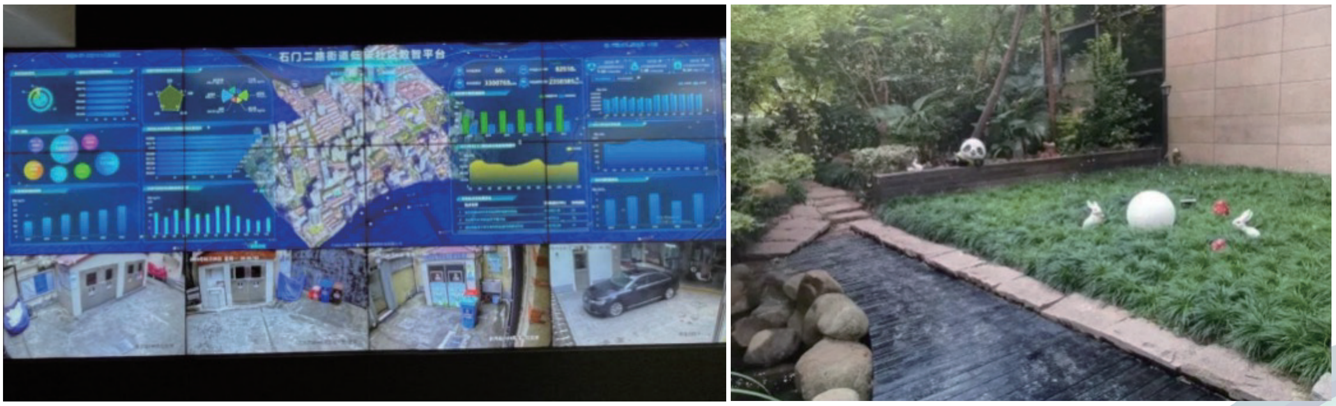


Figure 2-2: Shanghai's Strategic Framework for Low-Carbon Urban Development
Source: Shanghai Urban Planning Review, 2022, (03), 68-74. Land Science Developments, 2019(3):48-53.

In summary, global experiences in urban carbon mitigation and resilience demonstrate that, under the mandate of the Paris Agreement, nations are steering sustainable urban planning through shared standards such as Energy Star and LEED (Leadership in Energy and Environmental Design). Within the global framework of low-carbon and resilient urban development, standardized measures—including energy transition, green mobility, building energy efficiency, and Carbon Capture, Utilization, and Storage (CCUS)—have been widely deployed as collective contributions toward global carbon mitigation and resilience goals.

### 2.3.2 Case Analysis of Domestic and International Resilient City Planning

**(1) Pluvial Flood Resilience-Oriented Ecological Urban Design: A Case Study of the Sino-French Wuhan Ecological Demonstration City**

This case focuses on ecological resilience, exploring the nexus and operational convergence between pluvial flood resilience and "Eco-City" concepts. It adopts a multi-scalar approach to resolve ecological degradation and stormwater management challenges[35].

At the macro level, the focus is on identifying the ecological baseline and spatial development directives. By auditing the environmental landscape, the plan identifies the "Life Community" of essential elements, including mountains, water, forests, farmland, lakes, and grasslands. Urban space shaping targets the physical environment, where the operational agents of pluvial resilience synergize with eco-city spatial elements. This convergence facilitates multi-scalar solutions for ecological restoration and flood control [36]. This level prioritizes systemic interconnectivity. Based on ecological suitability assessments and biodiversity conservation mandates, the Sino-French Eco-City established an integrated framework of "Biodiversity Cores + Buffer Zones + Ecological Corridors." The demand for ecological corridors as adaptive composite spaces is manifested through three synergies: "Blue-Green Integration," "Socially-activated Greenery," and "Hydrological Seasonality Synergy."

At the meso level, analysis centers on regional hydro-ecological systems to identify overlapping functional spaces, thereby shaping the urban fabric and multi-purpose environments. "Blue-Green Integration" synergizes sponge-city retention with ecological functions, establishing a four-tier longitudinal system of blue-green corridors based on existing drainage networks. "Socially-activated Greenery" (Living Green) integrates public programming with ecological services. Multi-tier corridors serve as waterfronts that incorporate cultural venues, sports facilities, and recreational spaces. Tier-1 and Tier-2 corridors house sports and leisure hubs; Tier-3 corridors integrate pocket plazas and educational spaces; and Tier-4 corridors feature community gardens. Furthermore, Neighborhood Centers are strategically clustered along these corridors to provide diverse, accessible urban spaces. "Hydrological Seasonality Synergy" (Full-Dry) focuses on the temporal integration of drainage and public activity. Based on fluctuating water levels (flood, normal, and dry stages), the design establishes graded inundation sequences. Public activities are programmed according to the varying widths of the greenbelts adjacent to these inundation zones, maximizing the utility of the ecological corridors[37]. The creation of adaptive composite spaces represents a contemporary reinterpretation of traditional urban space, achieving a balance between ecological services, stormwater management, and social programming across both space and time.

The micro level addresses architectural and site design for residential and non-residential developments within the block. A performance-based indicator system (comprising 5 categories and 24 sub-items) was established to govern the "Control-Guide-Implement-Evaluate" lifecycle. To enhance block-level pluvial resilience, the plan mandates a total annual runoff control rate of ≥85%. Indicators for "Green Space Ratio in Built-up Areas" and "Green Building Standards" impose indirect runoff constraints on the roofscape and ground-level sites, fundamentally influencing architectural facade design and landscape architecture.

**(2) Resilience Governance — Beijing Special Spatial Plan for Resilient Cities (2022–2035)**

This plan represents a synergistic implementation of the vision, spatial resilience construction, and precision governance of a resilient city. It aims to establish a capital-city spatial governance system characterized by reliability, functional flexibility, rapid recovery, systemic integration, and future-readiness. Long-term Governance Objectives: **Operational Optimization and Adaptive Resilience:** Through the effective execution of planning measures, the city leverages autonomous recovery and adaptive response to manage low-to-medium impact disaster risks efficiently. **Robust Defense and Rapid Recovery:** By strengthening fortification standards and redundancy protocols across diverse districts, the plan enhances the resilience of core zones and fortifies infrastructure in vulnerable areas. This ensures timely and effective disaster prevention, mitigation, and response under high-impact risks, maintaining essential urban functions and facilitating rapid recovery. **Baseline Assurance and Functional Continuity:** By reinforcing the overall spatial layout and ensuring the structural underpinning of all resilience measures, the plan safeguards core capital functions and critical social operations during catastrophic events, prioritizing public safety and life preservation while achieving a systematic, full recovery. Integrated Resource and Governance Implementation: Utilizing a zoning and delineation strategy—including the urban core and Blue-Green Infrastructure (BGI) lifelines—targeted policies are applied to distinct functional sectors. Resilience indicators are cascaded and operationalized through a multi-scalar hierarchy: "Regional Catchments — Urban Clusters — Subdistrict/Township Units — Community Living Circles." Dual-Functionality for Routine and Emergency Operations: This includes strengthening strategic reserves for extreme scenarios, promoting the decentralized development of lifeline systems, perfecting mutual-aid networks, and expanding the functional scope of dual-use facilities. The plan prioritizes the provision of public infrastructure, the emergency conversion of strategic land reserves and multi-functional plots, and the enhancement of operational readiness through stress-testing via simulated contingency scenarios[38].

**Table 2-2: Implementation of the Beijing Special Spatial Plan for Urban Resilience**
**Source: Prepared by author**

| Objective | Chapter | Elements/Models |
|---|---|---|
| Defining Long-Term Resilience Development Objectives | Chapter 1 Establishing Resilience Objectives and Guiding Principles | Demographics, Economic Indicators |
| | Chapter 2 Establishing Spatial Patterns for Urban Persistence and Recovery | Development Scale, Spatial Layout, Lifeline Reliability Systems |
| Systemic Resource Integration and Spatial Zoning | Chapter 3 Ensuring Zonal Coordination and Lifeline Infrastructure Performance | Urban Core Area<br>BGI (Blue-Green Infrastructure) Lifelines |
| | Chapter 4 Operationalizing Resilience-based Cluster Partitioning | Regional Catchments, Urban Clusters, Subdistrict/Township Units, Community & Village Living Circles |
| Precision Governance | Chapter 5 Integrating Dual-Use for Routine & Emergency Operations and Strategic Reserves | Simulated Contingency Scenarios, Community Resilience Networks |

# 3. Guiding Concepts and Framework

## 3.1 Major Tasks

In alignment with the project brief, this study identifies two primary objectives: downscaling low-carbon and resilient urban strategies to the micro-level, and contextualizing these strategies within the unique urban fabric of Xi'an. Focusing on four functional unit typologies—Industrial, Residential, Regeneration, and Ecological units—the study aims to establish a framework of key regulatory indicators and differentiated indicators. Furthermore, it identifies tailored mitigation and resilience pathways for each typology to formulate Unit-Level Technical Guidelines for carbon mitigation and resilience.

## 3.2 Operational Framework

The research adopts a four-stage workflow: Mechanism Transmission → Baseline & Characteristic Analysis → Indicator System Construction → Pathway Formulation.

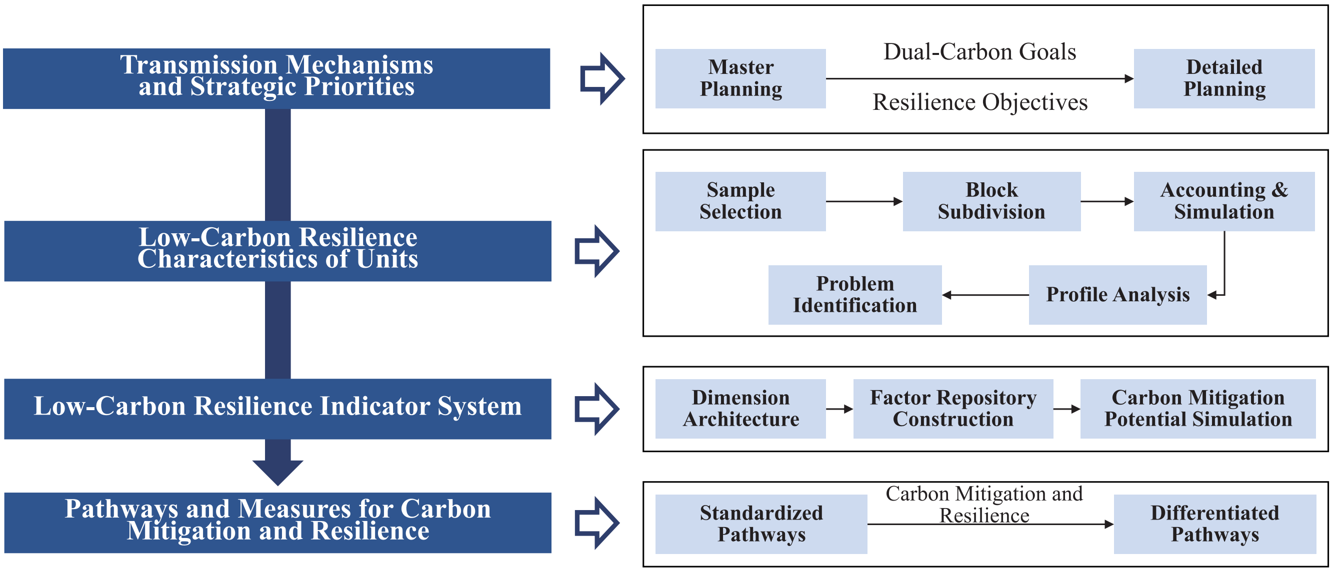



Figure 3-1: Operational Framework
Source: Prepared by author

# 4. Transmission Mechanisms and Strategic Priorities for Low-Carbon Resilience in Territorial Spatial Planning

## 4.1 Integration and Transmission of "Dual-Carbon" Goals within the TSP Framework

At the Master Plan level, the focus is on the spatial allocation of carbon intensity and total emission targets, disaggregating them from the regional scale down to specific functional zones. At the Detailed Planning level, the emphasis shifts toward achieving differentiated carbon intensity targets for specific land parcels through high-precision quantitative metrics.

As the primary spatial substrate for both carbon emissions and sequestration[39], territorial spatial planning plays a pivotal role in achieving "Dual-Carbon" objectives. Regarding master planning, it is essential to harmonize regional mitigation targets[40] with urban low-carbon development goals, establishing a dual-target management framework for both total emissions and carbon intensity at the regional scale. Furthermore, these macro-level controls must be refined into functional zones. Given that distinct zones encompass specific land-use activities, the downscaling of "dual-carbon" goals must account for the unique emission profiles and decarbonization potentials of each zone. For detailed planning, the priority is to translate strategic spatial policies into localized controls. Subsequently, mandatory low-carbon benchmarks—such as operational carbon intensity for buildings—should be integrated into the regulatory framework based on unit-specific characteristics and localized technical standards[41]. Detailed planning guided by carbon goals should address qualitative criteria, quantitative metrics, and morphological parameters[42]. This involves optimizing universal planning parameters—such as land-use mix, green space ratios[43], and parking provisions[44]—while introducing typology-specific metrics, such as total carbon caps and energy intensity per unit area, to drive systemic decarbonization.

## 4.2 Transmission Mechanisms and Strategic Priorities for Resilience in Territorial Spatial Planning

The Ministry of Natural Resources promulgated the *Guidelines for Resilient Urban Planning and Land Policies Integrating Routine and Emergency Functions*[45], establishing a regulatory framework for cities characterized by functional hybridity. These guidelines define a comprehensive indicator system across four dimensions: functional typology, spatial configuration, development scale, and conversion standards. It explicitly outlines requirements for the functional transition and multi-purpose utility of dual-use public infrastructure, such as the augmentation of localized emergency response capacities. By integrating hybrid requirements into the TSP hierarchy, the guidelines position spatial coordination as the core objective of the Master Plan, while Regulatory (Detailed) Planning prioritizes land-use controls and functional guidance. At the precinct (unit) level, two priorities are emphasized: 1. The disaggregation and implementation of Master Plan indicators and spatial layouts; 2. The precise specification of dual-use spatial siting, development scale, conversion protocols, and supporting amenities. Consequently, block-level resilience planning focuses on constructing an indicator system that integrates spatial configuration with contingency-ready infrastructure.

## 4.3 Integration of Low-Carbon Resilience Objectives within the Xi'an TSP Framework

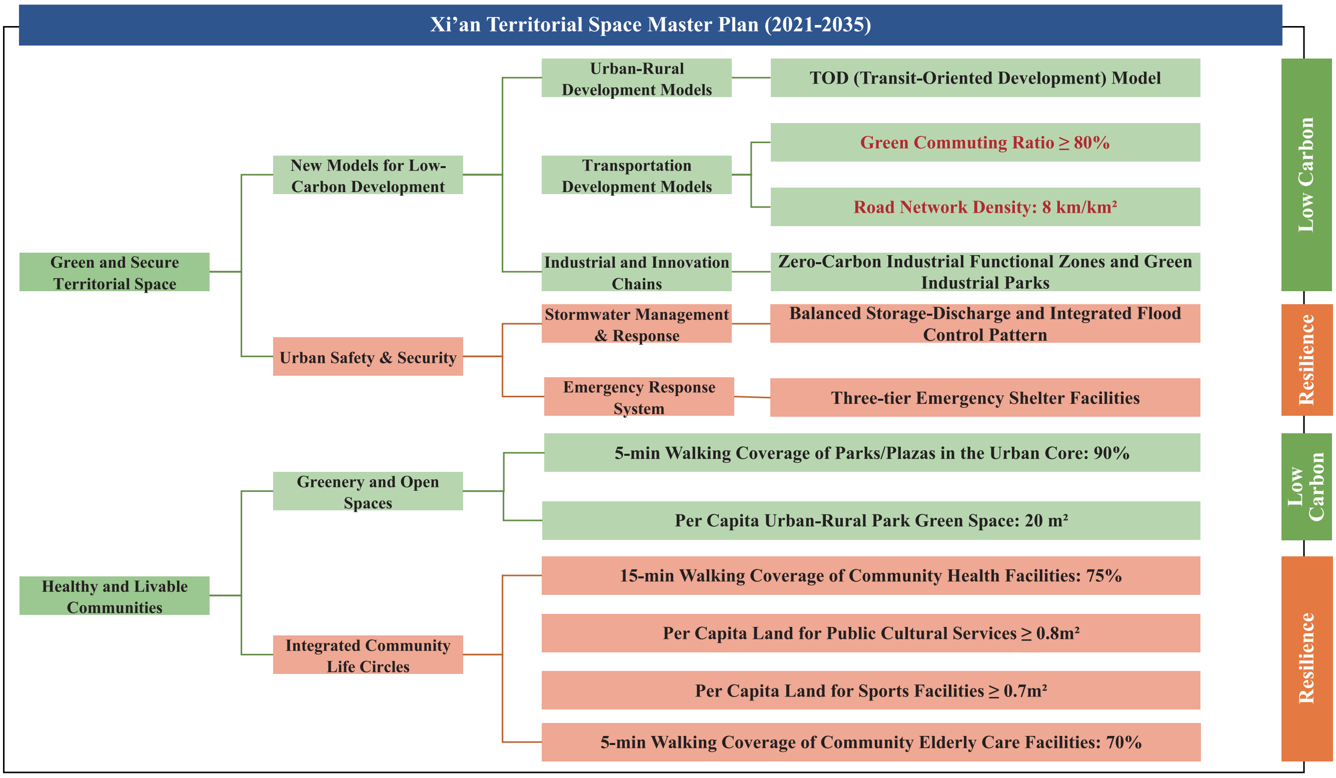



Figure 4-1: Framework of Low-Carbon and Resilience Components in the Xi'an Territorial Spatial Master Plan
Source: Prepared by author

The *Xi'an Territorial Space Master Plan (2021–2035)* establishes a strategic framework where numerous components directly or indirectly intersect with low-carbon and resilience mandates (Figure 4-1). Within the "Green & Secure Territory" and "Healthy & Livable Communities" directives, four key low-carbon metrics are established: green commuting ratio, road network density, the 5-minute walking catchment for central urban parks/plazas, and per-capita green space provision. Furthermore, the "Community Life Circle" directive specifies four resilience indicators: 15-minute walking accessibility for healthcare, per-capita land for cultural services, per-capita sports facility area, and the 5-minute walking catchment for aged-care infrastructure. This study cascades these metrics and their target values into precinct-level regulatory planning.

