Inspiration for Pathways towards Multi-Scale Green Urban Regeneration and Planning Construction under Dual Carbon Goals

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Abstract
Facing climate crises, integrating green low-carbon strategies into urban regeneration proves crucial for carbon neutrality. This study examines multi-scale planning across urban agglomerations, cities, and communities through international case comparisons (US, UK, Germany, China, Japan, South Korea). Key insights: (1) Planning systems need tiered approaches - coordinating regional resources at agglomeration level, optimizing city spatial structures, and applying adaptable carbon-reduction measures locally. (2) Technology systems require ecological-industrial synergy through green corridors/renewables regionally, while focusing on microclimate improvement and green buildings locally. (3) Implementation demands multi-actor collaboration: expert committees for intercity coordination, standardised city-level frameworks, and community initiatives engaging residents and social capital. The research illustrates spatial planning's role in harmonizing economic development with ecological sustainability across spatial scales.

Keywords: Carbon peaking and neutrality goals; Multiple spatial scales; Green low-carbon regenerations; Urban planning pathways

1. Introduction

In the context of intensifying global climate change, cities, major contributors to carbon emissions (IPCC, 2022), have prioritised ecological governance and low-carbon transitions as essential pathways to achieving the "Dual Carbon" objectives of carbon peaking and neutrality. Data from UN-Habitat (2021) indicates that urban regions consume 78% of the world's energy and produce more than 60% of greenhouse gas emissions. China, undergoing one of the globe's most rapid urbanization processes, has witnessed its built-up urban area grow by over 200% since 2000 (National Bureau of Statistics, 2021). However, this expansion has amplified issues such as energy dependence, ecological fragmentation, and inadequate climate resilience, thereby demanding systematic resolutions. The 20th National Congress of the Communist Party of China underscored the importance of "coordinating industrial restructuring, pollution control, ecological conservation, and climate response," offering strategic direction for multi-scale green low-carbon regeneration.

In recent years, there have been multidimensional advancements in the field of green low-carbon urban regeneration research. At the level of urban agglomeration, Chen et al. (2021) developed a climate governance network model for European urban agglomerations, revealing nonlinear relationships between policy instruments and spatial performance. However, the applicability of this model to institutional contexts in developing countries remains unverified. At the city scale, Zhang et al. (2022) demonstrated that smart city technologies could reduce building energy consumption by 18–25% in megacities like Beijing and Shanghai, but they overlooked social equity issues in technology diffusion. Li et al. (2023) highlighted that transit-oriented development (TOD) combined with distributed energy systems could cut transportation emissions by 31% in London and Singapore, but they neglected spatial constraints in high-density built environments. For communities, Sorensen (2023) systematised Japan's Danchi regeneration model—"property rights restructuring, technological integration, and community co-creation"—showing a 42% reduction in carbon intensity through refined governance, though its transferability to land-public-ownership systems remains questionable. Marquina et al. (2024) introduced a dual-driven framework integrating low-carbon infrastructure and social capital activation in Latin American slum upgrades, but its technical solutions lack validation in temperate climates.

Despite these advancements, several critical shortcomings remain: (1) Institutional Obstacles to Cross-Scale Synergy: Most prior research has primarily centered on optimizing at a singular level. For example, Zhou et al. (2023) constructed a carbon metabolism model for the Beijing-Tianjin-Hebei region to examine industrial synergy at the regional scale. However, they did not create a vertical governance framework that connects national objectives, provincial breakdowns, and municipal execution. In another instance, Kim & Coseo (2022) introduced metrics for assessing green infrastructure performance at the community level but neglected to consider dynamic alignment with broader city-level climate goals. (2) Disparity Between Technology, Institutions, and Society: Wu et al. (2024) highlighted in the Yangtze River Delta Eco-Green Integrated Development Zone that fragmented property rights resulted in the implementation rate of technological solutions (e.g., building-integrated photovoltaics) falling below 60% of the set targets. Additionally, Schwarz et al. (2022) found that limited public engagement reduced the efficiency of technical interventions in reducing emissions by 35–50% in the Ruhr industrial heritage regeneration projects in Germany. (3) Lack of Dynamic Adaptability: Gupta et al. (2022) showed in Chennai, India, that inflexible planning approaches were inadequate in addressing monsoon-induced failures of sponge city infrastructure. Furthermore, Yigitcanlar et al. (2023) developed a digital twin platform for real-time carbon monitoring in smart cities, but its decision-making algorithms did not incorporate feedback mechanisms for policy modifications.

Practical experiences exhibit three unique "objective-tool-actor" patterns in global green low-carbon regeneration practices. At the urban agglomeration level, the EU's Climate-Neutral Smart Cities Mission adopts a "cross-border agreement + industrial enclave" model. This model connects the industrial heritage regeneration of the Rhine-Ruhr region with the hydrogen transition in the Dutch Randstad ports, forming transnational low-carbon industrial chains (European Commission, 2023). These practices suggest that regional collaboration necessitates the disruption of traditional administrative barriers through a mechanism that encompasses mutual carbon accounting recognition, ecological compensation, and technology sharing. On the city scale, New York's 80×50 Plan innovatively links Floor Area Ratio (FAR) incentives to building carbon intensity, allowing developers to gain up to 20% additional FAR by installing rooftop photovoltaics or community microgrids (NYC Mayor's Office, 2017). This policy toolkit has led to a reduction in building-sector emissions by 23% from 2010 to 2020. At the community level, Singapore's HDB Green Towns Programme integrates "physical-digital-social" spaces through vertical greening (with a 15% annual carbon sequestration increase), smart meters (resulting in 62% resident energy-saving behavior adoption), and community carbon credit systems (with over 80% participation). This demonstrates the synergy of technological rigor, institutional flexibility, and social cohesion (HDB, 2022). However, practical challenges reveal disconnects between theory and implementation. Firstly, pervasive "data silos" are a significant issue—for instance, the Yangtze River Delta's carbon monitoring platform lacks access to 40% of enterprise-level microdata, which limits AI model accuracy (Liu et al., 2024). Secondly, policy innovation often lags behind technological advancements—hydrogen pipeline planning in Germany's Ruhr region has only achieved 65% of its 2030 green hydrogen supply target due to land acquisition regulations (RVR, 2023). Lastly, social cost considerations also pose a challenge.

This study presents an analysis of representative cases, including the Yangtze River Delta and Rhine-Ruhr urban conglomerations, transitional cities such as London and Tianjin, in addition to community-level practices like Japan's Danchi regeneration. These are utilised to construct a three-dimensional "planning-technology-implementation" framework. The paper addresses three scientific queries: (1) How can multi-level spatial governance facilitate the cross-scale transmission of carbon reduction targets? (2) What technological portfolios harmonise ecological restoration with industrial development? (3) How can collaboration among multiple stakeholders guarantee the long-term operation of regeneration projects? This research not only fills theoretical gaps in multi-scale integration but also provides replicable pathways for global urban low-carbon transitions within the framework of the Paris Agreement.

