Spatial Heterogeneity and Village Reclassification for Low-Carbon Transition: A Multi-scale Typology Framework in China

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Abstract

To address China's dual-carbon goals in rural cold zones, this study proposes a multi-scale classification framework for village redevelopment, with empirical focus on the North China Plain. Provincial housing datasets subjected to machine learning clustering reveal three distinct village prototypes differentiated by infrastructural capacity, policy alignment, and technological adoption levels. Geospatial analysis reveals concentrated technology-adoption hotspots in prosperous eastern zones, exhibiting distinct developmental hierarchies, while infrastructure-deficient villages aggregate in northern ecologically fragile zones with elevated seismic risks and incomplete retrofitting. Transitional zone settlements demonstrating policy alignment show regulatory adherence deficiencies that contradict their partial modernization achievements, revealing institutional inertia in adapting national standards to local contexts. Empirical linkages connect deficient regulation implementation, outdated construction materials, and residential emission profiles through causal analysis, advocating for circular economy integration in advanced zones and blockchain-enabled quality tracking in lagging regions. Spatially differentiated governance strategies target northern bioclimatic upgrades and eastern intelligent energy networks for emission reduction prioritization—this framework bridges rural revitalization with climate resilience. The findings challenge deterministic development models, emphasizing adaptive policy calibration to reconcile ecological thresholds with equitable progress in emerging economies.

Keywords: rural housing construction, village classification, machine learning

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Introduction

The decarbonization of rural built environments has emerged as a critical frontier in global climate governance, particularly for emerging economies navigating the dual imperatives of equitable development and planetary boundary compliance. China's pursuit of carbon peaking and neutrality—a policy agenda codified in its Nationally Determined Contributions—has exposed systemic tensions between rural modernization pathways and their unintended climatic externalities. China's rural housing stock contributes substantially to national carbon inventories, with legacy fossil-dependent thermal regulation systems and climate-mismatched vernacular architectures amplifying emission intensities. In cold zones, where suboptimal thermal performance amplifies household energy demands, rural per capita emissions exceed urban equivalents by a factor of 2.3, underscoring the urgency to reconceptualize housing systems as dynamic socio-technical networks rather than static physical assets.

Prevailing analytical frameworks inadequately address the co-evolution of rural housing materiality with place-specific developmental trajectories. Remote sensing-derived typologies, while effective in cataloging spatial distributions of building materials, often neglect the institutional path dependencies engendered by historical policy interventions. Provincial datasets reveal a paradoxical divergence between regulatory achievements and emission trajectories: Regions achieving high earthquake regulation adherence ($\geq 80\%$) show limited penetration of energy-saving renovations ($< 30\%$) in comparative analysis, reflecting misaligned incentives between safety mandates and climate objectives. Such disconnects underscore the need for multi-scalar methodologies that reconcile material stock dynamics with governance hybridity and lifecycle carbon accounting.

This investigation focuses on China's cold climatic zones, where frost-related structural vulnerabilities intersect with elevated heating demands to intensify the carbon-intensity of rural habitats. Grounded in a unique dataset across 126 counties, the study advances a machine learning-driven typology framework that transcends conventional weighted-index models. By applying k-shape clustering to 11 indicators spanning material resilience, energy transition, and regulatory efficacy, the analysis captures nonlinear interactions between policy-sensitive variables and contextual constraints. Analytical frameworks expose how infrastructure renewal successes can coincide with renewable technology stagnation when budgetary allocations compete—a pattern obscured by normative assessment paradigms.

Theoretical contributions emerge in redefining emission mitigation as a process of institutional-material co-evolution, where adaptive governance must reconcile technical standards with socioecological realities. Research outcomes contest linear development paradigms by revealing path-dependent constraints from past policy interventions. Practically, the framework equips policymakers with diagnostic tools to align spatial governance with typology-specific decarbonization leverage points, prioritizing bioclimatic retrofitting in ecologically fragile zones and smart grid deployment in industrializing corridors.

Materials and Methodology

Data Sources and Indicator System

The empirical foundation of this research stems from a multi-year, nationally coordinated survey initiative designed to capture the evolving dynamics of rural housing systems across China's heterogeneous climatic and socioeconomic landscapes. Sampling methodology covered 126 counties, ensuring proportional representation of geographic diversity, developmental gradients, and policy implementation contexts. This methodological architecture systematically integrates institutional statistical records, household-level perceptual surveys, and geospatial audits to triangulate multidimensional assessments of housing safety protocols, regulatory adherence, and modernization trajectories.

An analytical framework comprising 11 validated indicators was developed through iterative consultation with provincial construction authorities and interdisciplinary expert panels. Building structural integrity was quantified using earthquake regulation adherence rates, dangerous residence renovation metrics, and poverty-alleviation housing upgrade statistics. Regulatory robustness assessments quantified standardized design adoption frequencies, construction approval adherence rates, and artisan certification ratios, exposing systemic discrepancies between procedural formality and substantive quality oversight. Development progression was assessed through sanitation access rates and energy-saving renovation completion metrics, and clean energy utilization percentages, with spatial variance attributed to climatic exigencies and localized cultural practices.