In summary, low-carbon resilience at the regulatory planning level is defined by the overarching goals of Dual-Target Carbon Management and Routine-Emergency Functional Hybridity. These ensure ecological integrity, livability, and operational efficiency while facilitating sustainable growth for diverse functional units. The dimensions of low-carbon resilience are categorized into five domains: Overall Scale, Morphological Parameters, Infrastructure & Environment, Neighborhood Functions, and Development Performance. In alignment with the *Work Plan for Accelerating the Establishment of a Dual-Control System for Carbon Emissions*, specific carbon control metrics are assigned to distinct unit typologies: Industrial Units: The intensity control metric is Areal Carbon Intensity (emissions per unit area). Residential/Regeneration Units: The intensity control metric is Per-Capita Carbon Intensity. Ecological Units: The intensity control metric is Carbon Sink Intensity per Unit Area. Furthermore, office sub-units and regeneration units are identified as Priority Carbon-Control Precincts. The core resilience focus for each typology is defined as: Economic Resilience (Industrial), Spatial Resilience (Residential), Cultural Resilience (Regeneration), and Eco-Systemic/Disaster Resilience (Ecological).

# 5. Baseline Analysis of Low-Carbon Resilience Characteristics across Diversified Urban Units in Xi'an

## 5.1 Study Areas and Sample Selection

The study evaluates ten representative sample sites categorized into four functional unit typologies: (Industrial Units - 3 sites): BB-TB-03: A manufacturing unit within the Jingwei Industrial Park (Jingkai Zone). ZC-GX-03 & ZC-GX-09: Innovation-oriented units for software and information industry (High-Tech Zone). (Residential Units - 3 sites): BB-GL-26: Majiawan urban regeneration residential unit. BB-GL-02: Gaoling Old Town residential unit. CZ-JK-01: Short-term residential development unit in the Jingkai Zone. Regeneration Units - 2 sites): BL-03: Historic District Adaptive Reuse (Sanxue Street). BQ-05: Industrial Heritage Conversion (former Textile City factory redevelopment). Ecological Units - 2 sites): BB-GL-JY01: Riparian Ecological Unit (Jing-Wei Confluence). DMG-DYZ-01: Heritage Preservation Unit (Daming Palace National Heritage Park).

## 5.2 Baseline Characteristic Analysis

### 5.2.1 Industrial Units

The analytical scope encompasses three major industrial clusters in Xi'an: the Jingwei Industrial Park, the High-Tech Software Park, and the Information Industry Park. The study utilized a sample set comprising 31 industrial plots and 40 office-based plots. Based on field surveys and geospatial data extraction, the areal carbon intensity and theoretical mitigation potential for these clusters are summarized in Table 5-1.

Table 5-1: Carbon Intensity and Mitigation Potential of Surveyed Industrial Clusters
Source: Prepared by author

| Unit Name | Total (t/a) | Carbon Intensity | Building Operational Electricity Intensity | Building Operational Natural Gas Intensity | Mitigation Potential (t/a) |
|---|---|---|---|---|---|
| Jingwei Industrial Park | 233,773.43 | 35,808.13 | 34,441.78 | 1,841.69 | 227,611.85 |
| High-tech Software Park | 184,904.32 | 12,424.61 | 11,007.60 | 1,300.15 | 106,166.01 |
| Information Industry Park | 283,243.34 | 14,049.28 | 11,919.69 | 2,043.33 | 104,813.05 |

**(1) Total Emission Profiles**

In 2023, the annual carbon emissions of the three selected industrial parks totaled 701,921.09 t/a. The emissions profile exhibits a clear hierarchy: Information Industry Park > Jingwei Industrial Park > High-tech Software Park. Specifically, the Information Industry Park recorded the highest volume at 283,243 t/a, followed by the Jingwei Industrial Park at 233,773 t/a, while the High-tech Software Park recorded the lowest at 184,904 t/a.

Sectoral Composition: Regarding industrial typology, the Jingwei Industrial Park is dominated by industrial & warehousing emissions, accounting for 78% of its total. Conversely, the Information Industry Park and High-tech Software Park are primarily office-led, with administrative activities contributing 43% and 39% respectively. In terms of energy sources, Building Operational Electricity is the primary driver across all three parks, representing 94% of total emissions in Jingwei, and 84% in both the High-tech Software Park and the Information Industry Park.

Manufacturing-Industrial Units: These units generate an aggregate of 233,773.43 t/a with a mitigation potential of 227,611.85 t/a. Industrial & warehousing land represents the largest share at 78%, followed by office and commercial land (7% each), residential (2%), and civic/institutional land (1%).

Office Sub-units: These units generate 468,147.66 t/a with a mitigation potential of 210,979.06 t/a. Commercial and office land accounts for over 60% of total emissions, followed by industrial & warehousing land (8%–16%), residential land (6%), and civic & community land (1%).

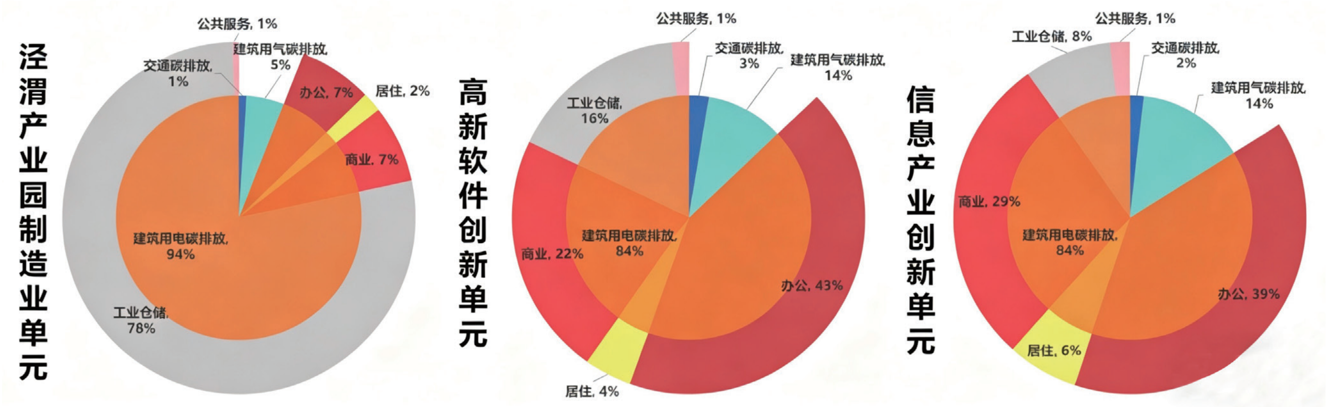



Figure 5-1: 2023 Sectoral Carbon Emission Composition of the Three Industrial Clusters
Source: Prepared by author

**(2) Emission Intensity Profiles**

Analysis of the three clusters reveals that the Jingwei Industrial Park records the highest carbon intensity at 35,808.1, indicative of relatively low carbon-use efficiency. Regarding Building Operational Electricity intensity, the Jingwei Industrial Park again demonstrates the maximum value at 34,441.8. Conversely, the High-tech Software Park recorded the lowest Building Operational Natural Gas intensity at 1,300.15, reflecting superior thermal energy efficiency.

In terms of mitigation potential, the Jingwei Industrial Park offers the most significant reduction capacity at 227,612 t/a. The High-tech Software Park (106,166 t/a) and Information Industry Park (104,813 t/a) show comparable potentials, both presenting strategic opportunities for efficiency gains.

The analysis suggests that the Jingwei Industrial Park is characterized by the highest emission intensity—dominated by industrial & warehousing emissions—and maintains the greatest theoretical mitigation capacity. The two innovation parks exhibit similar sectoral emission structures, though the High-tech Software Park demonstrates superior overall carbon performance. Manufacturing-Industrial Units and Office Sub-units exhibit distinct spatial typologies: Manufacturing-Industrial Units are composed of 78% industrial & warehousing land with a high concentration of carbon-intensive industrial assets. In contrast, Office Sub-units prioritize a jobs-housing balance and are characterized by asset-light, low-carbon service sectors. Building-related operational emissions remain the primary decarbonization priority across both typologies.

**(3) Mitigation Potential Profiles**

Across the three industrial clusters, the absolute mitigation potential is ranked as follows: Information Industry Park (283,243.34 $tCO_2/a$) > Jingwei Industrial Park (233,773.43 $tCO_2/a$) > High-tech Software Park (184,904.32 $tCO_2/a$). Consequently, the Information Industry Park presents the most substantial aggregate opportunity for carbon reduction among the three studied industrial clusters.

### 5.2.2 Residential Units

Adhering to the principles of typicality and representativeness, this study selects three residential typologies—the Majiawan Urban Regeneration unit, the Gaoling Old Town District unit, and the Short-term Jingkai Development unit—as sample sites for baseline low-carbon and resilience profiling.

**(1) Total Emission Profiles**

Using Xi'an's municipal electricity database, resident sustainable modal split data, and Xi'an-specific vegetation sequestration coefficients, the operational emissions, carbon sequestration, and mitigation potentials were quantified across the study sites, with results detailed below:

Table 5-2: Baseline Emissions, Sequestration, and Mitigation Potential for Residential Units
Source: Prepared by author

| | Majiawan Urban Regeneration Unit | Gaoling Old Town District Unit | Short-term Jingkai Development unit |
|---|---|---|---|
| Building Operational Electricity: Residential ($tCO_2$/a) | 16,030.59 | 7,043.83 | 38,639.43 |
| Building Operational Electricity: Commercial ($tCO_2$/a) | 11,991.31 | 10,895.39 | 61,648.39 |
| Building Operational Electricity: Industrial & Warehousing ($tCO_2$/a) | 6,598.94 | 9,551.79 | 1,959.84 |
| Building Operational Electricity: Office ($tCO_2$/a) | 2,901.74 | 3,880.43 | 47,687.88 |
| Building Operational Electricity: Civic & Community ($tCO_2$/a) | 1,827.43 | 1,482.30 | 4,006.25 |
| Building Operational Electricity ($tCO_2$/a) | 39,350.01 | 32,853.75 | 153,941.79 |
| Building Operational Natural Gas ($tCO_2$/a) | 24,231.02 | 15,990.76 | 62,561.57 |
| Transportation Carbon Emissions ($tCO_2$/a) | 1,559.62 | 2,363.40 | 4,154.84 |
| Total Carbon Emissions ($tCO_2$/a) | 65,140.65 | 51,207.91 | 220,658.20 |
| Total Carbon Sequestration ($tCO_2$/a) | 1,379.22 | 3,382.33 | 2,212.31 |
| Mitigation Potential ($tCO_2$/a) | 41,674.93 | 34,525.94 | 86,090.01 |

Among the three residential typologies, the Short-term Jingkai Development unit recorded both the highest total emissions and the most significant mitigation potential. Attributed to its high development intensity (FAR and construction density), the Jingkai unit's total emissions reached 220,658.20 $tCO_2$/a—more than four times that of the Gaoling Old Town District unit. The Gaoling Old Town unit exhibited the maximum carbon sequestration capacity at 3,382.33 $tCO_2$/a, approximately 2.5 times that of the Majiawan Urban Regeneration unit.

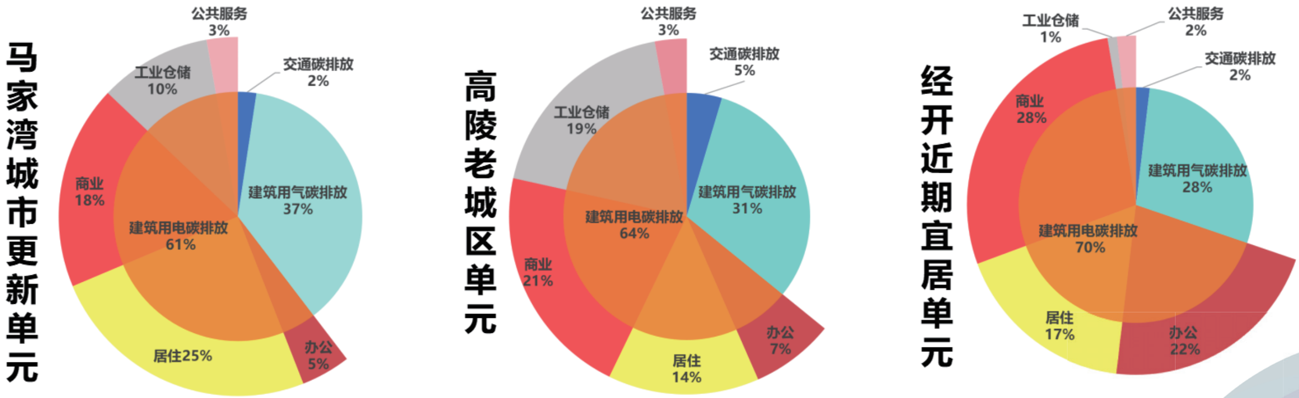



Figure 5-2: Baseline Carbon Emission Profiles for Residential Units
Source: Prepared by author

Regarding Building Operational Electricity, residential consumption represents the largest share in the Majiawan Urban Regeneration unit, accounting for 25% of its aggregate footprint. Conversely, commercial electricity demand was the primary driver for both the Gaoling Old Town and Short-term Jingkai Development units, totaling 10,895.39 $CO_2$/a and 61,648.39 $CO_2$/a, respectively. Among the three residential typologies, the Majiawan unit exhibited the highest reliance on Building Operational Natural Gas, with thermal emissions accounting for 37% of its total. This high proportion is likely correlated with the venerable building stock and legacy utility infrastructure, where aging pipeline networks result in significant systemic energy inefficiency. In the Gaoling Old Town unit, transportation carbon emissions accounted for 5% of the total—the highest among the samples. This can be attributed to a pronounced jobs-housing imbalance and insufficient public transport accessibility, necessitating higher reliance on private motorized travel.

In summary, the proportional composition of residential emissions exhibits a high degree of homogeneity, with stationary building operations serving as the predominant emission source across all sites. Specifically, the Majiawan profile is dominated by residential electricity load, whereas the Gaoling and Jingkai units are primarily driven by commercial electricity demand.

**(2) Emission Intensity Profiles**

Per capita emission and carbon sink intensities were derived by correlating aggregate emission inventories with population datasets for each residential unit. The results are detailed below:

Table 5-3: Baseline Per Capita Emission and Carbon Sink Intensities for Residential Units

Source: Prepared by author

| | Majiawan Urban Regeneration Unit | Gaoling Old Town District Unit | Short-term Jingkai Development unit |
|---|---|---|---|
| Building Operational Electricity Intensity ($tCO_2$ / (a · $10^4$ persons)) | 8,480.61 | 6,531.56 | 12,444.77 |
| Building Operational Natural Gas Intensity ($tCO_2$ / (a · $10^4$ persons)) | 5,222.20 | 3,179.08 | 5,057.52 |
| Transportation Carbon Emission Intensity ($tCO_2$ / (a · $10^4$ persons)) | 336.13 | 469.86 | 335.88 |
| Carbon Emission Intensity ($tCO_2$ / (a · $10^4$ persons)) | 14,038.93 | 10,180.50 | 17,838.17 |
| Carbon Sink Intensity ($tCO_2$ / (a · $10^4$ persons)) | 297.25 | 672.43 | 178.84 |

Among the three residential typologies, the Short-term Jingkai Development unit exhibits the maximum per capita emission intensity at 17,838.17 $tCO_2$/(a · $10^4$ persons), followed by the Majiawan Urban Regeneration unit at 14,038.93 $tCO_2$/(a · $10^4$ persons). The Gaoling Old Town unit recorded the highest carbon sink intensity at 672.43 $tCO_2$/(a · 104 persons), whereas the Jingkai unit recorded the lowest at 178.84 $tCO_2$/(a · $10^4$ persons). Sectoral Intensity Analysis: The Jingkai unit maintains the highest intensity for Building Operational Electricity, while the Majiawan unit shows the peak intensity for Building Operational Natural Gas. Notably, the Gaoling Old Town unit exhibits the highest transportation emission intensity.

In summary, mitigation priorities exhibit significant spatial differentiation based on the specific characteristics of each residential typology. For new-build and urban renewal precincts (Jingkai and Majiawan), decarbonization strategies should prioritize building-scale interventions, such as energy-efficiency retrofitting and electrified heating. Conversely, historic old town units (Gaoling) should focus on mobility-based mitigation, targeting improvements in public transit accessibility and the promotion of non-motorized transport.

**(3) Mitigation Potential Profiles**

Across the three residential typologies, the hierarchy of mitigation potential is as follows: the Short-term Jingkai Development unit (86,090.01 $tCO_2$/a) > the Majiawan Urban Regeneration unit (41,674.93 $tCO_2$/a) > the Gaoling Old Town unit (34,525.94 $tCO_2$/a). Consequently, the Short-term Jingkai Development unit offers the most significant aggregate opportunity for carbon reduction among the surveyed residential units.

### 5.2.3 Urban Regeneration Units

This study evaluates two distinct regeneration archetypes—the Sanxue Street Historic District (Beilin District) and the Textile City Industrial Retrofit unit (Baqiao District)—to establish their baseline low-carbon and resilience profiles.

**(1) Total Emission Profiles**

The Sanxue Street Historic District serves as a concentrated repository of Xi'an's stratified historical heritage, functioning as a cultural-tourism hub dominated by leisure and hospitality infrastructure. The emissions inventory estimates total operational footprint at 187,857.74 $tCO_2$/a, primarily driven by Building Operational Electricity, with commercial facilities identified as the primary point source of carbon. The Textile City Industrial Retrofit unit (Baqiao District) integrates residential high-rises, educational facilities, museums, and creative clusters, serving as a landmark for the adaptive reuse of textile industrial heritage and the integration of cultural industries. Total operational emissions are calculated at 87,268.15 $tCO_2$/a, with building electricity consumption again serving as the dominant contributor. Reflecting its current regeneration phase, both industrial & warehousing and commercial buildings account for substantial shares of the electricity-related carbon footprint. In summary, the sectoral composition of carbon emissions exhibits high proportional homogeneity across both regeneration units.