2. Methods and materials

2.1 Research framework

This study's research framework is organised in the following steps (Fig.1):

1. Case Analysis: This study systematically evaluates representative cases at the urban agglomeration, city, and urban area levels, employing three key dimensions—planning system, technical system, and implementation system.

2. Comparative Synthesis: This study provides a comparative analysis of strategic characteristics and divergences across various spatial scales, drawing on case studies. The focus is on examining different planning mechanisms, technological applications, and governance approaches.

3. Strategic Framework Development: Leveraging the aforementioned analysis, we have synthesised a goal-oriented strategic framework for green, low-carbon regeneration across various spatial scales. This framework provides actionable insights, enhancing practical planning and governance efforts.

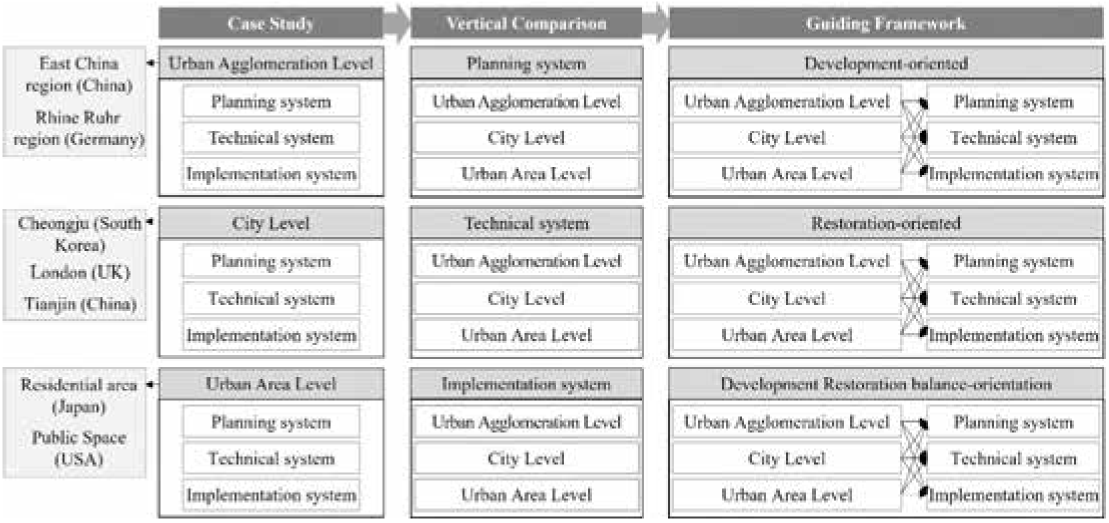

Fig. 1 Research framework

2.2 Illustrative cases of international green and low carbon regeneration efforts

This study conducts a comprehensive examination of representative cases by delving into their background, planning system, technical system, implementation strategy, and primary sources of inspiration.

2.2.1 Urban agglomeration

2.2.1.1 The Yangtze River Delta Urban Agglomeration

The Yangtze River Delta (YRD) urban agglomeration, encompassing Shanghai, Jiangsu, Zhejiang, and Anhui, represents China's most economically dynamic region, contributing 24.2% of the nation's GDP in 2023. Despite its rapid economic growth, the region faces significant carbon emission challenges. Data from the 2020 Multi-resolution Emission Inventory for China (MEIC) reveals that industrial and power sectors account for over 70% of total emissions (Liu et al., 2024). Key challenges include:

- Spatial imbalance: Emissions are concentrated in core cities such as Shanghai, Suzhou, and Hangzhou, with coastal areas exhibiting 30-45% higher emission intensity than inland regions.
- Ecological pressure: Rapid urbanization has fragmented critical ecological spaces (e.g., wetlands and forests), reducing carbon sequestration capacity by 18% since 2015.
- Policy urgency: Balancing economic expansion with dual carbon goals (peak emissions by 2030 and neutrality by 2060) requires urgent governance innovation.

(1) Planning system

To address these challenges, the YRD has adopted a dual-planning framework. First, a multi-level spatial governance system integrates cross-regional coordination at the provincial level—emphasizing ecological corridor protection and low-carbon industrial transitions through binding indicators (e.g., ≥23% forest coverage)—with localised urban-rural integration and low-carbon infrastructure development at the municipal level. Second, a spatial zoning system designates three functional areas:

- A core emission reduction zone (Shanghai-Suzhou corridor) restricting energy-intensive industries and promoting green transportation networks;
- An ecological conservation zone (southern Anhui) enhancing carbon sinks via wetland restoration;
- Carbon storage protection areas covering 30% of the territory.

(2) Technical system

The YRD employs data-driven tools, including a real-time carbon monitoring platform integrating MEIC data with transportation, energy, and land-use metrics. AI-powered scenario simulations project emission trajectories, identifying 2025 and 2028 as potential peaks under enhanced and baseline mitigation scenarios, respectively. Regional ecological networks are optimised using the InVEST model to pinpoint critical carbon sink nodes and restore blue carbon ecosystems.

(3) Implementation system
Implementation strategies combine policy innovation, industrial restructuring, and phased execution:

1. A carbon trading mechanism covering 1,200 enterprises and green finance initiatives supports market-driven decarbonization.
2. Industrial transitions target a 20% phaseout of coal-fired power plants by 2025 and promote “zero-carbon industrial parks,” achieving 70% electrification of public transport by 2030, complemented by the Ningbo-Nanjing hydrogen corridor.
3. Phased actions prioritise coal consumption control and cross-city carbon sink protection during the peak period (2021–2030), transitioning to full energy system electrification and enhanced annual carbon sequestration during the neutrality period (2041–2060).

The YRD case exemplifies a globally replicable model for megaregional decarbonization, integrating systematic planning, data-driven decision-making, and market incentives. Its innovation lies in synergizing strategic top-down design with precision technical tools, balancing economic growth with ecological security to reshape sustainable development pathways for urban agglomerations.

2.2.1.2 The Rhine Ruhr urban agglomeration
The Rhine-Ruhr metropolitan region, a polycentric urban agglomeration in western Germany anchored by Cologne, Düsseldorf, and Essen, emerged as Europe’s largest industrial hub, leaving a legacy of brownfields, ecological fragmentation, and carbon-intensive landscapes. Driven by the EU’s Carbon Neutrality 2050 target and Germany’s Federal Climate Protection Act, the region has adopted green infrastructure (GI) as a core instrument to integrate climate resilience, energy transition, and ecological restoration through multi-level planning. Key challenges include:

- Industrial brownfield regeneration;
- Cross-administrative ecological coordination;
- High-density urban regeneration.

(1) Planning system
The region integrates federal-state coordination and cross-city collaboration. At the federal level, the Spatial Planning Act establishes national ecological corridors (e.g., Rhine River), while the Federal Green Infrastructure Concept reserves renewable energy zones. North Rhine-Westphalia’s State Development Plan designates Ruhr brownfields as transition zones with ≥30% green space targets. The Regional Association Ruhr (RVR) coordinates 21 cities under the Ruhr GI Master Plan, restoring the Emscher Valley and creating a “brownfield-green core-blue network.” Cologne and Bonn jointly implement the Green Master Plan 3.0, forming a 200-km² Rhine-linked ecological network.