Methodological integration of machine learning-driven clustering techniques enabled granular dissection of latent development patterns obscured by conventional weighted-index models. This approach transcended heuristic categorization by exposing nonlinear interactions between policy-sensitive variables and contextual constraints, particularly the inverse relationship between seismic code enforcement rigor and renewable energy adoption rates in transitional economic corridors. The resultant framework establishes a diagnostic-prognostic tool for spatially adaptive policy formulation, aligning technical interventions with regionally embedded carbon mitigation potentials.

Methodology and K-shape Clustering

This investigation advances analytical rigor through time-series clustering, systematically decoding spatiotemporal variances in rural housing evolution. Unlike conventional clustering paradigms that prioritize static feature similarity, the k-shape algorithm was specifically leveraged for its capacity to dissect multidimensional developmental trajectories through dynamic time warping (DTW)-optimized centroid computation. This approach proved indispensable given the non-stationary nature of rural housing transitions, where asynchronous policy implementation cycles and regionally divergent modernization velocities generate nonlinear interactions between structural resilience, regulatory compliance, and energy transition indicators. Algorithm validation using silhouette analysis (maximum score 0.3429) demonstrated effective cluster differentiation through statistical verification, a critical advantage when confronting high-dimensional datasets characterized by collinear policy-sensitive variables.

The k-shape paradigm's unique suitability for this investigation stemmed from three synergistic attributes: First, its DTW-optimized distance metric accommodated asynchronous

progressions in housing modernization metrics—such as delayed seismic retrofitting relative to clean energy adoption—that conventional Euclidean measures would misinterpret as categorical dissimilarities. Second, the algorithm's invariance to variable scaling proved vital in harmonizing disparate measurement units across construction quality indicators, from percentage-based compliance rates to ordinal material resilience rankings. Third, its capacity to identify phase-shifted similarities enabled detection of regionally divergent yet structurally analogous development trajectories, such as northwestern counties achieving equivalent modernization outcomes through alternative sequences of policy interventions. By transcending the limitations of conventional cross-sectional clustering, this approach advanced rural housing analysis from static typology generation to dynamic pathway characterization—a paradigm shift essential for aligning decarbonization strategies with place-specific institutional and material evolution rhythms.

Results and Discussion

Current Status of Rural Housing Construction in National Sample Counties

The empirical assessment of rural housing systems across sampled counties unveiled profound asymmetries in structural integrity, institutional compliance, and technological modernization trajectories. Structural vulnerability manifested most critically in seismic resilience metrics, where adherence to earthquake-resistant design specifications remained critically deficient, with a national median compliance rate barely surpassing single-digit thresholds. This systemic precarity contrasted sharply with near-universal completion rates of poverty-alleviation housing initiatives, wherein over 95% of designated low-income households received retrofitting interventions—a testament to targeted fiscal prioritization. Policy-driven safety enhancements exhibited moderate success, with two-thirds of identified structurally compromised dwellings undergoing remediation, though pronounced interprovincial disparities persisted in material upgrading protocols. The adoption of contemporary construction methodologies revealed incremental progress, as evidenced by cast-in-place concrete utilization rates approximating three-fifths of new builds, yet persistent reliance on non-standardized techniques underscored unresolved tensions between vernacular practices and modern engineering paradigms.

Regulatory performance metrics exposed paradoxical governance dynamics, juxtaposing robust procedural adherence to land-use approvals and completion certifications against fragmented implementation of technical standardization mandates. While administrative compliance rates for statutory construction processes exceeded four-fifths nationally, professionalization of rural construction workforces lagged precipitously—certified artisan participation rates stagnated below one-third in economically transitional regions. This institutional dissonance between bureaucratic formality and operational rigor precipitated cyclical quality assurance failures, particularly evident in material procurement irregularities and thermal envelope performance deficits.

Geospatial analysis revealed hierarchical modernization gradients, wherein basic sanitation coverage achieved 73% penetration yet displayed 22% interregional disparity between coastal and inland zones. Energy transition metrics revealed coevolving contradictions: clean energy adoption plateaued at median rates of 50%, while solar water heater diffusion demonstrated extreme variance (40–80%) contingent upon localized microclimates and generational housing preferences. Insulation retrofitting initiatives achieved moderate success, with penetration rates nearing 60% in economically vibrant eastern corridors, yet