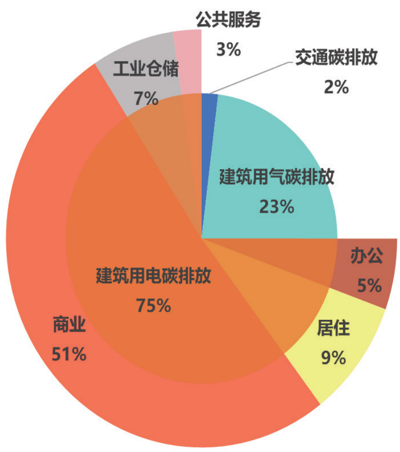



Figure 5-3: Emissions Composition Breakdown for Sanxue Street Historic District (Beilin District)
Source: Prepared by author

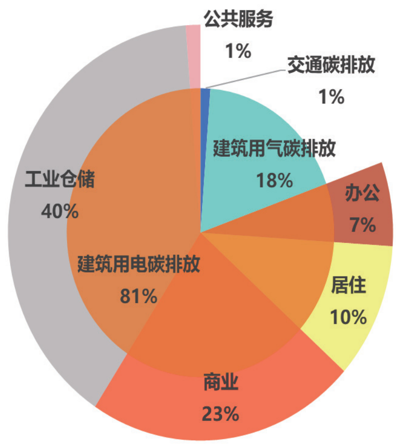



Figure 5-4: Emissions Composition Breakdown for Textile City Industrial Retrofit Unit (Baqiao District)
Source: Prepared by author

Regarding Resilience Characteristics, the Sanxue Street unit relies heavily on its tourism and leisure infrastructure; under recent development initiatives, the cultural-tourism sector has achieved high density and functional diversification. The Textile City unit has undergone a comprehensive strategic upgrade—including the Railway Theme Park and the adaptive reuse of former factory zones—introducing a diversified economic mix to enhance local systemic resilience. Within the Sanxue Street unit, the 500m service radius accessibility covers 90% of the area for bus services and 65% for metro transit. However, due to the high population density within this historic core, per capita green space provision remains comparatively constrained. The Textile City unit demonstrates a similar 90% bus accessibility within a 500m radius, while metro accessibility is recorded at 45%. Following its conservation-led redevelopment and the integration of new public realms, this unit exhibits a significantly higher per capita green space ratio.

**(2) Emission Intensity Profiles**

The Sanxue Street Historic District exhibits an aggregate emission intensity of 10,679.80 $tCO_2/(a \cdot 10^4$ persons). The intensity profile is primarily driven by Building Operational Electricity within commercial assets, with Building Operational Natural Gas serving as the secondary contributor. The Textile City Industrial Retrofit unit records a significantly higher intensity of 18,971.34 $tCO_2/(a \cdot 10^4$ persons). Intensity peaks are concentrated within industrial & warehousing and commercial sectors, designating these land-use typologies as priority zones for targeted decarbonization interventions.

Table 5-4: Operational Emission Inventory for the Sanxue Street Historic District (Beilin District)
Source: Prepared by author

| | | Total Emissions ($tCO_2/a$) | Carbon Emission Intensity ($tCO_2$ / (a · $10^4$ persons)) |
|---|---|---|---|
| Building Operational Electricity | Total | 187,857.74 | 10,679.80 |
| | Office | 13,752.18 | 781.82 |
| | Residential | 22,796.98 | 1,296.02 |
| | Commercial | 128,255.47 | 7,291.39 |
| | Industrial & Warehousing | 17,166.49 | 975.92 |
| | Civic & Community | 5,886.62 | 334.66 |
| Building Operational Natural Gas | | 57,771.25 | 3,284.32 |
| Transportation Carbon Emissions | | 4,909.90 | 500.50 |
| Carbon Sequestration | | 4,182.56 | 237.78 |
| Total Emissions | | 246,356.33 | 14,005.48 |
| Mitigation Potential | | 143,833.55 | 8,177.01 |

Table 5-5: Operational Emission Inventory for the Textile City Industrial Retrofit Unit (Baqiao District)
Source: Prepared by author

| | | Total Emissions ($tCO_2/a$) | Carbon Emission Intensity ($tCO_2$ / (a · $10^4$ persons)) |
|---|---|---|---|
| Building Operational Electricity | Total | 87,268.15 | 18,971.34 |
| | Office | 7,091.88 | 1,541.71 |
| | Residential | 11,446.10 | 2,488.28 |
| | Commercial | 24,528.49 | 5,332.28 |
| | Industrial & Warehousing | 42,864.49 | 9,318.37 |
| | Civic & Community | 1,337.19 | 290.69 |
| Building Operational Natural Gas | | 19,855.57 | 4,316.43 |
| Transportation Carbon Emissions | | 1,286.43 | 434.60 |
| Carbon Sequestration | | 4,182.56 | 909.25 |
| Total Emissions | | 104,227.59 | 22,658.17 |
| Mitigation Potential | | 43,783.71 | 9,518.20 |

Analysis reveals that while the Sanxue Street Historic District benefits from high street-level vitality and commercial permeability, the proportion of heritage-integrated commercial functions remains insufficient. Consequently, the district's cultural identity requires thematic enhancement to offset its disproportionately high commercial emission totals and intensities. From an infrastructure provisioning perspective, existing metro accessibility fails to accommodate peak pedestrian demand, and the quality of the green infrastructure and public realm requires strategic optimization. The core mandate for carbon mitigation and resilience is to realize a sustainable historic district that achieves a synergistic balance between heritage conservation and commercial viability. The Textile City Industrial Retrofit unit is characterized by high operational totals and intensities within its industrial & warehousing and commercial assets. This is exacerbated by a need for optimized road networks and parking facilities. High structural vacancy rates and abandoned industrial fabric indicate a significant underutilization of urban land, complicated by the absence of a codified low-carbon transition pathway. The primary carbon mitigation and resilience objective is to establish a low-carbon creative industry cluster.

**(3) Mitigation Potential Profiles**

Within the regeneration units, the mitigation potential of the Sanxue Street Historic District (143,833.55 $tCO_2/a$) exceeds that of the Textile City Industrial Retrofit unit (43,783.71 $tCO_2/a$). Consequently, the Sanxue Street unit represents the primary opportunity for aggregate emission reduction among the studied regeneration sites.

### 5.2.4 Ecological Units

This study evaluates the Jing-Wei Confluence and the Daming Palace Heritage Site as representative ecological units to establish baseline sequestration and resilience profiles.

**(1) Total Emission Profiles**

Using a multi-criteria classification method to quantify carbon sequestration, the results are as follows: The Jing-Wei Confluence unit achieves an annual sequestration of 17,303.30 t/a, while the Daming Palace Heritage Site records 18,397.16 t/a. Notably, 98.55% of the sequestration in the Jing-Wei Confluence derives from multi-layered arbor-shrub-grass communities. Conversely, 55% of the Daming Palace site's sequestration capacity is attributed to manicured turf and naturalistic grasslands. In summary, riparian ecological units primarily rely on multi-layered woody vegetation for sequestration, whereas heritage-led open spaces are characterized by expansive grasslands as their primary carbon sink.

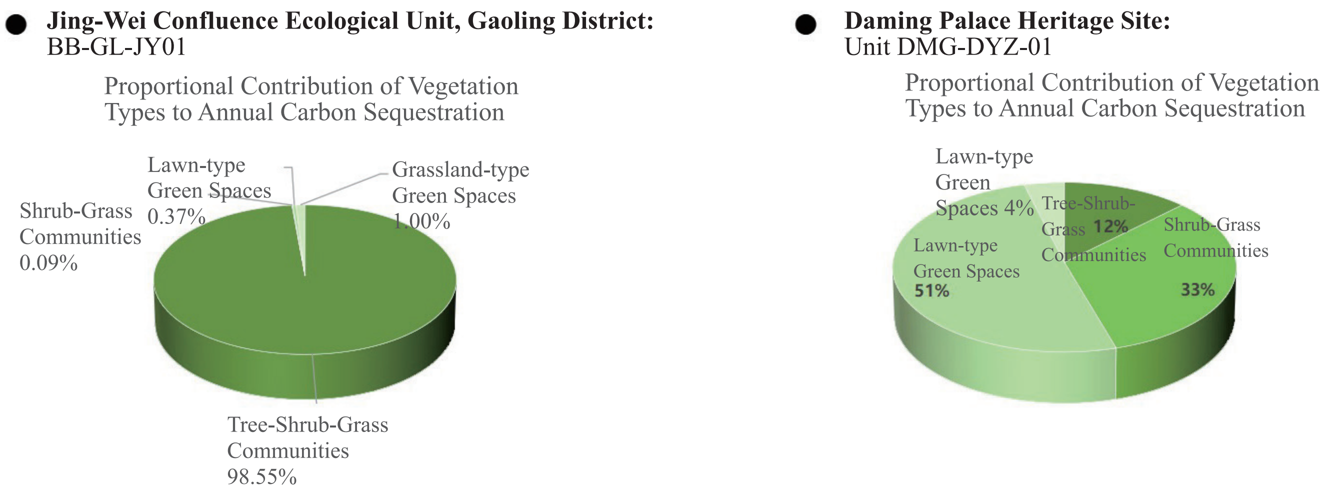



**Figure 5-5: Composition of Carbon Sequestration Sources across Ecological Units**
**Source: Prepared by author.**

**(2) Carbon Sink Intensity Profiles**

By correlating aggregate sequestration volumes with the areal extent of each ecological unit, the carbon sink intensity was quantified. The findings indicate that: While the Jing-Wei River Confluence possesses only one-third of the functional sequestration area compared to the Daming Palace Heritage Site, its carbon sink intensity (10,238.63 $tCO_2$ / ($a \cdot km^2$)) is 2.5 times higher.

Table 5-6: Baseline Carbon Sink Intensity Profiles for Ecological Units
Source: Prepared by author

| | Jing-Wei Confluence | Daming Palace Heritage Site |
|---|---|---|
| Functional Sequestration Area ($km^2$) | 1.69 | 4.39 |
| Carbon Sink Intensity $tCO_2$/($a \cdot km^2$) | 10,238.63 | 4,190.70 |

### 5.2.5 Comparative Summary of Functional Unit Profiles

Table 5-7: Summary of Total Carbon Emissions and Intensity Profiles by Unit Typology
Source: Prepared by author

| Unit Type | Mean Total per Sample | Total (t/a) | Mitigation Potential (t/a) | Carbon Intensity (t/a · $10^4$ persons) | Building Operational Electricity Intensity (t/a · $10^4$ persons) | Building Operational Natural Gas Intensity (t/a · $10^4$ persons) | Per Capita Transportation Carbon Emissions (t/a · $10^4$ persons) |
|---|---|---|---|---|---|---|---|
| Industrial Units | Total | 233,973.69 | 146,196.97 | 20,760.67 | 19,123.02 | 1,728.39 | 746.22 |
| | Jingwei Industrial Park | 233,773.43 | 227,611.85 | 35,808.13 | 34,441.78 | 1,841.69 | 801.98 |
| | High-tech Software Park | 184,904.32 | 106,166.01 | 12,424.61 | 11,007.60 | 1,300.15 | 695.24 |
| | Information Industry Park | 283,243.34 | 104,813.05 | 14,049.28 | 11,919.69 | 2,043.33 | 720.3 |
| Residential Units | Total | 110,010.96 | 54,096.96 | 13,636.36 | 9,152.31 | 4,486.26 | 456.13 |
| | Majiawan | 63,761.43 | 41,674.93 | 13,741.69 | 8,480.61 | 5,222.20 | 430.11 |
| | Gaoling Old Town | 47,825.58 | 34,525.94 | 9,508.07 | 6,531.56 | 3,179.08 | 467.34 |
| | Short-term Jingkai Development unit | 218,445.89 | 86,090.01 | 17,659.33 | 12,444.77 | 5,057.52 | 416.45 |
| Regeneration Units | Total | 175,291.95 | 93,808.63 | 18,331.82 | 14,825.56 | 3,800.37 | 467.81 |
| | Sanxue Street | 246,356.33 | 143,833.55 | 14,005.48 | 10,679.80 | 3,284.32 | 480.98 |
| | Textile City | 104,227.58 | 43,783.71 | 22,658.17 | 18,971.33 | 4,316.42 | 438.77 |

Comparative analysis confirms that among the three functional archetypes, Industrial Units exhibit the highest total emissions and peak intensities, with the Jing-Wei Industrial Park serving as the primary carbon-intensive benchmark. Regeneration Units follow in ranking, led by the Textile City precinct. Conversely, Residential Units and Office Sub-units demonstrate significantly lower emission profiles with a high degree of intra-typological homogeneity.

In terms of carbon emission composition, Industrial Units are dominated by industrial & warehousing land uses, which account for 78% of total emissions; while residential and commercial contributions remain marginal. The two office-based innovation parks share similar structures, primarily driven by Building Operational Electricity in office (40%) and commercial (30%) sectors. Among Residential Units, the Short-term Jingkai Development unit exhibits the highest intensity, driven largely by commercial electricity demand. In Regeneration Units, emissions are concentrated in the electricity consumption of industrial & warehousing assets within the Textile City Industrial Retrofit site.

Analysis identifies Industrial Units as possessing the optimum mitigation potential, followed by Regeneration and Residential Units. Potential mitigation offset ratios reach 62.48% for Industrial Units, 53.51% for Regeneration Units, and 49.17% for Residential Units, indicating substantial decarbonization capacity across all categories.

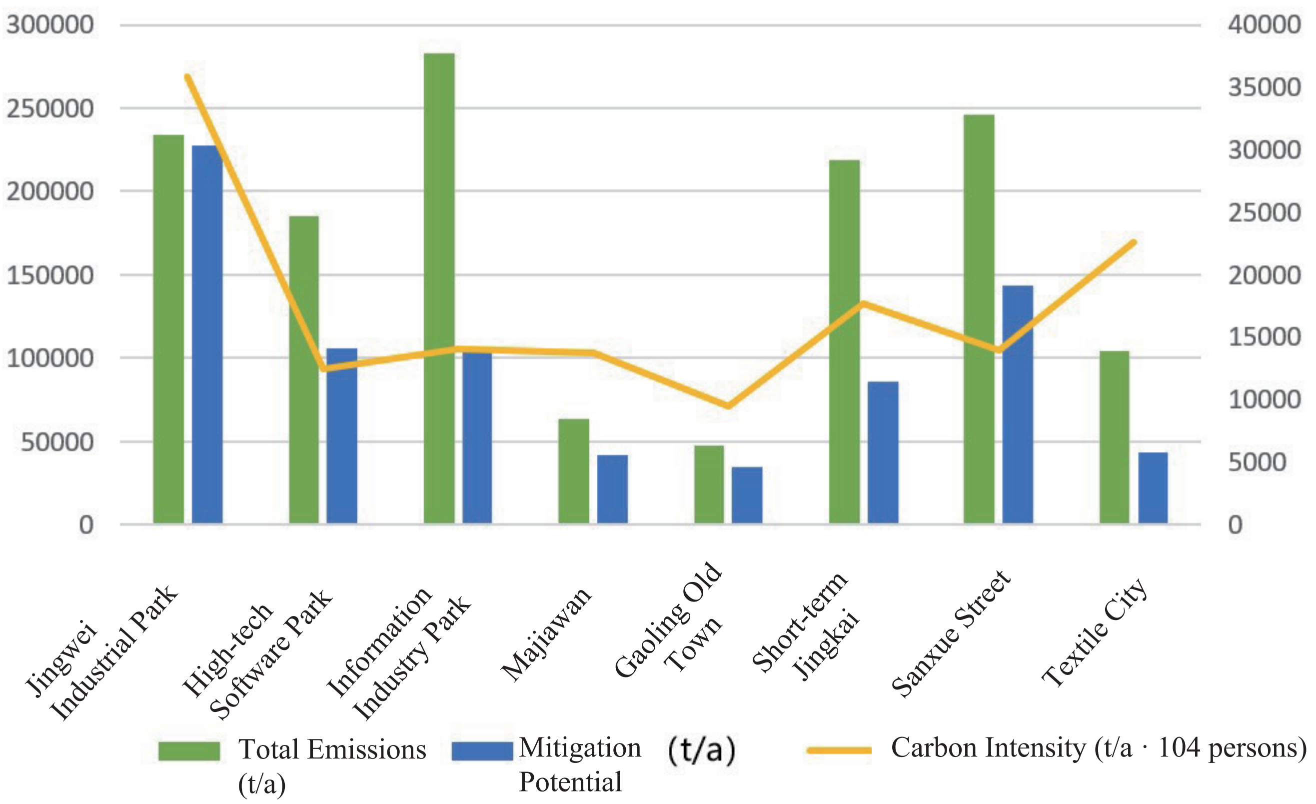



Figure 5-6: Summary of Total Carbon Emissions, Intensity, and Mitigation Potential by Unit Typology
Source: Prepared by author

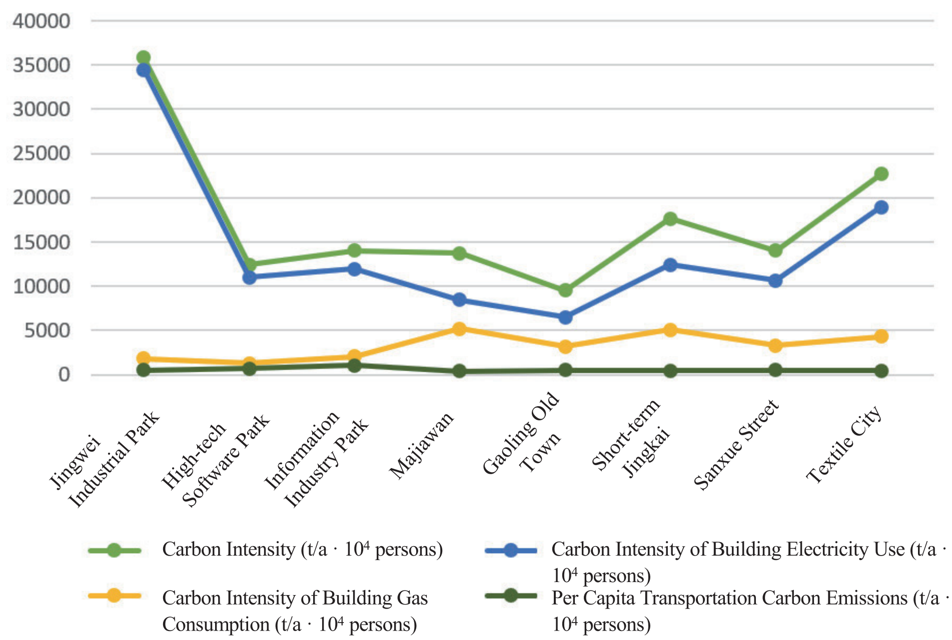



Figure 5-7: Summary of Emission Intensities and Sectoral Compositions by Unit Typology
Source: Prepared by author

Based on these findings, Industrial and Regeneration Units must be prioritized within subsequent regulatory frameworks due to their high emission baseline and significant mitigation upside. The Jing-Wei Industrial Park, dominated by carbon-intensive manufacturing, offers the greatest scope for energy-structure optimization. The prevalence of low-rise factory structures with expansive flat or pitched roofs provides high technical suitability for distributed solar photovoltaic (PV) arrays [46]. Consequently, management indicators should prioritize Clean Production Audit (CPA) standards and increasing renewable energy penetration. Regeneration Units are characterized by a venerable building stock with poor energy performance and low occupant comfort, leading to high reliance on inefficient appliances. The intensity of these units necessitates urgent building retrofits. Future control metrics should prioritize thermal insulation optimization, upgrading Energy Performance Certificate (EPC) ratings, and enhancing overall habitability[47].