(2) Technical system
In terms of technical systems, three interconnected technical approaches drive transformation: Firstly, ecological network optimization through blue-green corridor restoration and brownfield regeneration. Secondly, climate-adaptive technologies leveraging GIS simulations to identify urban heat islands, enforce “cool islands” and ventilation corridors in high-risk zones, and deploy low-carbon infrastructure. Thirdly, renewable energy integration, including dedicated zones for wind/solar facilities and Europe’s largest floating photovoltaic plant on coal-mining subsidence areas.

(3) Implementation system
Effective execution hinges on innovative policy development, active public participation, and astute monitoring and evaluation.

1. Policy innovation, exemplified by an ecological compensation mechanism requiring developers to purchase “eco-credits” for green space occupation (funding cross-regional wetland restoration) and climate budgeting aligning fiscal policies with emissions targets;

2. Public engagement, combining citizen science initiatives (e.g., mapping 5,000 protected heritage trees) and corporate partnerships (e.g., ThyssenKrupp converting 10% industrial land to public green spaces for carbon trading benefits);

3. Monitoring and evaluation via a GI performance platform tracking 12 indicators (green coverage, carbon sinks, etc.) and publishing annual resilience assessments.

The Rhine-Ruhr case demonstrates how multi-level governance, nature-based solutions (NbS), and cross-jurisdictional ecological compensation can transform post-industrial regions into climate-resilient models. Its integration of legal frameworks, technical innovation, and collaborative governance offers a replicable framework for global industrial urban agglomerations pursuing green transitions.

2.2.2 City

This study examines green-low carbon regeneration practices in three representative cities: Cheongju (South Korea), London (UK), and Tianjin (China), which exemplify central urban decay, megacity decarbonization, and industrial transformation, respectively.

Cheongju, the capital of Chungcheongbuk-do, faces urban decline in its central business district (CBD) due to population loss, aging infrastructure, and traffic congestion. Initiated in 2014, the Cheongju CBD Low-Carbon Green Regeneration Project redefined traditional high-carbon urban regeneration through systemic planning and technological innovation, establishing a Korean model for sustainable regeneration. London, the first global megacity to adopt a 2050 carbon neutrality target, achieved a 40% reduction in total emissions from 1990 to 2018. However, transportation (30% of emissions) and buildings (38%) remain critical decarbonization challenges. Tianjin, a major industrial hub in northern China, recorded a carbon intensity of 0.82 tons CO∆per 10,000-yuan GDP in 2018, with fossil fuels constituting 97.4% of its energy mix (vs. China's national average of 82%), underscoring urgent energy transition pressures.

The analysis discerns context-specific challenges and contrasts strategies along three dimensions: planning systems, technical systems, and implementation systems. Key insights are succinctly synthesised (Table 1), providing valuable, transferable lessons for diverse urban environments embarking on low-carbon transitions.

Table 1. Comparative Analysis of Green-Low Carbon Urban Regeneration Strategies in Cheongju, London, and Tianjin

Aspect	Cheongju (South Korea)	London (UK)	Tianjin-China-
Key Challenges	•FAR incentives exacerbating housing affordability; mandatory affordable housing allocation. • Reliance on external carbon accounting expertise; high operational costs.	• Energy infrastructure constraints in historic districts. • Stakeholder conflicts in ZEZs implementation. • Long-term civic engagement needs.	•High costs of heavy-industry greening. •Water scarcity limiting circular economy. •Port-related freight emissions exceeding standards.
Planning Systems	• *Low-Carbon Green Growth Act* **(30% emission reduction mandate).** • TOD-driven regeneration and ecological corridor restoration.	• Three-tier system: *London Plan 2021* **designates 33 ZEZs; 15% stricter building energy standards; geothermal infrastructure planning.**	• Delineated green barrier; increased forest stock volume. • Pre-zoned offshore/onshore wind clusters; targeted non-fossil energy share. • Established industrial control lines + high-energy enterprise negative lists; phased out inefficient off-park enterprises.
Technical Systems	• Life-cycle carbon accounting (construction, transport, green spaces). • Mandatory eco-concrete, 30% BIPV coverage, hydrogen buses, rainwater recycling.	• *London Carbon Calculator Model* **(LCCM) with <5% error rate.** • Canary Wharf retrofit: Façade-integrated PV + geothermal heat pumps.	• Established a land-sea-air carbon sink monitoring network. • Piloted CCUS technology in Nangang Industrial Zone to increase CO storage volumes.
Implementation Systems	• PPP models + community-led "Low-Carbon Committees." • KETS carbon trading revenue + sub-market green bonds.	• Annual *Zero Carbon Progress Report* **(156 actions tracked).** • "Climate Action Fund" incentivizing civic participation.	• Statutory spatial planning for renewable land protection. • Tax incentives for certified low-carbon industrial parks.
Planning Insights	Demonstrates systemic "policy-space-technology-capital" integration for equitable regeneration. Highlights risks of social cost externalization in East Asian cities.	Validates "systemic policy-technology-civic governance" synergy for historic megacity transitions.	Establishes "ecological anchoring + industrial restructuring + port decarbonization" model. Proves heavy-industry cities can achieve eco-industrial symbiosis.

***Note:** TOD = Transit-Oriented Development; ZEZs = Zero Emission Zones; BIPV = Building-Integrated Photovoltaics; CCUS = Carbon Capture, Utilization, and Storage; KETS = Korea Emissions Trading Scheme.

2.2.3 The urban area

2.2.3.1 Public spaceβGreen infrastructure regeneration, US

As a high-density metropolis in the northwestern United States, Seattle faces the dual challenges of population growth and ecological conservation, including issues such as disrupted natural water cycles, intensified urban heat island effects, and uneven distribution of public spaces due to urban expansion. This study summarises the primary challenges in achieving green low-carbon regeneration of public spaces and outlines corresponding strategies across planning, technological, and implementation dimensions, as systematically presented in Table 2.

Table 2. Correspondence between Key Challenges and Systems in Seattle's Green Low-Carbon Public Space Regeneration

Key Challenges	Planning System	Technical System	Implementation System
Ecological Restoration (30% urban tree canopy by 2037)	**Macro-Micro Green Network** :• Macro: "One Core, Three Rings" framework (Central Waterfront Park, Urban Forest Ring, Neighborhood Greenway Ring, Rain Garden Ring). • Micro: Street retrofits into "Green Shared Corridors" to reduce carbon emissions.	**Nature-Based Solutions:•** Rain garden networks with "soil-plant-microbe" purification systems enhance carbon sequestration. • Smart urban forest management prioritises high-carbon-sequestration tree species.	**Cross-Department Collaboration** :• "Green Corridor Task Force" integrates road upgrades and stormwater management. • Green infrastructure (GI) integration into departmental performance evaluations.
Climate Resilience (90% stormwater facility coverage; 70% runoff pollution reduction)	**Naturalised Stormwater Management:•** Zoning based on "Infiltration Potential Maps": rain gardens (high infiltration), green roofs (medium), and underground cisterns (low).	**Digital Decision-Support Tools** :• GIS platform prioritises pocket parks in low-income areas. • Carbon footprint tracking via smart meters in public buildings.	**Policy-Financial Incentives:•** Mandatory "Stormwater Credit" purchases for developers. • Subsidies for household rain gardens and green roofs.
Social Equity (100% 5-minute park/greenway access; 50% green space equity index increase)	**Equitable Spatial Allocation** :• Neighborhood Greenways prioritise pedestrians and cyclists to reduce car dependency.	**Data-Driven Equity:•** GIS integrates demographic data to guide park distribution. • "Carbon-Neutral Corridors" enhance accessibility.	**Public Participation Mechanisms:•** "Green Home Lab" educates residents on DIY green infrastructure. • "Green Points" system rewards tree-planting with transit passes. • Participatory budgeting for funding allocation.