## 5.3 Hypotheses and Analysis of Foundational Drivers for Low-Carbon Resilience

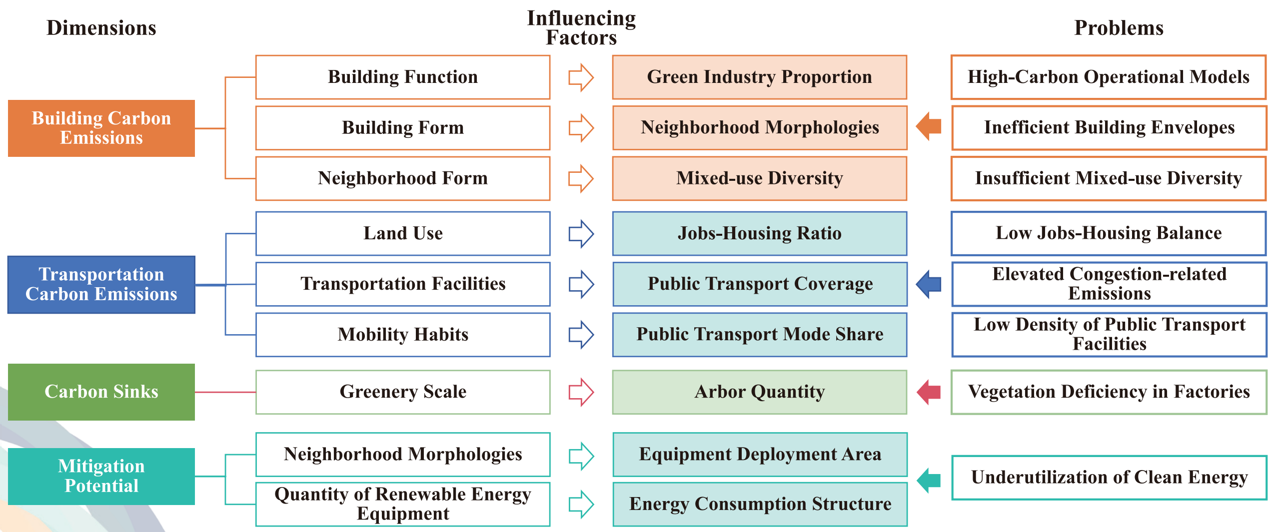



Figure 5-8: Hypothetical Framework of Foundational Drivers for Low-Carbon Resilience
Source: Prepared by author

Regarding building-scale emissions, three systemic inefficiencies require strategic optimization: carbon-intensive operational regimes, thermally inefficient building envelopes, and insufficient mixed-use diversity [48]. In industrial parks, high-carbon production behaviors are the primary drivers of intensive operational regimes. Consequently, this study proposes industrial entry thresholds for green sectors to guide the transition of high-emission enterprises. By adjusting the internal functional composition and fostering a cleaner sectoral structure, units can effectively lower their aggregate building energy intensity [49]. Operational emissions from buildings with inefficient envelopes represent another significant source of carbon within the built environment. Beyond the thermal properties of building materials, envelope performance is also influenced—from an urban planning perspective—by block morphology. Specifically, indicators such as the street aspect ratio (D/H), Floor Area Ratio (FAR), and building height dictate the local urban microclimate, which in turn dictates the thermal energy demand for heating and cooling. Consequently, this study introduces neighborhood morphologies as a core low-carbon control factor to systematically reduce building-related carbon emissions within a precinct. Lower neighborhood mixed-use diversity tends to reduce human activity within the area, thereby increasing the overall building carbon emission intensity. Consequently, enhancing neighborhood mixed-use diversity is a critical indicator for achieving low-carbon development in neighborhood buildings.

Regarding transportation carbon emissions, the primary systemic challenges include a low jobs-housing balance, elevated congestion-related emissions, and low density of public transport facilities. To address these, the study adopts a tripartite framework—land use, infrastructure, and mobility habits—to propose control indicators for the jobs-to-housing ratio, public transport coverage, and public transport modal share. These measures aim to shorten commuting distances, reduce per capita transport emissions, and optimize the overall urban mobility structure through targeted carbon management.

In terms of carbon sinks, the study identifies fragmented green infrastructure and local sequestration voids within the research area. As urban greenery is a vital source of sequestration, increasing the canopy cover ratio—specifically by prioritizing arbor planting density—is a critical measure for optimizing the urban sequestration hierarchy and capacity.

Regarding mitigation potential, a prevalent issue across all functional units in Xi'an is the significant underutilization of renewable energy. This study proposes regulatory controls on neighborhood morphologies and installed capacity density to optimize roof geometry and incentivize distributed rooftop solar arrays, thereby maximizing the effective installation area for renewable systems. For precincts with the requisite infrastructure for centralized renewable systems, policy guidance should actively facilitate the development of district energy stations [50]. These facilities serve to decarbonize the energy matrix by substituting conventional fuels with renewable sources, effectively offsetting fossil-fuel-based emissions.

# 6. Key Regulatory and Differentiated Indicator Systems across Unit Typologies

## 6.1 Industrial Units

### 6.1.1 Indicator Framework Development

Anchored in the established research framework and guided by the objective of transmitting carbon-resilience strategies to the micro-spatial scale, this study develops an adaptive framework comprising key regulatory indicators and differentiated indicators. By integrating the localized specificities of Xi'an, the research formulates customized decarbonization and resilience-enhancement measures and pathways tailored to diverse unit typologies. Crucially, the primary strategic objective for Industrial Units is defined as the regulation of Land-use Carbon Emission Intensity. The framework is structured across five overarching dimensions: Overall Scale, Built Form, Development Performance, Neighborhood Functions, and Infrastructure & Environment. It incorporates ten major sectoral benchmarks—including the *Guidelines for low-carbon green assessment of industrial parks* and the *14th Five-Year Plan for Green Industrial Development*—to calibrate the formulation of the Carbon Mitigation and Resilience Assessment Framework for industrial units. The specific formulation process is detailed in Figure 6-1.

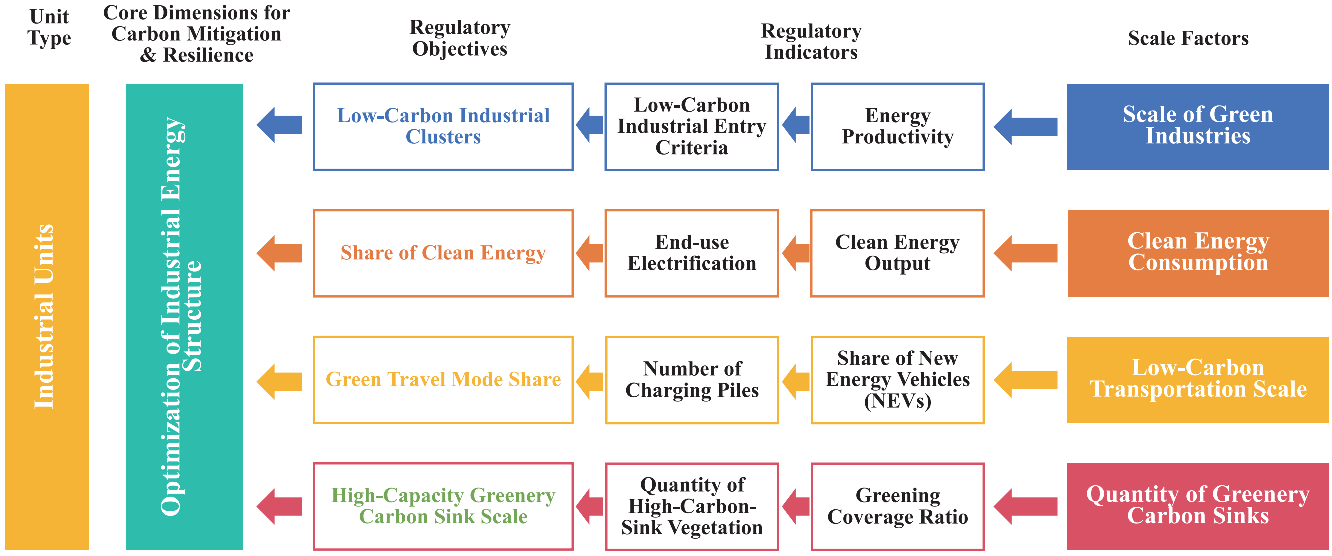



Figure 6-1: Methodological Formulation of the Carbon Mitigation and Resilience Assessment Framework for Industrial Units
Source: Prepared by author

**(1) Strategic Decomposition of Control Objectives for Industrial Units**

For Industrial Units (encompassing both administrative-office and manufacturing-industrial sub-units), the foundational pillar for carbon mitigation and resilience is **the optimization of the industrial energy matrix** [51]. This core pillar is decomposed into four strategic control objectives: A: Low-carbon industrial cluster optimization; B: Share of clean energy regulation; C: Green modal split management; D: Expansion of high-capacity greenery carbon sinks. Each objective corresponds to a quantitative planning driver: A: Green-industrial land and employment scale; B: Renewable energy installation density; C: EV mobility infrastructure provisioning; and D: Spatial extent of greenery carbon sinks. Furthermore, each objective is linked to two specific Key Performance Indicators (KPIs): A: Sectoral admittance thresholds and energy productivity; B: End-use electrification and renewable energy output; C: Number of charging piles and share of new energy vehicles (NEVs); and D: Quantity of high-carbon-sink vegetation and greening coverage ratio. Collectively, these metrics constitute the adaptive regulatory system for the carbon mitigation and resilience of industrial units.

**(2) Construction of the Carbon Mitigation and Resilience Indicator Framework for Industrial Units**

The framework is established through a phased construction process, culminating in a comprehensive Indicator Repository centered on four core strategic pillars: Development Performance, Built Form, Facilities & Equipment, and Greenery Carbon Sinks.

1) Hierarchy Construction: A — Criteria Level Establishment: Defining the primary criteria as Development Performance, Built Form, Facilities & Equipment, and Greenery Carbon Sinks. B — Indicator Layer Calibration: Key sub-indicators include Energy Productivity, Reduction Rate of Carbon Intensity per Unit of Industrial Added Value, Industrial Added Value per Capita, Proportion of Green Industry Added Value in Total Industrial Added Value, Ratio of 2-Star and Above Green Building Area, Renewable Energy Usage Ratio / Facility Installation Ratio, Share of Energy-Efficient and New Energy Vehicles, EV Charging Infrastructure Provision Ratio for New Parking Facilities, Air and Water Pollution Monitoring, Green Coverage Ratio, etc.

2) Target Value Benchmarking for Short-term and Long-term Horizons: Specific quantitative targets are assigned to each indicator across distinct planning horizons. For instance, Industrial Energy Productivity is benchmarked at ≥30,000 RMB/tce for the short-term and ≥50,000 RMB/tce for the long-term horizon[59].

3) Categorization of Indicator Attributes: A — Mandatory (Binding) Thresholds: These represent non-negotiable requirements, such as energy productivity, GVA-based carbon intensity reduction, and green infrastructure coverage. B — Incentive-based (Indicative) Guidelines: These serve as directional targets, such as the share of green industrial value added, certified green building proportions, and renewable energy facility deployment.

| Criterion Level | Indicator Level | Near-Term Planning Target Value | Long-Term Planning Target Value | Indicator Attribute | Reference Standard |
|---|---|---|---|---|---|
| Development Performance | Energy Productivity | ≥ RMB 30,000/tce | ≥ RMB 50,000/tce | Binding | Zhejiang Province Technical Guidelines for the Evaluation of Green and Low-Carbon Industrial Park Construction (2022 Edition) |
| | Reduction Rate of Carbon Intensity per Unit of Industrial Added Value | 3~10% | ≥10% | Binding | Plan for the Green Development of Industrial Sectors during the 14th Five-Year Plan Period |
| | Industrial Added Value per Capita | > RMB 200,000/person | > RMB 250,000/person | Binding | T/CIECCPA 010-2023 Guidelines for low-carbon green assessment of industrial parks |
| | Proportion of Green Industry Added Value in Total Industrial Added Value | ≥45% | ≥60% | Guiding | Jiangsu Construction Specification for Provincial Demonstration Eco-Industrial Parks (Draft for Comments) (2021) |
| Built Form | Share of floor area certified at Two-Star Green Building level or above | 20~50% | ≥50% | Guiding | *Shenzhen Implementation Plan for the Pilot Development of Near-Zero Carbon Emission Districts* |
| Facilities & Equipment | Renewable Energy Usage Ratio / Facility Installation Ratio | 5~15% | ≥15% | Binding | Green Park Evaluation Requirements (2016) |
| | Share of Energy-Efficient and New Energy Vehicles | ≥30% | ≥50% | Guiding | Zhejiang Province Technical Guidelines for the Evaluation of Green and Low-Carbon Industrial Park Construction (2022 Edition) |
| | EV Charging Infrastructure Provision Ratio for New Parking Facilities | ≥40% | ≥50% | Guiding | *Shenzhen Implementation Plan for the Pilot Development of Near-Zero Carbon Emission Districts* |
| | Air and Water Pollution Monitoring | ≥ 0.06 units/km² | ≥ 0.1 units/km² | Guiding | Urban Resilience Evaluation Guide (Draft for Comments) |
| Greenery Carbon Sinks | Green Coverage Ratio | 20~30% | ≥35% | Binding | T/CIECCPA 031-2023 *General principles for assessment of zero-carbon park* |

Figure 6-2: Indicator Repository for Carbon Mitigation and Resilience in Industrial Units
Source: Compiled by the authors based on relevant standards

## 6.1.2 Identification of Key Indicators

**(1) Office Sub-units**

1) Identification Process for Key Carbon Mitigation and Resilience Indicators

Drawing from the aforementioned Indicator Repository, this study selects **Urban Morphology** as the primary analytical dimension from the four core criteria: Development Performance, Built Form, Facilities & Equipment, and Greenery Carbon Sinks [52]. The rationale is threefold: First, the evaluation and regulation of morphological parameters are essential for operationalizing low-carbon and resilient urban planning philosophies. Second, morphological data offer superior accessibility and spatial granularity for large-scale urban audits. Third, carbon mitigation and resilience strategies derived from urban morphology demonstrate higher policy actionability within the scope of spatial planning practice.

Guided by an extensive literature review and empirical research, ten candidate morphological indicators were **preliminarily identified**[53]. Through the calculation of 2023 annual carbon emissions for office units in Xi'an and subsequent **correlation analyses**, the final key indicators for carbon mitigation and resilience were established. The candidate indicator pool encompasses: Year of Completion, Building Age, Plot Area, Floor Area Ratio (FAR), Building Coverage Ratio (BCR), Average Storey Count, Plot Perimeter, Form Factor, and Window-to-Wall Ratio (WWR).

2) 2023 Operational Emissions and Morphological Profiles of Administrative-Office Sub-unit Samples

① Statistical Summary and Sample Selection

The spatial scope of this research encompasses office clusters within Xi'an, Shaanxi Province, specifically focusing on the Jing-Wei Industrial Park, High-Tech Software Park, and Information Industry Park. A total of 33 Administrative-Office sub-units across these three parks were selected as primary case studies. Through GIS-based spatial analysis and attribute extraction, morphological and operational parameters were quantified for each unit. The dataset includes: 2023 annual electricity consumption, Gross Floor Area (GFA), Building Footprint Area, Year of Completion, Building Age, Plot Area, Floor Area Ratio (FAR), Building Coverage Ratio (BCR), Average Storey Count, Plot Perimeter, Form Factor, and Window-to-Wall Ratio (WWR). Table 6-1 summarizes the quantified dataset and sample characteristics.