Seattle achieves green low-carbon regeneration of public spaces through a closed-loop framework integrating "target quantification, spatial retrofitting, technological modularization, and governance empowerment." The application of innovative technologies and broad societal participation serve as essential enabling conditions for the successful implementation of this initiative.

2.2.3.2 Residential area: Danchi regeneration, Japan

Japan has pinpointed the renovation of aging residential areas as a crucial component of low-carbon urban development. A prime example of this is the "Danchi Regeneration," primarily focused on centralised public residential areas constructed post World War II. This paper outlines the primary challenges encountered in this practice and pairs them with the corresponding strategies from the planning system, technical system, and implementation system. This pairing offers an intuitive understanding of the project's status (Table 3).

Table 3. Correspondence between Key Challenges and Systems in Danchi Regeneration

Key Challenges	Planning System	**Technical System**	**Implementation System**
Building Aging & High Carbon Emissions	Legal framework: The Low-Carbon City Promotion Act (2012) mandates emission reduction targets for old residential areas.	Building energy retrofitting: KSI housing system extends building lifespan to 100 years; solar power and ground-source heat pumps reduce carbon emissions.	Property-function replacement mechanism: Government retains public facility ownership; commercial land leases fund low-carbon retrofitting.
Community Aging & Declining Vitality	Specialised planning: Links with national plans to align spatial strategies (e.g., job-housing balance) with social sustainability goals.	/	Community co-creation: Resident participation in shared facilities (e.g., "community flower beds") lowers costs; elderly-friendly housing improves demographic balance.
Inefficient Land Use	Specialised planning: Promotes Transit-Oriented Development (TOD) to optimise land use.	Eco-restoration technologies: Permeable paving and 3D greening reduce heat island effects by 60%.	Chain-style regeneration: Phased relocation, FAR incentives, and reserved land for green spaces/public facilities enhance land efficiency.
Financial & Technical Bottlenecks	Independent management agency: UR Agency coordinates stakeholders and integrates cross-sector resources.	Resource recycling: 90% construction waste reuse; on-site composting reduces external resource dependence.	Green Bank platform: Social capital bids for low- carbon technology applications, balancing public subsidies and private investment.

Japan's "Danchi Regeneration" demonstrates that green regeneration of aging residential areas necessitates "institutional frameworks as the foundation, technological innovation as the tool, and community engagement as the core." By adopting refined planning, whole-process technological integration, and inclusive governance , this approach achieves carbon neutrality goals and provides a replicable paradigm for global low-carbon community development.

3. Results

This study performs a comprehensive analysis of representative cases across various spatial scales, aiming to delineate the common strategic features of green and low-carbon regeneration strategies within each spatial hierarchy. These strategies are examined in relation to three core systems: planning, technical, and implementation systems. Additionally, a vertical comparison is conducted to illuminate the distinct methodologies employed at different scales.

3.1 Comparative analysis of planning system

One strategic commonality across spatial scales is the adoption of multi-scale collaborative governance. Yet, there are strategic differentiations among spatial hierarchies. Urban agglomerations resolve scale mismatches with transboundary agreements and scenario modelling. Cities use statutory instruments for regulatory enforcement. Districts deploy metric-based spatial controls (Fig 2).

In urban agglomerations, planning for green and low-carbon regeneration is facilitated by a three-tiered governance framework that amalgamates national directives, regional coordination, and local implementation. Insightful case studies from the Yangtze River Delta and Rhine-Ruhr demonstrate clear organizational roles:

(1) National or Federal Policy Agencies, such as China's Ministry of Natural Resources and Germany's Federal Ministry for the Environment, establish overarching targets like carbon neutrality and provide funding for cross-regional projects; (2) Regional Coordination Bodies, for example, the Yangtze River Delta Integration Office and the Rhine-Ruhr Regional Association, arbitrate intercity infrastructure coordination tasks such as renewable energy grids and resolve jurisdictional disputes; (3) Provincial or State Governments translate national objectives into actionable plans, illustrated by Zhejiang's low-carbon industrial clusters and North Rhine-Westphalia's coal phaseout roadmap.

The implementation of the operational workflow involves three consecutive steps: (i) policy formulation, (ii) regional planning, and (iii) real-time monitoring. The federal/national level legislates emission reduction targets through climate protection acts that provide binding regulatory frameworks. Regional authorities develop spatially explicit action plans (e.g., renewable energy corridors) to ensure that the targets are met in line with local ecological and socioeconomic conditions. Multi-stakeholder working groups use common databases (e.g., GIS-based emission inventories) for implementation, monitoring and dynamic adjustment of strategies. The federal government provides legislation and financial instruments (e.g., carbon pricing) and regional authorities coordinate resource allocation. Local authorities implement site-specific projects (e.g., retrofitting green infrastructure) that link strategic objectives with their practical implementation on the ground. This hierarchical and integrated approach ensures vertical policy coherence while allowing for regional flexibility.