Table 6-1: Statistical Summary and Sample Selection for Office Sub-units
Source: Prepared by author

| Plot Name | Building Age | Plot Area | FAR | BCR | GFA | Building Footprint Area | Avg. Storey Count | Plot Perimeter | Form Factor | WWR | Annual Carbon Emissions (2023) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Xi'an National Digital Publishing Base | 7 | 64,426 | 4.476670909 | 0.347313197 | 288,414 | 22,376 | 12.88943511 | 2,764 | 0.354495 | 0.46 | 21,021,557.66 |
| GLP Software Park Phase II | 5 | 29,909 | 7.785917282 | 0.262496239 | 232,869 | 7,851 | 29.66106229 | 801 | 0.113846 | 0.55 | 16,973,063.41 |
| Ascendas Kehui City | 5 | 20,660 | 6.328460794 | 0.267376573 | 130,746 | 5,524 | 23.66871832 | 520 | 0.095101 | 0.52 | 9,529,650.358 |
| Chinasoft International Xi'an Technology Park | 12 | 56,851 | 3.295720392 | 0.403211905 | 187,365 | 22,923 | 8.173668368 | 1,587 | 0.069337 | 0.41 | 13,656,424.97 |
| Xi'an GLP I-Park | 10 | 59,640 | 2.171512408 | 0.263581489 | 129,509 | 15,720 | 8.238486005 | 1,414 | 0.09495 | 0.39 | 9,439,489.454 |
| Software New Town Cloud Valley | 3 | 64,389 | 4.115283666 | 0.290002951 | 264,979 | 18,673 | 14.19048894 | 1,628 | 0.388601 | 0.49 | 19,313,456.8 |

| Plot Name | Building Age | Plot Area | FAR | BCR | GFA | Building Footprint Area | Avg. Storey Count | Plot Perimeter | Form Factor | WWR | Annual Carbon Emissions (2023) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Xi'an Hi-Tech Zone Water Group Co., Ltd. | 8 | 116,724 | 3.992366608 | 0.376820534 | 466,005 | 43,984 | 10.59487541 | 4,654 | 0.146746 | 0.56 | 33,965,587.59 |
| Xi'an Hi-Tech Zone Thermal Co., Ltd. | 4 | 287,053 | 0.408426318 | 0.136577566 | 117,240 | 39,205 | 2.990434894 | 7,068 | 0.341835 | 0.3 | 8,545,241.98 |
| Sunresin | 17 | 77,445 | 1.46862935 | 0.287713861 | 113,738 | 22,282 | 5.104478952 | 3,249 | 0.334689 | 0.33 | 8,289,992.599 |
| Xi'an Flight Automatic Control Research Institute, (AVIC) (Jinye Industrial Park) | 23 | 16,687 | 2.025828489 | 0.28375382 | 33,805 | 4,735 | 7.13938754 | 532 | 0.401863 | 0.47 | 2,463,936.414 |
| Huawei Xi'an Research Institute Phase II | 2024 | 120,679 | 2.562906554 | 0.447335493 | 309,289 | 53,984 | 5.729271636 | 3,560 | 0.304107 | 0.61 | 22,543,068.46 |
| Xi'an Semiconductor Industrial Park | 3 | 304,848 | 1.576697239 | 0.203268514 | 480,653 | 61,966 | 7.756721428 | 5507 | 0.133483 | 0.64 | 35,033,232.63 |
| China State Shipbuilding Corporation | 13 | 187,812 | 3.367511128 | 0.340153984 | 632,459 | 63,885 | 9.899960867 | 4,720 | 0.285511 | 0.47 | 46,097,877.84 |
| Xi'an XD Power Systems Co., Ltd., China XD Group | 24 | 102,689 | 1.780550984 | 0.290634829 | 182,843 | 29,845 | 6.126419836 | 2,823 | 0.453721 | 0.42 | 13,326,831.11 |
| Schneider Electric Equipment Engineering (Xi'an) Co., Ltd. | 11 | 68,155 | 2.2170347 | 0.531993251 | 151,102 | 36,258 | 4.16741133 | 2,028 | 0.417979 | 0.42 | 11,013,332.94 |
| Shaanxi Sirui Advanced Materials Co., Ltd. | 29 | 46,838 | 2.716576284 | 0.648704044 | 127,239 | 30,384 | 4.187697472 | 1,686 | 0.564442 | 0.26 | 9,274,036.543 |
| PetroChina Shaanxi Marketing Company | 24 | 11,245 | 1.00 | 30.43% | 11,194 | 3,422 | 3.271186441 | 605 | 0.27 | 0.36 | 815,894.2232 |
| Fengjing SOHO International | 6 | 12,594 | 0.57 | 7.31% | 7,190 | 921 | 7.806731813 | 163 | 0.49 | 0.44 | 524,055.6963 |

| Plot Name | Building Age | Plot Area | FAR | BCR | GFA | Building Footprint Area | Avg. Storey Count | Plot Perimeter | Form Factor | WWR | Annual Carbon Emissions (2023) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Shuangwei Building | 23 | 9,185 | 0.69 | 17.89% | 6,350 | 1643 | 3.864881315 | 306 | 0.38 | 0.32 | 462,830.8306 |
| Rongxin Science & Technology Park | 31 | 9,284 | 1.77 | 27.25% | 16,443 | 2,530 | 6.499209486 | 430 | 0.20 | 0.35 | 1,198,476.748 |
| FiberHome Science & Technology Park | 31 | 13,204 | 2.29 | 30.49% | 30,276 | 4,026 | 7.520119225 | 575 | 0.49 | 0.36 | 2,206,719.091 |
| Cultural Relics Science & Technology Building | 13 | 9,974 | 1.78 | 37.50% | 17,786 | 3,740 | 4.755614973 | 554 | 0.18 | 0.32 | 1,296,363.646 |
| Shengfang Science & Technology Park | 17 | 7,783 | 2.66 | 33.19% | 20701 | 2,583 | 8.014324429 | 340 | 0.13 | 0.38 | 1,508,828.508 |
| Xi'an Grape City Information Technology Co., Ltd. | 36 | 7,731 | 0.62 | 13.57% | 4,808 | 1,049 | 4.583412774 | 220 | 0.41 | 0.34 | 350,439.4698 |
| Xi'an Optoelectronics Park | 14 | 25,812 | 5.00 | 37.07% | 129,035 | 9,569 | 13.48469015 | 1,056 | 0.42 | 0.48 | 9,404,941.137 |
| Takeoff Innovation Center | 23 | 14,833 | 3.32 | 41.33% | 49,319 | 6,130 | 8.045513866 | 496 | 0.36 | 0.51 | 3,594,701.375 |
| Zhongke Dejing Sci-Tech Innovation Park | 27 | 11,546 | 0.44 | 8.55% | 5,135 | 987 | 5.202634245 | 175 | 0.43 | 0.55 | 374273.4354 |
| Xi'an Software Park - West Zone | 6 | 72,085 | 2.72 | 23.64% | 195,940 | 17,038 | 11.50017608 | 2,689 | 0.26 | 0.8 | 14,281,428.81 |
| Zero One Plaza | 25 | 29,291 | 3.28 | 34.18% | 95,998 | 10,011 | 9.589251823 | 865 | 0.25 | 0.7 | 6,996,981.744 |
| Xi'an Software Park - East Zone | 6 | 46,253 | 1.63 | 27.06% | 75443 | 12,516 | 6.027724513 | 1,782 | 0.28 | 0.45 | 5,498,794.701 |
| Navigation Science & Technology Park Office Building | 23 | 31,213 | 8.468746996 | 0.40668952 | 264,335 | 12,694 | 20.82361746 | 1,512 | 0.74927 | 0.64 | 19,266,517.73 |
| Huihaoshu Center | 26 | 10,508 | 6.079558432 | 0.272744576 | 63,884 | 2,866 | 22.29030007 | 336 | 0.118551 | 0.71 | 4,656,296.816 |
| Sanyi Group | 13 | 21,256 | 2.00348137 | 0.303114415 | 42,586 | 6,443 | 6.609653888 | 971 | 0.402286 | 0.6 | 3,103,954.921 |

② Bivariate Correlation Analysis: Carbon Emissions vs. Morphological Indicators

Statistical analysis was performed using SPSS to examine the relationship between the 2023 annual carbon emissions of office units and their respective morphological parameters. Prior to formal quantification, Exploratory Data Analysis (EDA) was conducted via scatter plots to visualize the distribution and identify potential linear associations or outliers (see Figure 6-3).

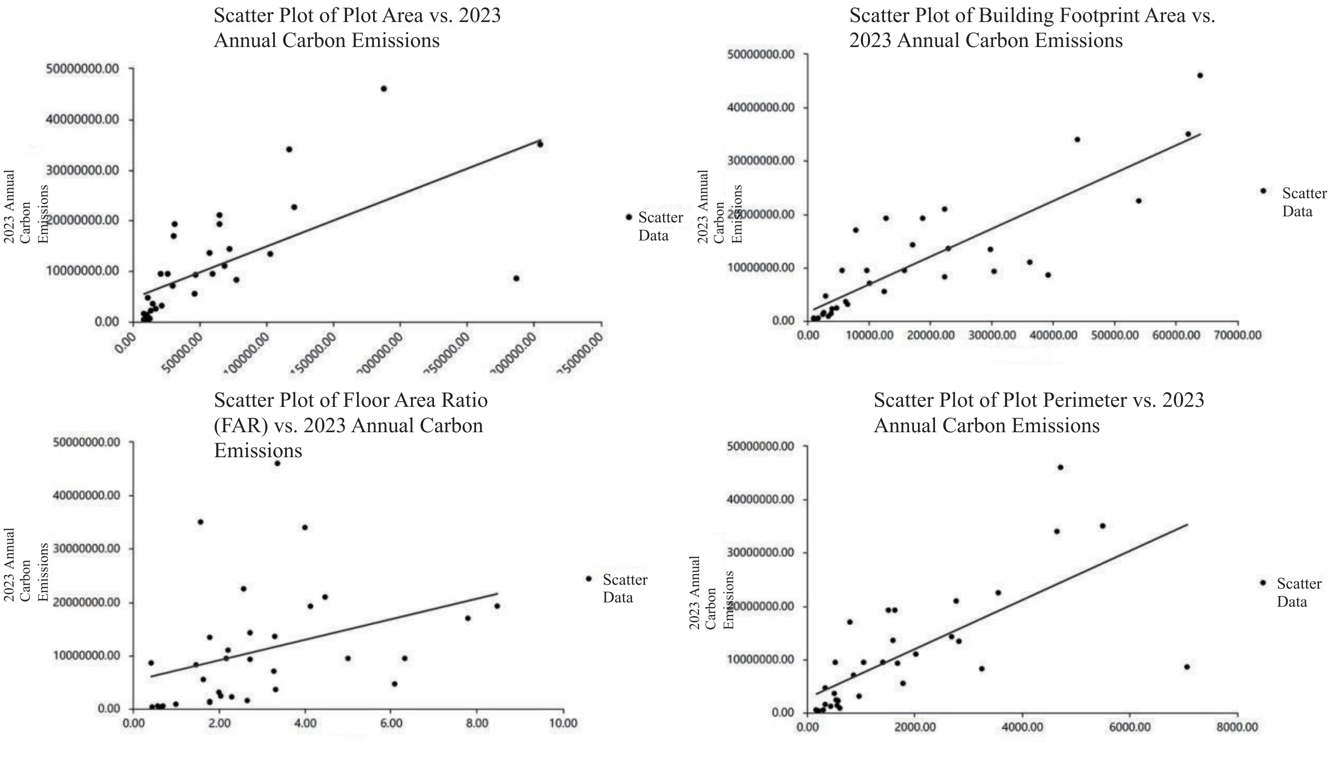



**Figure 6-3: Scatter Plot Analysis of Carbon Emissions vs. Morphological Indicators in Office Sub-units**
**Source: Prepared by author**

The Pearson Correlation Coefficient (*r*) was employed to quantify the strength and direction of the linear associations between the variables. Through this analysis, the study determined the correlations between 2023 annual carbon emissions and ten specific morphological indicators: Gross Floor Area (GFA), Building Footprint Area, Building Age, Floor Area Ratio (FAR), Building Coverage Ratio (BCR), Average Storey Count, Plot Area, Plot Perimeter, Window-to-Wall Ratio (WWR), and Form Factor. The detailed statistical results are documented in Table 6-2:

**Table 6-2: Pearson Correlation Matrix: 2023 Annual Carbon Emissions vs. Morphological Indicators for Office Sub-units**
**Source: Prepared by author**

| | Annual Carbon Emissions (2023) |
|---|---|
| Building Age | 0.177 |
| FAR | 0.349* |
| Building Footprint Area | 0.848** |
| BCR | 0.234 |

| | Annual Carbon Emissions (2023) |
|---|---|
| Avg. Storey Count | 0.258 |
| Plot Area | 0.675** |
| Plot Perimeter | 0.713** |
| WWR | 0.342 |
| Form Factor | -0.149 |
| * p<0.05 ** p<0.01 | |

The empirical analysis demonstrates that for Office Sub-units in 2023, the Pearson correlation coefficient (r) between annual carbon emissions and **Building Footprint Area** is 0.848, which is statistically significant at the 0.01 level ($p < 0.01$), indicating a strong positive correlation. Furthermore, for Office Sub-units in 2023, significant positive correlations were observed between carbon emissions and **Floor Area Ratio (FAR)**, **Plot Area**, and **Plot Perimeter**. Conversely, no statistically significant associations were identified between 2023 emissions and Building Coverage Ratio (BCR), Average Storey Count, or Window-to-Wall Ratio (WWR). Accordingly, the study identifies **Building Footprint Area**, **FAR**, **Plot Area**, and **Plot Perimeter** as the primary Key Control Indicators for carbon mitigation and resilience in office sub-units.

**(2) Manufacturing-Industrial Units**

**1) Identification of Key Carbon Mitigation and Resilience Indicators**

Adhering to the methodological framework established for office sub-units, this study preliminarily identifies key indicators based on spatial parameters. By calculating the 2023 annual carbon emissions of industrial sub-units in Xi'an, we conducted correlation analyses to isolate the core morphological drivers. Subsequently, an analysis of Gross Value Added (GVA) data was performed to evaluate the impact of non-spatial socio-economic factors—such as industrial structure and energy intensity—on overall mitigation potential.

**2) Correlation Analysis**

As illustrated in Figures 6-4 and 6-5, total carbon emissions exhibit statistically significant positive correlations with both Gross Floor Area (GFA) and Building Footprint Area. The Pearson correlation coefficients (*r*) are 0.532 and 0.527, respectively; both values are greater than zero ($r > 0$), confirming a direct positive association. Notably, the linear correlation becomes significantly more pronounced within specific GFA intervals.

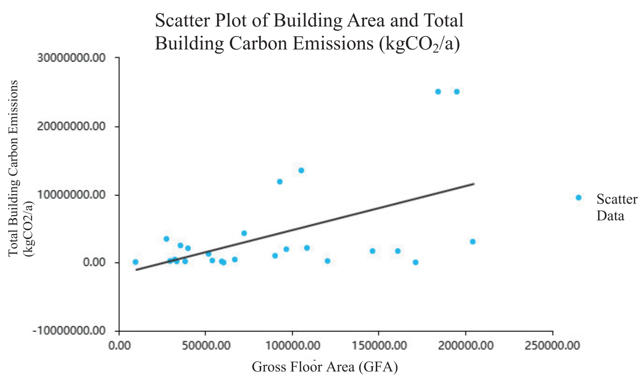



Figure 6-4: Scatter Plot of Positive Correlation Between Total Emissions and GFA

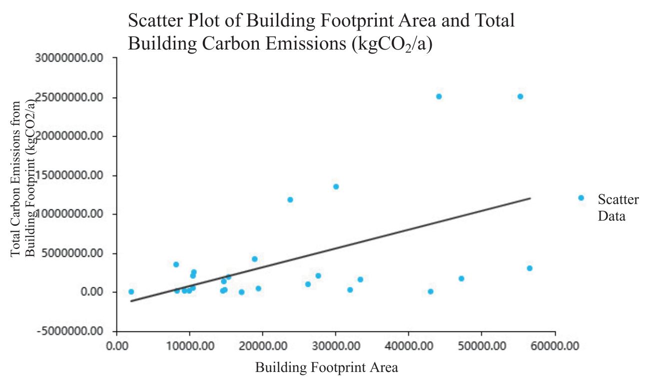



Figure 6-5: Scatter Plot of Positive Correlation Between Total Emissions and Building Footprint Area

Source: Prepared by author

Quantitative analysis of the datasets in Figures 6-6 and 6-7 reveals the synergistic impacts of GFA–Building Height and the Building Footprint Area–to–Non-built-up Area Ratio on total emissions. For units with a GFA below 100,000 $m^2$, total carbon emissions exhibit only marginal fluctuations, with the predominant typology being low-rise industrial buildings. Conversely, when the GFA exceeds 100,000 m2, emissions are driven by a multi-faceted interplay of factors, including building height, typology (multi-storey or high-rise), industrial sectoral composition, and the energy matrix. When the Building Footprint Area exceeds the non-built-up area, total carbon emissions tend to reach a steady state (stabilize). However, when the footprint area is smaller than the non-built-up area, total emissions typically exceed the sample average; this is primarily attributed to higher vacancy rates, which result in operational inefficiencies.

**Impact of Gross Floor Area (GFA) on Building Carbon Emissions**

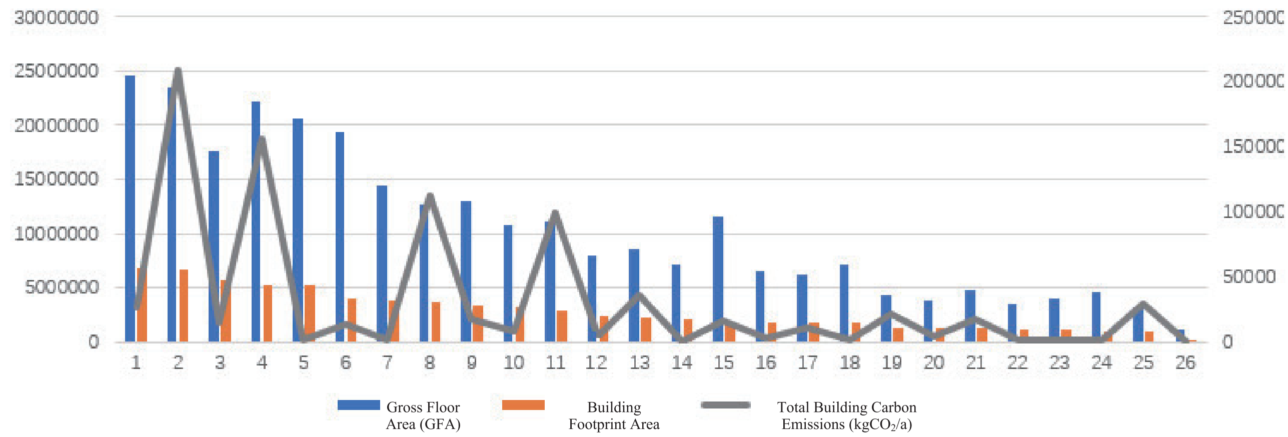



Figure 6-6: Impact of Gross Floor Area (GFA) on Building Carbon Emissions
Source: Prepared by author

**Impact of Building Footprint Area (Site Coverage Ratio) on Building Carbon Emissions**

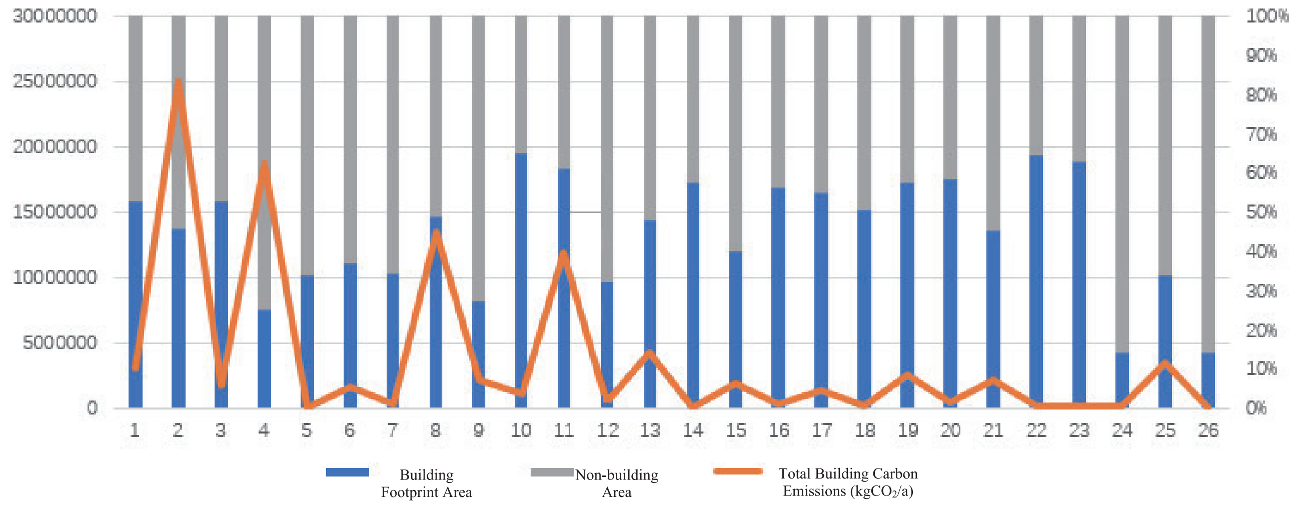



Figure 6-7: Impact of Building Footprint Area on Building Carbon Emissions
Source: Prepared by author

Furthermore, total emissions per unit GFA demonstrate a statistically significant negative correlation with Building Age. In contrast, the carbon intensity of Industrial Gross Value Added (GVA) shows no statistically significant correlation with spatial or morphological parameters.