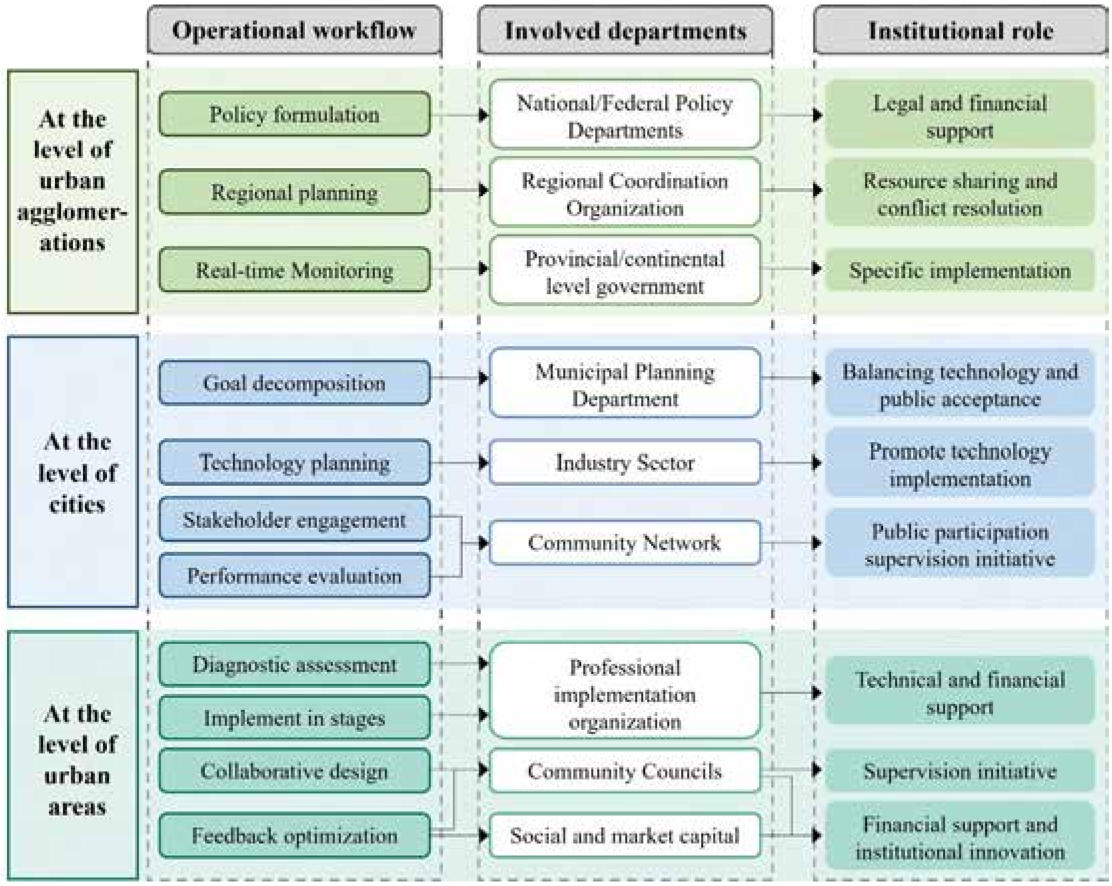

Fig. 2 Planning Processes Across Different Spatial Scales: Involved Departments and Their Roles

City-scale planning places a significant emphasis on cross-sectoral integration. Municipal authorities, such as the Greater London Authority, are responsible for formulating citywide strategies, such as the London Environment Strategy 2050. In contrast, sectoral departments like transport and energy are tasked with implementing domain-specific measures, such as Ultra-Low Emission Zones. Community networks, such as Sejong's Green Citizen Committees, serve to institutionalise participatory decision-making processes, including rooftop solar adoption. The urban planning workflow is comprised of four iterative phases: (1) the decomposition of national climate objectives into local targets; (2) the development of context-specific technical solutions, such as smart grids; (3) the embedding of social equity through stakeholder engagement, such as co-creation forums; and (4) progress tracking through digital platforms, such as IoT-enabled monitoring. This structured approach requires a delicate balance: municipal governments must reconcile technical feasibility with public acceptability, sectoral departments must drive innovation, and communities must ensure compliance with sustainability mandates.

In urban area-scale regeneration, tactical interventions are prioritised through the collaboration of multiple stakeholders. Specific agencies, such as Japan's UR Urban Renaissance Agency, oversee the entire project cycle, ranging from diagnostics to post-occupancy evaluations. Community councils like Tokyo Neighborhood Associations engage in co-designing solutions, such as energy-efficient retrofits. Meanwhile, private partners, including Mitsui Fudosan, offer their expertise and financial support, often through public-private partnership (PPP) models. The district-scale workflow is cyclical: (1) technical audits pinpoint vulnerabilities like aging infrastructure; (2) phased implementation reduces disruption by offering incremental upgrades, such as modular housing; (3) participatory workshops ensure that technical solutions align with socio-cultural priorities, including heritage preservation; and (4) the use of IoT sensors and post-occupancy surveys facilitates iterative refinements. Implementation agencies maintain technical rigor via lifecycle cost-benefit analyses, residents ensure social inclusivity via feedback mechanisms, and private stakeholders incorporate scalable technologies like prefabricated green systems. This holistic approach harmoniously blends technical precision with community adaptability in intricate regeneration scenarios.

3.2 Comparative analysis of technological system

Data-driven and modular technologies are amalgamated to establish a comprehensive hierarchical framework, spanning macro-scale simulation, meso-level integration, and micro-scale measurement. The prioritization of innovation varies across different spatial hierarchies: Urban agglomerations emphasise systemic interconnectivity. Cities have prioritised sectoral deep decarbonization, while urban areas are adopting replicable near-zero-carbon modules.

Carbon reduction strategies, when viewed across different spatial scales, exhibit hierarchical differentiation in their choice of indicators (Table 6):

Table 6. Multi-scale Carbon Emission Assessment: A Synthesis of Evaluation Dimensions and Indicators Across Spatial Hierarchies

Spatial Level	Indicator Category	Specific Indicator	Indicator Description
Urban Agglo-mera-ti-on **Level**	Energy Structure Optimization	Carbon emission intensity of industrial sectors (tons/10,000 CNY GDP)	Carbon emissions per unit of industrial output, reflecting the low-carbon transition level of industrial structure.
	Industrial De-car-bonization	Annual carbon reduction rate of ener-gy-intensive industries (%)	Annual carbon emission reductions in traditional industryies (e.g., steel, chemicals) through technological upgrades.
	Energy Networ-k Integration	Compatibility rate between renewable energy generation and grid stability (%)	Synergy between variable renewable energy (e.g., wind, solar) and grid peak-shaving capacity.
	Carbon Sink Ca-pacity	Total annual carbon sequestration in ecological spaces (mill-ion tons CO/year)	Annual carbon sequestration by forests, wetlands, and other ecological areas.
	Transportation Synergy	Intercity railway coverage rate (%)	Proportion of cities within the agglomeration connected by high-speed rail or intercity rail networks.
	Regional Carb-on Trading	Cross-city carbon quota tradin-g vol-ume (million tons/year)	Annual carbon quota transactions in regional markets, reflecting emission reductions driven by market mechanisms.