Figure 6-8: Scatter Plot of Negative Correlation Between Building Age and Carbon Emissions
Source: Prepared by author

**3) Analysis of Industrial GVA and Economic Carbon Intensity**

The carbon emission intensity per unit of Gross Value Added (GVA) for industrial and warehousing land is intrinsically linked to the industrial sectoral composition, showing no significant direct correlation with spatial morphological parameters. Empirical analysis indicates that when carbon intensity exceeds the threshold of 200 $kgCO_2$/10,000 RMB, light industry accounts for 55% and heavy industry for 36%, with emerging power and renewable energy sectors occupying a predominant position within the cluster. Conversely, when carbon intensity falls below 200 $kgCO_2$/10,000 RMB, the share of heavy industry rises to 63% while light industry drops to 37%. This confirms that heavy industry remains the structural primary source of emissions, even within high-efficiency production brackets.

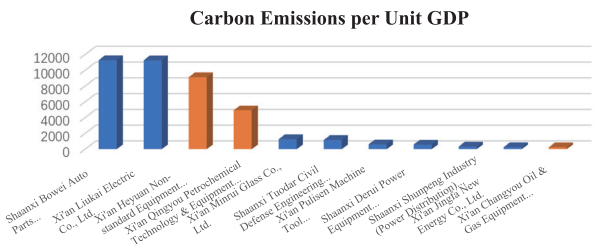



Figure 6-9: Sectoral Distribution of Carbon Intensity > 200 $kgCO_2$/10,000 RMB

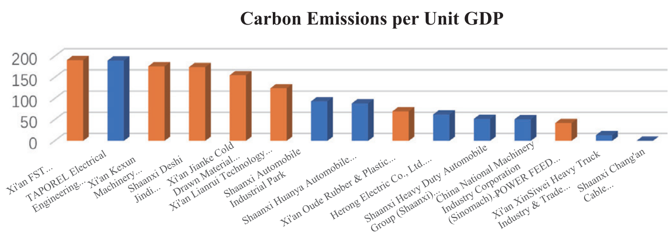



Figure 6-10: Sectoral Distribution of Carbon Intensity < 200 $kgCO_2$/10,000 RMB

Source: Prepared by author

### 6.1.3 Regulatory Standards & Strategy Formulation

As established, the Key Control Indicators for carbon mitigation and resilience in office sub-units are Building Footprint Area, Floor Area Ratio (FAR), Plot Area, and Plot Perimeter. Based on the empirical findings and the benchmarking standards integrated into the Indicator Repository, differentiated regulatory strategies have been formulated. This study prioritizes the regulation of morphological parameters of Office Sub-units. For indicators governed by existing carbon mitigation and resilience assessment standards, strategies are tailored to their operational contexts and impact profiles. For indicators lacking established benchmarks, flexible (elastic) strategies are derived from the mechanistic analysis of the underlying drivers.

The specific strategies are as follows:

**(1) Regulation of Building Footprint Area**

Empirical evidence suggests that, holding the Floor Area Ratio (FAR) constant, the Building Footprint Area exhibits a significant positive correlation with total building carbon emissions. In accordance with the *Guidelines for Low-Carbon Industrial Park Construction*, regulatory focus is placed on augmenting green design and construction management. This involves accelerating the integration of prefabricated building systems and strictly regulating the footprint of new office units to minimize baseline energy demand. Optimizing footprint constraints enhances architectural energy efficiency and systematically lowers the operational carbon footprint. Simultaneously, limiting the Simultaneously, limiting footprint expansion curtail land consumption, fostering a Smart Growth model while preserving vital spatial capacity for vegetated carbon sequestration [63][54].

**(2) Regulation of Floor Area Ratio (FAR)**

As a pivotal metric for spatial development intensity, FAR exerts a decisive influence on both carbon mitigation trajectories and urban structural resilience. In alignment with the *Green Building Regulations of the Shenzhen Special Economic Zone*, sustainable developments are eligible for FAR Incentives (Bonuses). For instance, green buildings utilizing Industrialized Building Systems (IBS) benefit from an exclusionary provision where the floor area of prefabricated exterior wall components (up to 3% of above-grade GFA) is exempted from FAR calculations. FAR must be prudently regulated to prevent resource inefficiencies associated with excessive densification. By establishing differentiated FAR thresholds, urban planning can steer the development of high-density, resource-optimized office clusters. This approach ensures the provisioning of ample public open spaces and green belts, thereby fortifying ecological resilience and mitigating the Urban Heat Island (UHI) effect.

**(3) Regulation of Plot Area**

In accordance with the *Beijing Urban Resilience Evaluation Guidelines (Draft)*, urban land-use intensity must be strictly regulated, with a recommended Land Development Ratio (LDR) of below 44% for plain regions. For greenfield office sub-units, the strategic planning of plot sizes is essential to incentivize Mixed-Use Development (MXD) and maximize integrated land-use efficiency. The rationalized allocation of plot sizes is a critical determinant in achieving carbon mitigation and structural resilience for office sub-units. Differentiated plot-size standards must be established based on the locational context, functional requirements, and environmental characteristics of each site. This study advocates for compact development models that optimize land-use efficiency[55]. Furthermore, through mixed-use zoning and functional integration, planning should facilitate the organic synergy of office, commercial, and residential uses. This approach mitigates transit-induced carbon loads by reducing reliance on motorized travel and promoting active travel patterns.

**(4) Regulation of Building Coverage Ratio**

Regulating the Building Coverage Ratio (BCR) is instrumental in optimizing urban morphology to facilitate carbon mitigation and structural resilience. By re-evaluating spatial metrics to encourage nucleated building clusters, the excessive expansion of urban transport networks can be curtailed[58]. This spatial concentration effectively lowers transportation carbon emissions and optimizes infrastructure service radii, thereby reducing both initial capital expenditure and life-cycle operational costs. Furthermore, compact spatial configurations enhance urban legibility and public safety, fortifying the city's disaster preparedness and defensive resilience[56].

In the implementation of these regulatory standards, Xi'an must integrate context-sensitive adaptations based on localized conditions. This necessitates the formulation of detailed implementation guidelines and longitudinal evaluation mechanisms to safeguard the methodological rigor and operational efficacy of the spatial planning. Through the execution of these measures, office sub-units in Xi'an will be steered toward a trajectory of enhanced sustainability, efficiency, and resilience, thereby advancing the city's transition toward Sustainable Development Goals.

The carbon mitigation potential of industrial sub-units is fundamentally concentrated in two areas: Development Performance and Built Form. Consequently, the regulatory indicator framework must be anchored in these dual dimensions to maximize decarbonization impact.

**(1) Typological Classification and Tiered Management**

Industrial sectors and park typologies should be managed through tiered classification, with customized low-carbon strategies tailored to each category. In alignment with the *Guidelines for Low-Carbon Industrial Park Construction*, parks are categorized based on their energy profiles. This includes classification based on the decoupling of economic growth from total energy consumption (absolute vs. relative decoupling) and the proportional share of fossil fuel-derived energy within the total energy mix.

**(2) Land-Use Efficiency**

Planning must proactively mitigate high land vacancy rates and address insufficient green space ratios. By regulating the aggregate development scale and internal land-use proportions, the intensity of industrial land use can be optimized. High carbon emissions from industrial zones can be partially offset by increasing the allocation for public service land and green cover. Through scientific spatial planning and the enhancement of the park's systemic composition, industrial clusters can transition toward a Net-Zero or Low-GHG emission paradigm.

**(3) Built Form**

The implementation of low-carbon building systems is central to carbon-mitigating industrial parks[57]. Regulatory focus includes site selection, synergy with ecological assets, the implementation ratio of Industrialized Building Systems (IBS), Window-to-Wall Ratios (WWR), material specifications, and optimization of building massing and orientation. Operational focus includes improving building energy performance and the deployment of integrated Energy Monitoring Systems (EMS).

**(4) Energy System Optimization**

Strategies must enhance the processing and conversion efficiency of fossil fuels while implementing phased caps on total conventional energy consumption. The deployment of state-of-the-art (SOTA) industrial processes is required to maximize energy productivity and minimize systemic waste across the energy lifecycle.

## 6.2 Residential Units

### 6.2.1 Indicator System Architecture

Building upon established research regarding the spatial drivers of residential carbon emissions, and addressing the context-specific urban challenges in Xi'an, this study defines four primary control objectives: land-use intensification, spatial layout optimization, low-carbon mobility promotion, and the expansion of ecological blue-green spaces. The core regulatory elements for carbon mitigation and resilience are identified across four dimensions: Overall Scale, Building Layout, Infrastructure & Environment, and Greenery Carbon Sinks. The causal mechanisms are delineated as follows:

The overall development scale dictates population capacity and associated energy demands, thereby determining the magnitude of aggregate building emissions. Parameters such as site area, Floor Area Ratio (FAR), and Building Coverage Ratio (BCR) influence emissions by defining total consumption and modulating thermal gain-loss dynamics. Specifically, optimized urban block granularity and FAR effectively regulate energy demand and enhance utilization efficiency. The relationship between Building Coverage Ratio (BCR) and emissions follows an inverted U-curve: at a constant FAR, excessively low BCR leads to excessive thermal dissipation, increasing heating loads. Conversely, hyper-density triggers localized heat island effects, trapping excess heat and driving up cooling-related emissions.

Building layout impacts emissions through two primary pathways: first, by directly determining solar accessibility via architectural morphology[58]; and second, by modulating the intra-neighborhood microclimate. These factors collectively govern the building's thermodynamic exchange processes. Specifically, building massing configurations and the high-rise ratio[59] significantly influence the thermal environment, ventilation patterns (wind environment), and solar gain, thereby determining the aggregate carbon footprint.

The service infrastructure dictates the configuration of public transport facilities, directly influencing the green commuting ratio[60] and aggregate transportation carbon emissions. High Transit Service Coverage (stop density) effectively alleviates congestion and enhances traffic flow efficiency, resulting in a systemic reduction in carbon emissions.

Greenery carbon sinks influence the residential carbon balance via two mechanisms: First, an increased Green Space Ratio (GSR) enhances overall carbon sequestration potential[61] while regulating the microclimate to lower ambient temperatures, thereby reducing cooling-related emissions. Second, the area of public open space improves the wind environment and provides environmental buffering during extreme weather events, reducing pressure on critical infrastructure. Furthermore, these open spaces function as emergency evacuation shelters[62], providing safe refuge and bolstering the overall structural resilience of the residential unit.

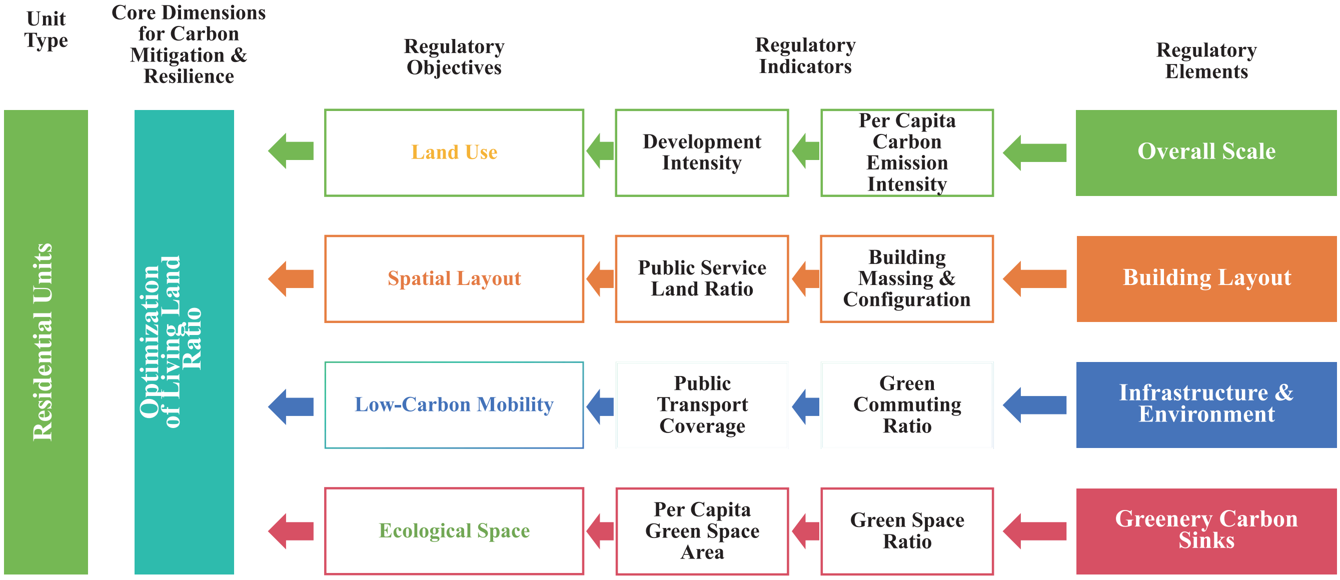



Figure 6-11: Logical Framework for the Residential Unit Indicator System
Source: Prepared by author

### 6.2.2 Identification of Key Indicators

Building operational electricity emissions constitute the primary carbon source for Residential Units. To identify the pivotal spatial planning parameters for low-carbon resilience, this study employs correlation analysis to determine the key indicators, which are summarized in the table below.

Table 6-3: Key Indicator System for Carbon Mitigation and Resilience in Residential Units
Source: Prepared by author

| Criterion Level | Indicator Level | Correlation / Impact Trajectory |
|---|---|---|
| Overall Scale | Land Area (Plot Size) | Positive Linear Correlation |
| | FAR (Floor Area Ratio) | Inverted U-shaped (Non-monotonic) |
| | BCR (Building Coverage Ratio) | U-shaped (Non-monotonic) |
| Building Layout | Public Service Land Ratio | U-shaped (Non-monotonic) |
| | Building Massing & Configuration | —— |
| | High-rise Ratio | Positive Linear Correlation |

At the Overall Scale level, Plot Size maintains a positive linear correlation with both aggregate carbon emissions and Carbon Emission Intensity (CEI). Floor Area Ratio (FAR) exhibits a non-monotonic, inverted U-curve relationship with emissions (initial increase followed by a decrease). Conversely, Building Coverage Ratio (BCR) follows a U-curve trajectory, where emissions are minimized at moderate densities but escalate at both extremely low and high density thresholds.

Within the Building Layout dimension, the proportion of public service land shows a U-curve correlation with emission intensity. The High-rise Ratio maintains a positive linear correlation with total emissions. Among spatial configurations, Perimeter (Enclosed) Blocks represent the optimal morphological typology, significantly outperforming Linear (Row) or Point-Block (Cluster) arrangements in terms of carbon mitigation per unit of GFA.

### 6.2.3 Regulatory Standards & Strategy Formulation

The calibration of regulatory thresholds for the residential low-carbon resilience system must integrate environmental objectives with broader strategic priorities, including economic viability, public health, and urban safety. Consequently, based on the empirical findings of this study and aligned with prevailing technical codes, this report establishes planning intervals for both short-term and long-term horizons. These standards are governed by the principle of "Floor-limit compliance for mandatory constraints and ceiling-target achievement for aspirational guidelines."

| Criterion Level | Indicator Level | Near-Term Planning Target Value | Long-Term Planning Target Value | Indicator Attribute | Reference Standard |
|---|---|---|---|---|---|
| Overall Scale | Land Area | (5.5ha, 15ha) | [3.5ha-5.5ha] | Guiding | Standard for Planning and Design of Urban Residential Areas<br>Urban Resilience Evaluation Guide<br>Xi'an Technical Directives for Urban and Rural Planning Management |
| | Floor Area Ratio | [1.0, 2.8) | [2.0, 2.7] | Binding | |
| | Building Coverage Ratio | [20%, 32% ) | [24%, 32%] | Binding | |
| Building Layout | Public Service Land Ratio | ≥10% | [15%, 20%] | Guiding | Standard for Planning and Design of Urban Residential Areas |
| | Building Configuration | Enclosed + Mixed | Enclosed | Guiding | —— |
| | High-rise Ratio | (30%, 50] | ≤30% | Binding | Beijing Local Standard: Community Resilience Evaluation Guide |
| Infrastructure & Environment | Public Transport Station Coverage Rate | 100% | 100% | Guiding | Guidance on green and low-carbon community construction and evaluation technology |
| | Proximity to Nearest Metro Station | < 1.2km | < 0.8km | Guiding | |
| | Green Commuting Ratio | ≥70% | > 80% | Guiding | Green Travel Creation Action Plan<br>Xi'an Territorial Space Master Plan |
| | 15-Min Walking Coverage of Community Health Facilities | ≥75% | ≥80% | Binding | Xi'an Territorial Space Master Plan<br>Standard for Planning and Design of Urban Residential Areas |
| Greenery Carbon Sinks | Per Capita Public Open Space | (7m², 8.3m²] | > 8.3m² | Binding | Beijing Local Standard: Community Resilience Evaluation Guide |
| | Green Space Ratio | ≥35% | ≥40% | Binding | Standard for Planning and Design of Urban Residential Areas |

Figure 6-12: Regulatory Threshold Standards for the Residential Unit Indicator System
Source: Prepared by author

**(1) Overall Scale**

Urban planning should calibrate FAR and BCR to favor bimodal optimization—promoting either low-density or high-efficiency high-density clusters while avoiding the carbon-intensive "mid-range." Site area magnitudes must be strictly regulated to foster moderately compact neighborhood morphologies.