City Level	Ecological Agr-i-culture	Blue-green space ratio (%)	Proportion of water bodies (blue) and green spaces (forests, parks) in total urban land area.
		Forest stock volume (10,000 m³/ha)	Carbon storage per unit of forest area, indicating carbon sink capacity.
		Chemical fertiliser application intensity (kg/ha)	Fertiliser use per unit of agricultural land, reflecting efforts to reduce agricultural non-point source pollution.
	Energy Resou-rces	Share of locally generated renewable energy (%)	Proportion of renewable energy (e.g., wind, solar) in total energy consumption.
		Coverage rate of distributed energy supply centers (%)	Proportion of urban areas served by decentralised energy systems (e.g., combined heat and power plants).
		Installed solar PV capacity (MW)	Total solar power capacity installed on rooftops and vacant urban land.
		Coverage rate of district heating networks (%)	Proportion of urban areas served by low-carbon heating systems (e.g., waste heat recovery, geothermal).
	Industrial Deve-lopment	Proportion of value-added from strategic emerging industries in GDP (%)	Contribution of low-carbon industries (e.g., new energy, energy efficien-cy) to economic output.
		Reduction rate of energy-inten-sive enterprises (%)	Proportion of high-emission enterprises phased out through industrial restructuring.
	Transportation	Public transport modal share (%)	Proportion of trips made via metro, buses, and other green transit modes.
		Share of new energy vehicles (NEVs) in total vehicles (%)	Proportion of electric or hydrogen-fueled vehicles in the urban fleet.
		Bicycle lane density (km/km²)	Length of dedicated bicycle lanes per unit area, promoting non-motorised travel.
	Resource Circu-larity	Waste recycling and reuse rate (%)	Proportion of municipal solid waste and industrial by-products recycled or repurposed.
	Carbon Peak Tar-gets	Reduction rate of total carbon emis-sions relative to peak year (%)	Percentage reduction in total emissions by 2035 compared to the peak year (2005). Example: 5% reduction by 2035.
	Green Infrastru-cture	500-meter coverage rate of parks and green spaces (%)	Proportion of residential areas within a 500-meter walking distance of parks or green spaces.
	Building Energy Efficiency	Retrofitting rate of existing buildings (%)	Proportion of buildings upgraded with energy-saving measures (e.g., insulation, high-efficiency equipment).
	Building Decarbo-nization	Utilization rate of eco-friendly con-struction materials (%)	Proportion of low-carbon materials (e.g., recycled concrete) used in building construction.
Urban Area Level	Environmental Performance	CASBEE Community BEE Score (1–5)	Comprehensive assessment of environmental efficiency (BEE = Q/L), where Q = environmental quality and L = environmental load.
	Carbon-Neutral Communities	Number of certified carbon-neutral communities	Communities meeting standards for zero-carbon buildings and 100% renewable energy adoption.
	Energy Self-Suffi-ciency	Community renewable energy self-suf-ficiency rate (%)	Proportion of energy demand met by localised renewables (e.g., rooftop solar, geothermal).
	Resource Circu-larity	Greywater reuse rate (%)	Proportion of treated domestic wastewater reused for irrigation, toilet flushing, etc.
	Social Equity	Coverage rate of elderly-friendly facilities (%)	Proportion of residential units with age-friendly infrastr-ucture (e.g., barrier-free access, community clinics).
	Stormwater Ma-nagement	Permeable pavement coverage rate (%)	Proportion of paved surfaces using permeable materials to reduce runoff and enhance water infiltration.
	Biodiversity	Ecological corridor connectivity index (0–1)	Connectivity of green and blue spaces based on GIS n-etwork analysis (0 = fragmented, 1 = fully connected).
	Low-Carbon Buildings	Green roof coverage rate (%)	Proportion of building rooftops covered with vegetation to reduce ur-ban heat island effects.
	Low-Carbon Transportation	Share of new energy public transit routes (%)	Proportion of bus routes operated by electric or hydrogen-powered vehicles.

Urban agglomerations prioritise regional energy-industrial coordination and infrastructure-policy synergies. The Rhine-Ruhr region, for instance, exemplifies renewable energy-grid compatibility, such as wind-solar-grid matching rates, and engages in cross-border carbon trading to diminish industrial carbon intensity, particularly in sectors like steel and chemicals. These approaches tackle overarching challenges, such as energy network externalities, using collective metrics like carbon sink capacity and emission reduction ratios.

Cities are increasingly adopting multidimensional governance structures and localised transition strategies. For example, both Tianjin and London strive to balance economic growth with decarbonization objectives. They do this by maintaining blue-green space ratios of 30%, ensuring renewable energy self-sufficiency, and aiming for public transport modal shares of 40%. Their policy toolkits encompass incentives for green building and phased withdrawals from polluting industries, bolstered by moderate-granularity data such as CO∆ emissions per unit of GDP.

In urban areas, technology-driven and resident-centric solutions are implemented. For instance, Japan's Danchi Regeneration and Seattle's green infrastructure projects use metrics such as per-meable pavement coverage (≥20%) and CASBEE community BEE scores (1–5) to gauge their performance. These initiatives seamlessly combine low-carbon technologies, like rooftop solar PV, with social equity measures, such as elderly-friendly facilities, and climate resilience strategies.

The hierarchical structure unveils a scalar transition from comprehensive systemic coordination to focused local action. In this context, national strategies, such as carbon markets, establish broad parameters that are then refined into city-specific objectives. These, in turn, cascade into precise community technical standards. Employing a nested governance model ensures complementarity across scales, harmonizing macro-level assessments with micro-level execution.

3.3 Comparative analysis of implementation system

Governance transitions have moved from bilateral relations between governments and markets (e.g., carbon trading in industry) to triadic relations that include civil society. Parallel to this, decision-making has shifted from strategic dominance to adaptive learning in iterative processes. The strategic differences across spatial hierarchies are as follows: Urban agglomerations focus on cross-border policy innovations for sustainability. Cities adopt market-based strategies to address financing issues.
Urban communities have been the vanguard of community-based instruments.

This study delves deeper into the analysis of disparities concerning green-low carbon transitions at various spatial levels. It does so by integrating perspectives from multiple stakeholders and employing mechanisms that balance interests (Fig. 3).

In urban conglomerations, coordination among multiple actors is underscored by cross-jurisdictional governance and industrial symbiosis. Collaboration between national/regional agencies, energy/manufacturing alliances, and research institutions is facilitated through legally binding frameworks, such as carbon trading, and shared infrastructure like renewable grids. The Rhine-Ruhr Metropolitan Association manages land-use zoning and sets emission caps, whereas East China utilises fiscal transfers to strike a balance between ecological conservation and industrial expansion. Interregional competition for resources is alleviated by compensation mechanisms, including carbon-sink subsidies, and technology-sharing platforms.

In cities such as Cheongju, London, and Tianjin, local governments use regulatory tools (e.g., low-emission zones) and public-private partnerships to steer markets toward sustainability, with planning/environmental departments, developers, utilities, and citizen assemblies often being key actors. For example, London's Ultra Low Emission Zone (ULEZ) sets stringent emission standards but provides subsidies for green retrofits. Meanwhile, Tianjin Eco-City incorporates resident input on green infrastructure design through digital platforms. To address conflicts between economic efficiency (e.g., developer profits) and equity (e.g., affordable housing), hybrid financing (e.g., green bonds) and community benefit agreements (CBAs) are used to ensure equitable distribution of benefits.