1) Land Area

Per the *Standard for Planning and Design of Urban Residential Areas*, inter-block street spacing should not exceed 300m (optimally 150–250m), which corresponds to a theoretical block area of 2.25–6.25 ha. Consequently, residential land area is capped at 3.5–15 ha for the short-term horizon and consolidated to 3.5–5.5 ha for the long-term strategic vision. Developments exceeding 15 ha or falling below 3.5 ha are not recommended due to reduced resilience and infrastructure inefficiencies.

2) Floor Area Ratio - FAR

The *Xi'an Technical Directives for Urban and Rural Planning Management* prescribe a residential FAR between 1.0 and 2.8. Conversely, the *Community Resilience Evaluation Guidelines* suggest that optimal resilience performance is associated with a higher density interval of 2.0–4.0. Balancing statutory constraints with resilience goals, this report recommends a short-term threshold of 1.0–2.8 and a long-term optimization of 2.0–2.7, strictly adhering to the regulatory ceiling of 2.8.

3) Building Coverage Ratio - BCR

Per the *Xi'an Technical Directives for Urban and Rural Planning Management*, the permissible BCR for residential areas ranges from 20% to 35%. To optimize carbon resilience, this study recommends a regulatory ceiling of 32%. Specifically, density should be managed within 20%–32% for the short-term horizon and calibrated to a strategic range of 24%–32% in the long term.

**(2) Building Layout**

1) Public Service Land Ratio

In accordance with the *Standard for Planning and Design of Urban Residential Areas*, the "5-minute walkable neighborhood" must provide integrated amenities including childcare, community services, healthcare, and commercial hubs. Consequently, the prescribed minimum for public service land is set at 10%, with target ranges of 10%–20% for the short term and 15%–20% for the long-term horizon.

2) Morphological Configurations

Perimeter (Enclosed) layouts are prioritized as the optimal configuration for thermal efficiency and microclimate regulation. While linear (row) or hybrid forms may be integrated, the use of dispersed point-block clusters as the dominant typology is strongly discouraged.

3) High-rise Ratio

Per the *Community Resilience Evaluation Guidelines*, a high-rise ratio of ≤30% is classified as "Excellent," while 30%–50% is rated as "Moderate." Therefore, the high-rise proportion should be strictly regulated below a 50% threshold in the short term and optimized to <30% in the long term to attain peak resilience ratings.

**(3) Infrastructure & Environment**

1) Public Transport Station Coverage Rate

The *Guidance on green and low-carbon community construction and evaluation technology* recommends that the walking distance from community entrances to transit stops be within 500 m. Benchmarked against exemplary ecological districts—including Kunming's Chenggong New District, Wuhan's Sixin Eco-New Town, and Beijing's Changxindian Ecological City—where 500 m service catchments have achieved 100% coverage, this study mandates a full 100% public transport station coverage within a 500 m radius for all units.

2) Proximity to Metro Stations

Aligned with the *Guidance on green and low-carbon community construction and evaluation technology* advocating for metro access within an 800 m radius, this study sets a proximity cap of 1.2 km for the short term, with a long-term strategic target of 0.8 km.

3) Green Commuting Ratio

The *Green Travel Creation Action Plan* sets a benchmark of >70% for sustainable transport, while the *Xi'an Territorial Space Master Plan (2021–2035)* defines a new low-carbon development model for a green and secure territory, mandating a green commuting ratio of over 80%. Consequently, the threshold is set at 70% for the short term and a mandatory target of >80% for the long-term horizon.

4) 15-min Walking Coverage of Community Health Facilities

To fulfill the "15-minute neighborhood service circle" delineated in the *Xi'an Territorial Space Master Plan*, the 15-min walking coverage of community health facilities is set at a mandatory minimum of 75% for the short term, escalating to ≥80% in the long-term vision.

**(4) Greenery Carbon Sinks**

1) Per Capita Public Open Space

According to the *Community Resilience Evaluation Guidelines*, resilience performance is classified as "Excellent" when per capita public open space exceeds 8.3 $m^2$, and "Moderate" within the 7.0–8.0 $m^2$ range. Accordingly, the regulatory interval for this metric is set at 7.0–8.3 $m^2$ for the short term. For the long-term strategic horizon, the per capita allocation must surpass the 8.3 $m^2$ benchmark to attain an "Excellent" resilience rating.

2) Green Space Ratio - GSR

The *Standard for Planning and Design of Urban Residential Areas* mandates the spatial provisioning of consolidated green spaces within residential blocks, with requirements set at a minimum of 0.5 $m^2$/person for new greenfield developments and 0.35 $m^2$/person for urban regeneration projects. Consequently, the green space ratio for residential areas is stipulated to be no less than 35% in the short term, and no less than 40% in the long term.

## 6.3 Regeneration Units

### 6.3.1 Indicator System Architecture

This study initiates a comprehensive review of extant literature to synthesize determinants influencing building and transportation carbon emissions, as well as carbon sequestration pathways. By delineating their respective causal mechanisms, we have established a robust audit-based parameter database. By integrating Xi'an's Territorial Spatial Planning with prevailing technical standards and granular carbon data, we conducted a mechanism-based verification to formulate an indicator system precisely tailored to the local urban fabric of Xi'an and its representative regeneration pilot sites.

The selected regeneration sites encompass a multifunctional urban fabric, spanning historical tourism, cultural leisure, commercial services, and residential living. The diversity and Land-Use Mix (LUM) of these programs are directly correlated with urban vitality and community sustainability—key indicators of systemic robustness and recovery capacity when facing external stressors. Given the high programmatic density and population concentration within these units, they face exacerbated pedestrian and vehicular egress loads during emergencies. Consequently, the strategic configuration of public transport facilities and emergency evacuation spaces is prioritized in this research.

Consequently, synthesized with the mechanistic underpinnings of sectoral carbon emissions at the detailed planning scale, and informed by the analysis of prevailing context-specific issues, this research framework designates Programmatic Mix Regulation and Infrastructure & Environmental Optimization as the primary regulatory axes for carbon mitigation and resilience within Regeneration Units. The primary regulatory objectives focus on: optimizing programmatic ratios, optimizing building energy consumption structures, promoting low-carbon mobility, and expanding ecological spaces.

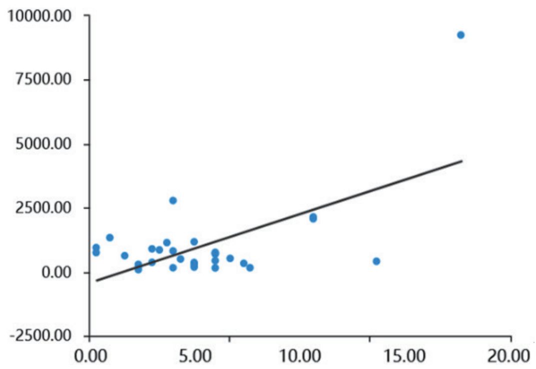
Table 6-4: Indicator System for Regeneration Units
Source: Prepared by author

| Core Dimensions for Carbon Mitigation & Resilience | Regulatory Elements | Regulatory Objectives | Regulatory Metrics |
|---|---|---|---|
| Programmatic Mix Modulation | Neighborhood Functions | Land-Use Ratios | Mixed-use Diversity |
| | | | Programmatic Density / Diversity |
| Infrastructure & Environmental Optimization | Energy Systems & Technology | Building Energy Consumption Structure | Operational Energy Intensity |
| | | | Renewable Energy Penetration Rate |
| | Infrastructure & Environment | Low-Carbon Mobility | Public Transport Coverage |
| | | | Green Commuting Ratio |
| | Greenery Carbon Sinks | Ecological Space | Per Capita Green Space Area |
| | | | Green Space Ratio (GSR) |

### 6.3.2 Identification of Key Indicators

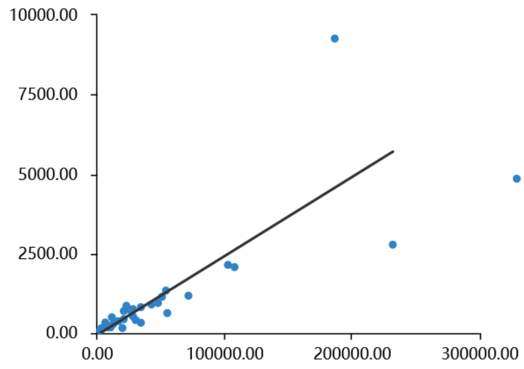
To identify key regulatory indicators for Xi'an's regeneration units at the detailed planning scale, it is essential to substantiate the causal mechanisms through which spatial configurations drive sectoral emissions. Given that the impact of spatial elements on carbon emissions is primarily indirect, this study synthesizes empirical findings from Xi'an and peer cities at analogous latitudes to evaluate the significance and orientation of these spatial determinants.

The analytical framework employs Stepwise Linear Regression via SPSS. Following an initial screening through correlation analysis, planning indicators were modeled against Annual Building Operational Emissions and Carbon Emission Intensity (CEI). Regression coefficients were estimated using a stepwise approach, with residuals validated through Durbin-Watson statistics and case diagnostics. Additionally, multicollinearity (VIF) and partial correlation diagnostics were conducted to ensure the statistical robustness of the model.



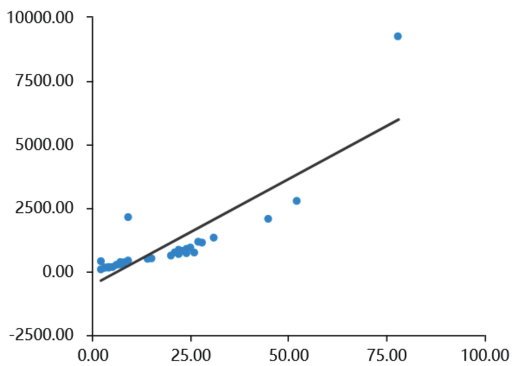

(y=-427.753+89.483x，$R^2$=0.371)

Figure 6-13: Scatter Plot of Mean Floors vs. Annual Operational Emissions
Source: Prepared by author



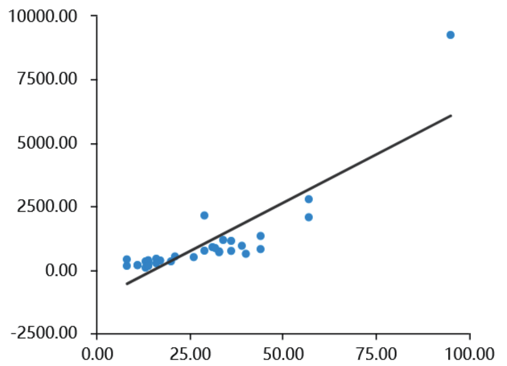

(y=-57.275+0.025x, $R^2$=0.609)

Figure 6-14: Scatter Plot of Total Floor Area vs. Annual Operational Emissions
Source: Prepared by author



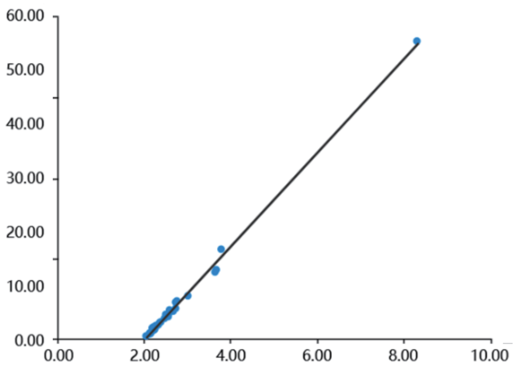

(y=-524.005+83.388x, $R^2$=0.715)

Figure 6-15: Scatter Plot of F&B Quantity vs. Annual Operational Emissions
Source: Prepared by author



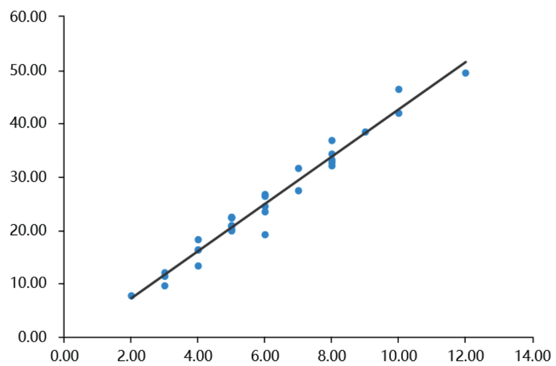

(y=-1163.164+76.134x, =0.723)

Figure 6-16: Scatter Plot of Total Programmatic Volume vs. Annual Operational Emissions
Source: Prepared by author




(y=-1.619+4.427x, $R^2$=0.667)

Figure 6-17: Scatter Plot of FAR vs. Carbon Emission Intensity (CEI)
Source: Prepared by author




(y=37.232+4.340x, $R^2$=0.523)

Figure 6-18: Scatter Plot of Leisure/Entertainment Quantity vs. CEI
Source: Prepared by author

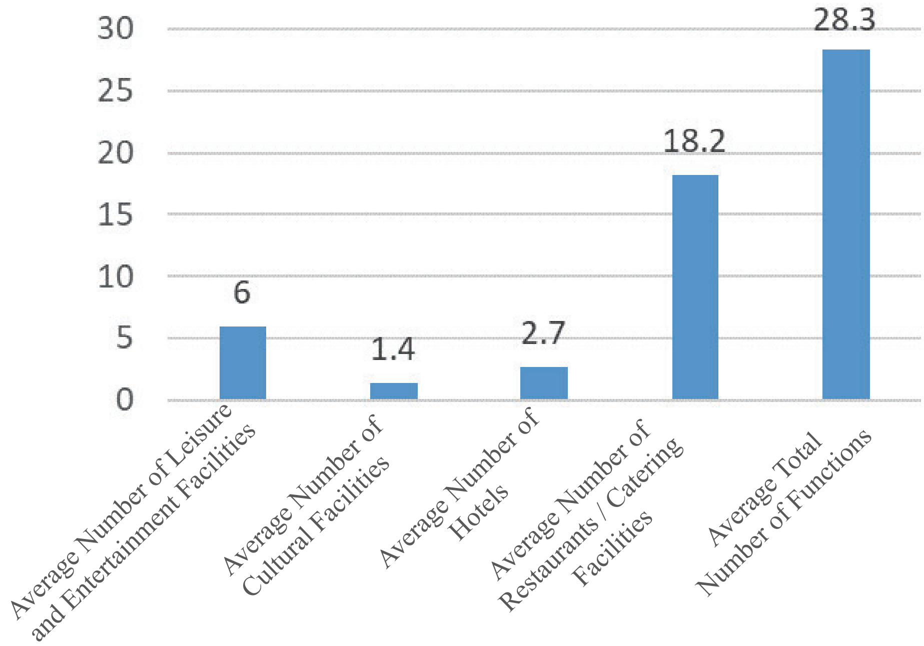



Table 6-19: Functional Composition of Neighborhoods in Regeneration Units
Source: Prepared by author

Model validation reveals that at the Programmatic Mix level, both F&B Quantity and Total Programmatic Volume exhibit a positive linear correlation with Annual Operational Emissions, while the density of leisure/entertainment facilities is positively correlated with CEI. Higher concentrations of F&B outlets and diversified programs significantly escalate operational carbon loads within commercial typologies. Empirical data shows a pronounced imbalance in the selected sites, characterized by a deficit in leisure facilities and a surplus of F&B outlets. Regarding the Building Energy System, both the Mean Number of Floors and Total Floor Area are positively correlated with annual emissions, whereas Floor Area Ratio (FAR) maintains a negative correlation with CEI. This indicates that while larger-scale commercial buildings generate higher total emissions, higher-density developments (via FAR optimization) enhance carbon efficiency per unit of GFA. Based on these findings, integrated with established research and prevailing issues within the regeneration units, the following key indicators were established.