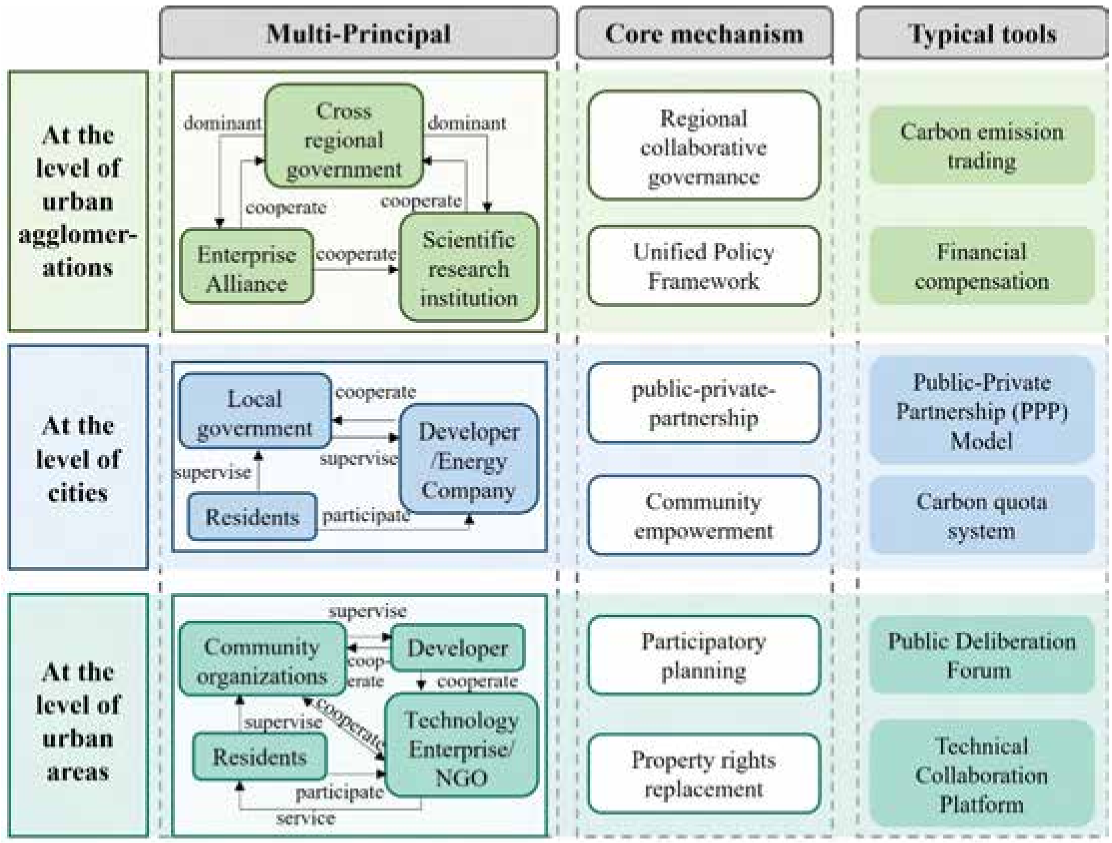

Fig. 3 Implementation Mechanisms Across Spatial Scales: Multi-Actor Interactions and Collaborative Dynamics

In urban areas, coordination among various actors is primarily focused on localised participation and micro-institutional innovation. The driving forces behind outcomes are resident committees, non-governmental organizations (NGOs), technical providers, and municipal agencies. For instance, Japan's UR Urban Agency restructures property rights in Danchi regeneration by compensating displaced residents with shared green spaces. Similarly, Seattle's grassroots organizations co-design rain gardens and pedestrian networks through citizen workshops. Land-use disputes are typically resolved through negotiated trade-offs, such as density bonuses for green roofs, and decentralised decision-making processes, thereby ensuring hyper-local legitimacy. In summary, the main features that distinguish hierarchies are as follows:

- Governance Authority: Urban agglomerations rely heavily on supranational frameworks, such as EU directives, while urban areas give precedence to community self-organization.
- Conflict Resolution: Macro-level conflicts are resolved utilizing economic tools such as carbon pricing. However, micro-level conflicts require social negotiations, for example, through the implementation of participatory budgeting.
- Actor Power Dynamics: Corporations exert a dominant influence on the agendas of city clusters, whereas non-governmental organizations (NGOs) and residents are pivotal in determining outcomes at the district level.

This structured synthesis illuminates the way spatial hierarchies shape stakeholder roles, institutional adaptability, and conflict resolution mechanisms during green-low carbon transitions. It offers concrete insights for the development of multi-scalar governance.

4. Discussion

4.1 Development-Restoration Balanced Strategies Across Scales

Green low-carbon regeneration is intrinsically connected to the strategic positioning of regional and urban development. It serves a dual purpose: the first aims to bolster urban sustainability via development-oriented interventions, and the second seeks to rehabilitate high-carbon-emission spaces that threaten urban resilience, grounded in restoration-oriented priorities. These contrasting development orientations give rise to distinct strategic methodologies. Consequently, this study classifies strategies into three distinct typologies—development-oriented, restoration-oriented, and development-restoration balanced approaches—to cohesively summarise a multi-scale green low-carbon regeneration framework, thereby providing practical insights applicable to various spatial contexts (Fig.4).

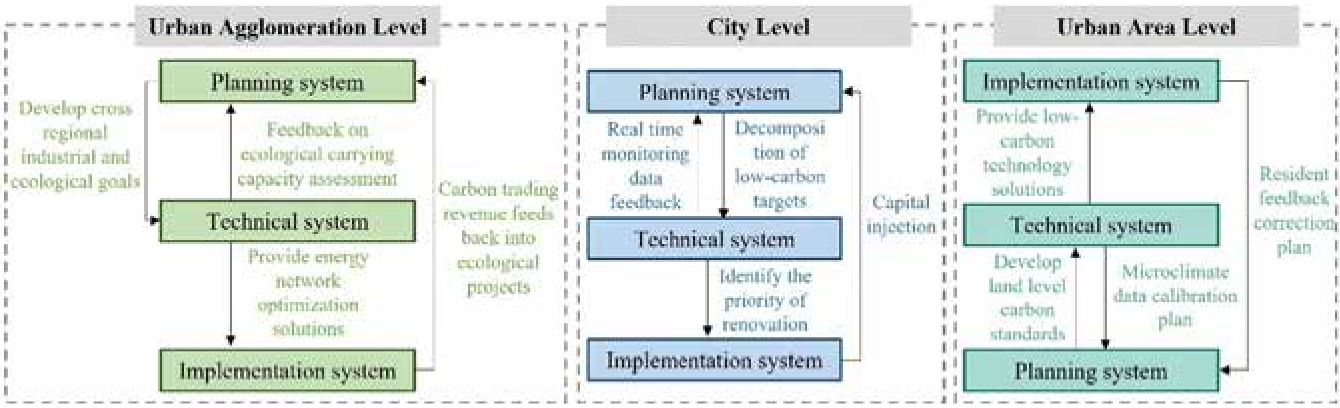

Fig. 4 Interaction mechanisms among multi-scale planning, technical, and implementation systems

4.1.1 Urban Agglomeration Level

(1) Planning system

- Development: The establishment of cross-regional renewable energy corridors and low-carbon industrial clusters is proposed as a strategy to decouple economic growth from emissions (Lin et al., 2022). Furthermore, the integration of "sponge city" principles into regional flood-resilient infrastructure planning is advocated (Yang et al., 2024).
- Restoration: Utilise circuit theory to design ecological security patterns, aiming to reconnect fragmented habitats and establish carbon sink protection redlines that encompass at least 30% of the territorial area (Liu et al., 2024).
- Integration: The implementation of a dual-control zoning system serves to strike a balance between industrial decarbonization and nature-based carbon sequestration (Bao et al., 2022).