Table 6-5: Key Regulatory Metrics for Regeneration Units
Source: Prepared by author

| Criterion Level | Indicator Level |
|---|---|
| Neighborhood Functions | Mixed-use Diversity |
| | Public Access Ratio of Street-fronting Cultural/Tourism Units |
| Energy Systems & Technology | Average Energy-Efficiency Rate for Public Buildings |
| | Thermal Demand Intensity per Unit Area |
| | Commercial Vacancy Rate |
| Infrastructure & Environment | Public Transport Station Coverage Rate |
| | Proximity to Nearest Metro Station |
| | Green Commuting Ratio |
| | Ratio of Clean-Energy Public Transit Fleet |
| Greenery Carbon Sinks | Per Capita Park Green Space in Built-up Areas |

### 6.3.3 Regulatory Standards & Strategy Formulation

At the regulatory planning scale, carbon-control metrics for the building, transport, and carbon-sink sectors are intrinsically intertwined with broader socio-economic strategic priorities, including economic viability, quality of life, and public safety. Decarbonization and resilience mandates should not supersede these core objectives or impede essential urban development[63]. Consequently, a differentiated regulatory framework is required, leveraging empirical findings and benchmarking against prevailing statutory codes. This report accounts for the internal development mechanisms and impact characteristics of indicators across various standard thresholds. For metrics governed by existing codes, we synthesized current standards; for indicators currently lacking statutory benchmarks, we introduced regulatory elasticity informed by mechanistic analysis. This process culminated in a comprehensive set of Xi'an Territorial Spatial Planning (TSP) indicators, specifying target values for both short-term and long-term planning horizons as follows:

| Criterion Level | Indicator Level | Near-Term Planning Target Value | Long-Term Planning Target Value | Indicator Attribute | Reference Standard |
|---|---|---|---|---|---|
| Neighborhood Functions | **Mixed-use Diversity** | (0.3,0.5] | (0.5,1] | Guiding | Existing Research |
| | **Public Access Ratio of Street-fronting Cultural/Tourism Units** | ≥70% | ≥70% | Guiding | LB/T 082-2021 *Classifications for Tourist and Leisure Streets*; GB/T 36309 *Classifications for Public Cultural Resources* |
| Energy Systems & Technology | Average Energy-Efficiency Rate for Public Buildings | ≥72% | ≥72% | Binding | *General code for energy efficiency and renewable energy application in buildings* GB 55015-2021 |
| | Commercial Vacancy Rate | ≤5% | ≤3% | Guiding | GB/T 39067-2020 *Public service specification for office building* |
| Infrastructure & Environment | **Public Transport Station Coverage Rate** | 100% | 100% | Binding | Guidance on green and low-carbon community construction and evaluation technology |
| | Proximity to Nearest Metro Station | < 1.2km | < 0.8km | Guiding | |
| | Green Commuting Ratio | ≥70% | ≥80% | Guiding | Green Travel Creation Action Plan<br>Xi'an Territorial Space Master Plan |
| | Ratio of Clean-Energy Public Transit Fleet | ≥55% | ≥60% | Guiding | |
| Greenery Carbon Sinks | **Per Capita Park Green Space in Built-up Areas** | [17,20] | >20 | Binding | Beijing Local Standard Urban Resilience Evaluation Guide<br>Xi'an Territorial Space Master Plan |

Figure 6-20: Regulatory Standards for the Regeneration Unit Indicator System
Source: Prepared by author

## 6.4 Ecological Units

### 6.4.1 Indicator System Architecture

The regulatory objectives for Ecological Units are anchored in optimizing plant community structures[64], enhancing biodiversity[65], and augmenting Green Volume (GV)[66]. This study designates the core regulatory axes for carbon-sink enhancement and resilience across three dimensions: Scale, Morphology, and Space Types.

Green Space Scale functions as a mediated determinant of unit-area carbon sequestration intensity. Variation in scale dictates specific planting methodologies; for instance, ecological spaces smaller than 1 ha are typically constrained to monofunctional land-use profiles prioritizing recreational aesthetics. These high-intensity zones necessitate elevated planting densities, which directly shape the community structure. Ultimately, establishing a stable and resilient community structure is the foundational requirement for optimizing systemic carbon sequestration capacity.

Green Space Morphology indirectly influences sequestration potential by governing planting design configurations. These configurations determine the complexity of multi-layered vegetative stratification, a primary driver of biodiversity. Ecological spaces that synergistically integrate high biodiversity with complex, stable community structures demonstrate significantly superior carbon sequestration performance.

Green Space Types are significantly correlated with unit-area carbon sequestration intensity. The tree-shrub-grass ratio within an ecological unit directly determines its Green Volume. As a decisive parameter in carbon modeling, Green Volume is the primary factor influencing sequestration efficiency; consequently, optimizing biomass through typological selection generates a statistically significant positive effect on overall carbon performance.

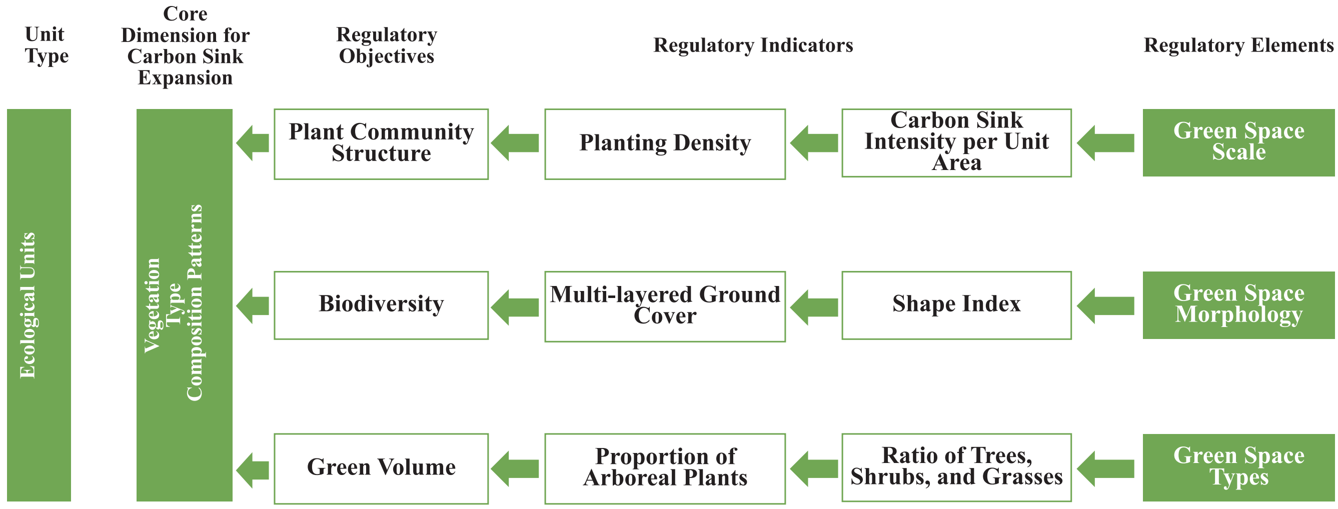



Figure 6-21: Logical Framework for the Ecological Unit Indicator System
Source: Prepared by author

### 6.4.2 Identification of Key Indicators

To determine the key determinants of low-carbon performance and resilience within Ecological Units, this study identifies critical indicators through bivariate correlation analysis, as synthesized in the following table.

Table 6-6: Key Indicator System for Carbon Mitigation and Resilience in Ecological Units
Source: Prepared by author

| Criterion Level | Indicator Level | Correlation / Impact Trajectory | |
|---|---|---|---|
| | | Total Carbon Sequestration | Carbon Sink Intensity |
| Overall Scale | Green Space Scale | Positive Correlation | Negative Correlation |
| Vegetation Type | Arbor-Shrub Coverage | Positive Correlation | Positive Correlation |
| | Arbor Canopy Coverage | Positive Correlation | Positive Correlation |

At the overall scale level, green space scale exhibits a positive correlation with total carbon sinks but a negative correlation with carbon sink intensity. Regarding vegetation typology, both Arbor-Shrub Coverage and Arbor Canopy Coverage exhibit a positive correlation with both total carbon sequestration and intensity.

### 6.4.3 Regulatory Standards & Strategy Formulation

The calibration of regulatory thresholds for Ecological Units must balance carbon-resilience objectives with site-specific ecological suitability and bioclimatic constraints governing plant growth. Consequently, leveraging the empirical insights derived from the ecological indicator framework and benchmarking against prevailing statutory codes, this report applies the dual-threshold principle: "Floor-limit compliance for mandatory constraints and ceiling-target achievement for aspirational guidelines." This approach establishes specific regulatory intervals for both short-term and long-term planning horizons, as detailed below:

| Criterion Level | Indicator Level | Near-Term Planning Target Value | Long-Term Planning Target Value | Indicator Attribute | Reference Standard |
|---|---|---|---|---|---|
| Overall Scale | Green Space Scale | [1ha, 2ha) | <1ha | Guiding | Provisional Guidelines for Pocket Park Construction |
| | Effective Emergency Refuge Area | (55%, 60%] | >60% | Guiding | GB/T 40947-2021 *Guidelines for the Evaluation of Safe and Resilient Cities* |
| Spatial Morphology | Shape Index | [1, 1.5] | >1.5 | Guiding | —— |
| Vegetation Type | Arbor-Shrub Coverage | (70%, 80%] | > 80% | Binding | Xi'an Urban Greenery Planting Design Guidelines |
| | Arbor Canopy Coverage | [60%, 70%] | >70% | Binding | |
| | Native Tree Species Coverage | (70%, 80%] | > 80% | Guiding | |

Figure 6-22: Regulatory Threshold Standards for the Ecological Unit Indicator System
Source: Prepared by author

**(1) Overall Scale**

1) Green Space Scale

The *Provisional Guidelines for Pocket Park Construction* established a scale-based classification, designating facilities between 5,000 and 10,000 m² as "Large-scale Pocket Parks." Synthesizing the preceding mechanistic analysis, the regulatory threshold for Green Space Scale is prescribed at 1–2 ha in the short term. For the long-term horizon, this is narrowed to <1 ha.

2) Effective Emergency Refuge Area

The *Guidelines for Disaster Prevention and Emergency Shelter Design in Urban Green Spaces* stipulate mandatory Effective Refuge Ratios: >60% for long-term evacuation sites, >40% for intermediate-term shelters, and >30% for immediate-response muster points. Accordingly, the Effective Refuge Provision within ecological units is established at a regulatory interval of 30%–60% in the short term, escalating to a strategic minimum of 60% in the long term to ensure peak systemic resilience.

**(2) Vegetation Typology**

The *Guidelines of Xi'an for Urban Greening Plant Configuration Design* prescribe an Arbor-to-Shrub Numerical Ratio between 1:3 and 3:7. Furthermore, Indigenous Species Composition must account for >80% of the total arboreal count. In terms of spatial coverage, the Composite Arbor-Shrub Coverage must exceed 70% of the total site area, with a mandatory Arbor Canopy Coverage of at least 60%. Consequently, the regulatory targets are established as follows: Near-term: Composite Arbor-Shrub Coverage (70%–80%), Arbor Canopy Cover (60%–70%), and Indigenous Species Ratio (70%–80%). Long-term: These benchmarks are optimized to a mandatory minimum of 80% for both composite coverage and indigenous species, with arbor canopy coverage elevated to >70%.

# 7. Conclusions and Future Work

## 7.1 Research Conclusions

Grounded in the dual principles of low-carbon development and systemic resilience, this study first delineates the transmission mechanisms for carbon mitigation and resilience within the Territorial Spatial Planning (TSP) framework. It validates the implementation pathways for Xi'an's Dual Carbon (Peak & Neutrality) targets and designates Office Sub-units in Industrial Units and Residential Units as the primary carbon-control focal points. By establishing a localized Repository of Emission and Sink Factors, this research provides a baseline characteristic analysis for Industrial, Residential, Regeneration, and Ecological units. Through bivariate correlation analysis, the critical spatial determinants were identified, forming the basis for the Indicator System Architecture tailored to each unit type. Finally, a holistic strategy framework was established, integrating sustainable spatial layouts, green building technologies, renewable energy systems, and high-capacity carbon sinks. This culminated in the proposal of Modular Strategies—categorized as either Carbon Mitigation-Dominant or Resilience-Dominant—tailored to the unique morphological and functional profiles of each unit.

**(1) Industrial Units**

1) Office Sub-units

The research scope for Office Sub-units encompasses three representative industrial parks within Xi'an: Jingwei Industrial Park, High-tech Software Park, and Information Industry Park. Among these, Jingwei Industrial Park exhibits the highest carbon emission intensity, largely driven by industrial and warehousing activities, which consequently indicates the most significant potential for decarbonization. The two innovation-oriented sub-units (High-Tech Software and Information parks) exhibit negligible variation in their carbon structural composition; however, the High-tech Software Park demonstrates superior performance in terms of carbon intensity. This study designates the mitigation of Area-based Carbon Intensity (ACI) as the core regulatory objective for Office Sub-units. Within the four established analytical dimensions—Development Performance, Built Form, Facilities & Equipment, and Greenery Carbon Sinks—Built Form was identified as the decisive assessment parameter. Based on 2023 annual carbon modeling for Office Sub-units and subsequent correlation analysis, the critical regulatory metrics are identified as: **Building Footprint Area**, **Floor Area Ratio (FAR)**, **Plot Area**, and **Plot Perimeter**. Leveraging these empirical findings and benchmarking against statutory standards, this study proposes differentiated strategies for Office Sub-units, specifically: optimizing morphological design, implementing tiered FAR regulations, and maximizing land-use efficiency.

2) Industrial Units

Jingwei Industrial Park represents a legacy industrial cluster with a diversified structure spanning petrochemicals and automotive assembly, alongside emerging sectors such as new energy and advanced machinery. Carbon emissions are primarily driven by operational building demands within industrial production, the reliance on fossil-fuel-powered heavy-duty logistics, and a critically low Green Space Ratio (GSR). These issues collectively mandate that the regulatory focus of carbon mitigation be centered on energy intensity and industrial restructuring, alongside building energy efficiency and morphological control. Future strategies must prioritize the operationalization of energy productivity and conversion thresholds. Specifically, the annual reduction rate of carbon intensity per unit of Value-Added Industrial Output (VAI) must reach a minimum of 3%, while green industries should account for at least 45% of total VAI. Furthermore, strict regulations on park scale and building morphology are required to minimize land vacancy rates and expand ecological carbon sinks. The integration of advanced energy technologies—including intelligent IoT electricity metering, unified digital energy management platforms, and integrated terminal energy supply systems—will facilitate synchronous carbon mitigation. Finally, through systematic, module-based evaluations, precise strategies can be deployed to achieve the absolute decoupling of economic growth from energy consumption.

**(2) Residential Units**

The compositional profile of carbon emissions across residential unit typologies exhibits no statistically significant variance, with built-form operational emissions constituting the dominant share of the total carbon load. However, the strategic focal points for decarbonization intensity vary across different spatial contexts: newly-built and urban renewal zones should prioritize mitigation at the architectural level, whereas legacy urban districts must emphasize transport-sector decarbonization and resilience enhancement. Guided by the dual perspective of low-carbon development and resilience, the primary regulatory objectives for residential units are defined as: intensive land utilization, spatial layout optimization, the promotion of low-carbon mobility, and the expansion of ecological sinks. The core dimension for carbon mitigation and resilience is the optimization of residential land-use proportions. To this end, a specialized regulatory toolbox has been established, incorporating key planning instruments such as: Refining land-use scales; Calibrating Floor Area Ratio (FAR) and Building Coverage Ratio (BCR); Enhancing residential block enclosure degrees; and Accelerating the integration of rail transit infrastructure. For decarbonization-led residential units, the framework proposes a dual-track planning strategy focusing on both low-carbon technological interventions and the promotion of sustainable lifestyles. For resilience-led units, the strategy prioritizes two critical dimensions: the enhancement of essential public service infrastructure and the strengthening of emergency response capacity.

**(3) Regeneration Units**

The overall compositional profile of carbon emissions within Regeneration Units exhibits no significant variance, with operational electricity consumption as the primary source. Specifically, commercial, industrial, and warehousing facilities account for high total emissions and elevated carbon intensity, identifying them as the focal points for carbon control. Regarding social and ecological resilience, cultural and tourism-related programs have diversified under the impetus of regeneration projects, yet significant development potential remains untapped. Current challenges include low public transit station coverage, inadequate emergency evacuation capacity within the road transport network, and a deficit in emergency refuge space. From a low-carbon resilience perspective, the primary regulatory objectives focus on four areas: modulating programmatic ratios, optimizing building energy consumption structures, promoting low-carbon mobility, and expanding ecological sinks. The core dimensions for carbon mitigation and resilience are programmatic mix regulation and infrastructure & environment optimization. Four strategic directions are established: Balancing decarbonization with commercial vitality to bolster social resilience; Reducing indirect building energy consumption to elevate energy efficiency; Prioritizing public transit by strengthening rail and infrastructure integration; Enhancing ecological resilience and environmental co-benefits. For decarbonization-led units, planning strategies focus on regulating commercial facility proportions. For resilience-led units, the strategy prioritizes enhancing urban safety and evacuation capacity.

**(4) Ecological Units**

Carbon sequestration sources in Ecological Units vary significantly by typology: riverfront units derive sinks primarily from tree-shrub-grass communities, whereas heritage-site units rely predominantly on lawn-type green spaces. From a low-carbon resilience perspective, the primary regulatory objectives focus on three areas: optimizing plant community structures, enhancing biodiversity, and increasing green volume (GV). The core dimension for carbon sink expansion is adjusting vegetation composition patterns. Two strategic pathways are established: Developing pocket parks to increase carbon sequestration in riverfront green spaces; Optimizing plant configurations by increasing the proportion of tree-shrub-grass layers. For sequestration-led units, the strategy emphasizes strengthening green space sequestration capacity and enriching low-carbon infrastructure. For resilience-led units, the focus is on assessing hydrological baselines and analyzing simulated inundation scenarios.

## 7.2 Future Work

Subsequent research will focus on the strategic refinement and practical scaling of this study through the following three priorities:

**(1) Construction of a Baseline Carbon Mitigation and Resilience Database for Xi'an's Urban Units.** While refining the differentiated indicator systems for typical urban units, this study will establish a comprehensive foundational database supported by systematic data harvesting. This repository will integrate building, transport, and carbon sink accounting, urban green space data, and spatial governance technical parameters. The framework will support longitudinal tracking and routine updates, ensuring the database evolves through empirical application and iterative refinement.

**(2) Formulation of Standardized, Replicable, and Scalable Carbon Mitigation and Resilience Operational Guidelines.** Aligned with climate change adaptation and Territorial Spatial Planning (TSP) objectives, this study will optimize the modular strategy toolkits for Industrial, Residential, and Regeneration Units. These efforts will culminate in standardized, replicable, and scalable Carbon Mitigation and Resilience Operational Guidelines, providing a practical reference for municipal authorities, such as the Xi'an Natural Resources Bureau and the Ecological Environment Bureau, to operationalize carbon mitigation and resilience initiatives.

**(3) Knowledge Transfer and Public Outreach: Carbon Mitigation and Resilience "Action-Oriented Factsheets."** Upon the completion of research and academic publications, findings will be translated into accessible formats for non-expert stakeholders. This involves developing Public Outreach Briefings (Action-Oriented Factsheets) to bridge the gap between researchers, industry practitioners, and the public, thereby facilitating the transformation, application, and societal promotion of carbon mitigation and resilience outcomes.

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