(2) Technical system

- Development: Deploy AI-powered carbon accounting platforms for real-time monitoring of cross-border industrial emissions (error rate <5%) (Feng et al., 2022). Optimise multi-energy complementary systems (e.g., wind-PV-hydrogen storage) to achieve ≥75% renewable penetration (Wang et al., 2018).
- Restoration: Apply InVEST habitat quality models to prioritise wetland restoration sites and quantify carbon sink gains (Liu et al., 2024).
- Integration: Develop GIS-based conflict maps to resolve land-use disputes between energy facilities and protected areas (Sanchez et al., 2018).

(3) Implementation system

- Development: Initiate cross-city carbon trading markets and establish green finance hubs to facilitate funding for low-carbon transitions (Lin et al., 2022).
- Restoration: The implementation of ecological compensation mechanisms is proposed, whereby developers are required to finance off-site conservation efforts for greenfield occupation (Bao et al., 2022).
- Integration: Establish multi-stakeholder committees to synchronise industrial policies with biodiversity objectives (Xiong et al., 2021).

4.1.2 City Level

(1) Planning system

- Development: Implement transit-oriented development (TOD) mandates and 15-minute city frameworks with the objective of reducing transportation emissions by 40% (Deakin et al., 2012).
- Restoration: The process of restoring urban ecological networks and ensuring the implementation of 35%

blue-green space ratios within masterplans is imperative (Haase, 2024).

- Integration: The application of circular economy zoning is proposed as a strategy for co-locating waste recycling hubs within industrial parks, thereby enhancing sustainability (Jiang, 2024).

(2) Technical system

- Development: Enhance district heating networks through the integration of waste heat recovery systems, and ensure a minimum of 50% solar PV coverage on public buildings (Wang et al., 2015).
- Restoration: Utilise microclimate simulation tools, such as ENVI-met, to conceptualise urban forest designs capable of mitigating heat island intensity by 2–3°C (Sanchez et al., 2018).
- Integration: The process involves the creation of digital twins with the primary objective of optimizing the management of the energy-water-food nexus (Xiong et al., 2021).

(3) Implementation system

- Development: Implement carbon intensity quotas for industries and associate municipal bonds with green certification (Jiang, 2024).
- Restoration: The establishment of community land trusts is proposed as a strategic measure to safeguard green spaces against the encroachment of gentrification (Bouzarovski et al., 2018).
- Integration: Implement participatory climate budgeting to ensure congruence between fiscal policies and the priorities of citizens (Deakin et al., 2012).

4.1.3 Urban Area Level

(1) Planning system

- Development: Establish net-zero building codes and implement TOD-oriented land readjustment strategies (Wang et al., 2015).
- Restoration: The implementation of biophilic street design standards, such as having a minimum of 25% permeable surfaces and the use of native tree planting, can significantly enhance biodiversity (Sanchez et al., 2018).
- Integration: Utilise form-based coding techniques to align green infrastructure development with heritage preservation (Haase, 2024).

(2) Technical system

- Development: Scale building-integrated photovoltaics (BIPV) and shared energy storage systems to achieve 100% renewable energy blocks (Jiang, 2024).
- Restoration: Implement modular green walls and rainwater harvesting systems to decrease potable water consumption by 30% (Sanchez et al., 2018).
- Integration: Utilise IoT-enabled smart meters to monitor real-time carbon footprints of households and distribute green subsidies fairly (Bouzarovski et al., 2018).

(3) Implementation system

- Development: Provide tax rebates for environmentally friendly retrofits, such as a 20% reduction for the adoption of Building Integrated Photovoltaics (BIPV), and award density bonuses for affordable housing located near transit hubs (Wang et al., 2015).
- Restoration: The institutionalization of co-design workshops is recommended as an effective strategy for engaging marginalised groups in the planning process of green spaces (Bouzarovski et al., 2018).
- Integration: Establish eco-friendly asset management platforms to generate revenue from carbon savings and finance community initiatives (Jiang, 2024).

4.2 Theoretical Contributions and Innovations

This study advances existing literature in three dimensions:

1. Multi-Scale Vertical Comparison: Previous research has primarily centered on interventions at a singular scale, such as community-level Nature-based Solutions (NbS) (Wang et al., 2015) or city-level policy integration (Feng et al., 2022). In contrast, this study elucidates scalar interdependencies, showcasing how urban agglomeration carbon markets facilitate city-scale industrial transitions that subsequently finance district-level retrofitting. This addresses the pervasive “scale mismatch” criticism in sustainability governance (Haase, 2024).

2. Systemic Multi-Dimensional Framework: Differing from sector-specific analyses, such as energy systems (Lin et al., 2022) or social equity (Bouzarovski et al., 2018), this research amalgamates planning, technical, and implementation systems into a unified matrix. The Rhine-Ruhr case exemplifies this approach, showcasing how federal spatial planning (planning system) collaborates with regional GIS tools (technical system) and eco-credit mechanisms (implementation system) to realise comprehensive decarbonization.

3. Dual-Objective Strategy Framework: Previous research has predominantly focused on either growth-oriented strategy, such as green gentrification (Bao et al., 2022), or conservation-centric approaches like ecological restoration (Liu et al., 2024). This study offers a comprehensive strategy framework that harmonises both objectives. For instance, Tianjin's "ecological anchoring + port decarbonization" model concurrently promotes the upgradation of heavy industries (development) and the restoration of coastal wetlands (restoration), effectively addressing the dichotomy between economic progression and carbon neutrality (Xiong et al., 2021).

5. Conclusion

This study addresses urban ecological governance under climate change, exploring multi-scale green regeneration pathways aligned with Dual Carbon Goals. Through comparative analysis of urban agglomerations, cities, and communities across six nations, three key insights emerge: (1) A multi-tiered governance framework enables strategic carbon management – coordinating regional resource allocation (agglomeration scale), optimizing spatial structures (city scale), and implementing adaptive mitigation (community level). (2) Technical systems require horizontal integration of ecological restoration, industrial decarbonization, and smart governance, balancing anthropogenic-ecological synergies regionally while enhancing microclimates and green buildings locally. (3) Implementation necessitates policy-market-society coordination: expert committees for cross-regional evaluation, standardised planning protocols, and participatory models leveraging social capital. The research proposes a tripartite framework integrating planning, technical, and implementation systems, resolving fragmentation in traditional approaches through cross-scale carbon accounting and multi-stakeholder mechanisms. These findings advance sustainable urban theory and offer actionable strategies for cities at varying development stages to achieve low-carbon transitions.

This study also has two limitations. First, geographical coverage bias: the cases are concentrated in East Asia (China, South Korea, Japan) and Europe (Germany, UK), and lack representation from cities in the Global South which face distinct challenges (e.g., informal settlements in Africa). Future studies could expand the database with cases from São Paulo's favela electrification programs or Nairobi's slum-upgrading initiatives to enhance generalizability (Sanchez et al., 2018). Secondly, there are significant gaps in dynamic adaptation. The current framework prioritises static spatial strategies while neglecting the importance of temporal resilience. For instance, it reviews the phased coal phaseout in the YRD region compared to abrupt policy shifts. The inclusion of adaptive pathway methodologies such as climate-responsive zoning could enhance strategic flexibility (Yang et al., 2024).

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