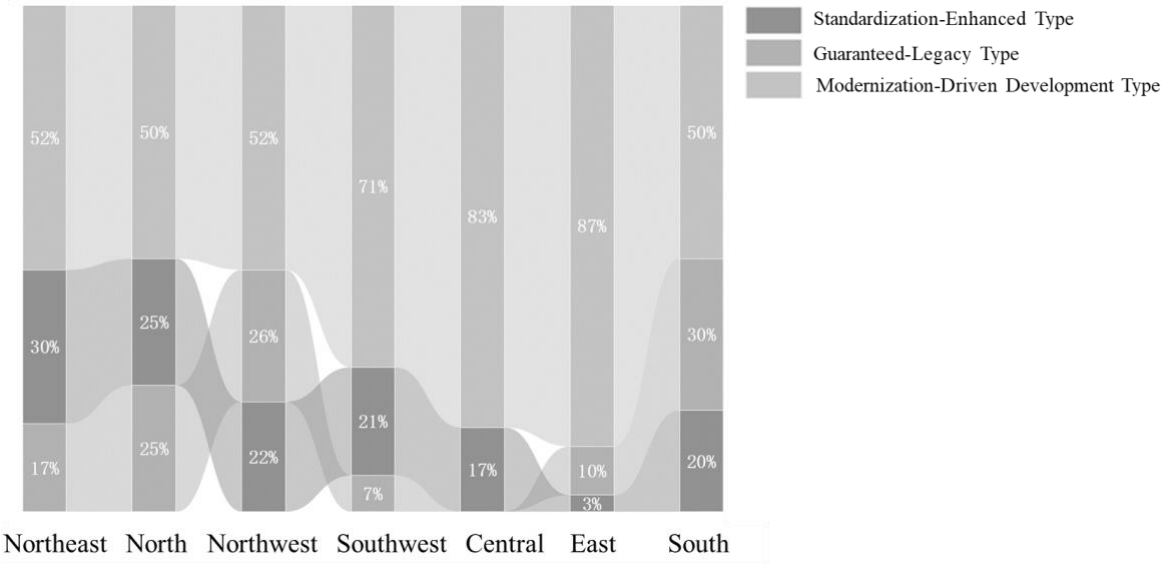
persistent reliance on coal-fired heating systems in northern cold zones negated potential emission reductions. These findings collectively delineate a transitional landscape where rapid infrastructural expansion coexists with entrenched technical-institutional bottlenecks. Multiscalar governance protocols must calibrate infrastructure investments to localized socio-metabolic thresholds.

Typological Differentiation of Rural Housing Development

The application of machine learning-driven clustering to multidimensional housing indicators yielded three distinct archetypes, each representing unique intersections of structural resilience, institutional compliance, and technological modernization. The first cluster, characterized by infrastructural deficiencies, exhibited critical vulnerabilities in seismic retrofitting progress and energy performance metrics. Analysis revealed that less than one-tenth of dwellings in these regions adhered to earthquake-resistant design specifications, with incomplete implementation of poverty-alleviation housing initiatives further exacerbating material obsolescence. Geographically concentrated in ecologically fragile northern territories, these settlements demonstrated a persistent reliance on coal-dependent heating systems, contributing to per capita carbon footprints 1.8 times higher than national averages.

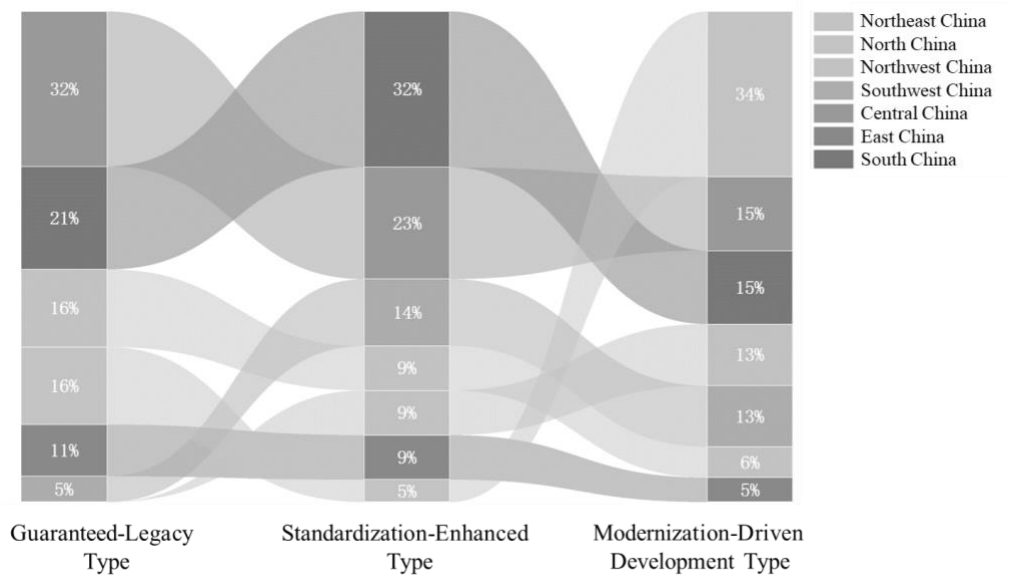
Figure 1

This is the Distribution of Various Types Classified by Region



A second typology emerged in transitional economic corridors, where procedural adherence to statutory approvals masked systemic gaps in construction standardization. While achieving four-fifths compliance with land-use permitting protocols, these regions struggled with inconsistent adoption of energy-efficient retrofitting techniques, resulting in a 35% disparity in insulation penetration rates compared to advanced clusters. The coexistence of moderate clean energy adoption and fossil fuel dependency highlighted institutional inertia in aligning regulatory frameworks with decarbonization imperatives. Workforce professionalization emerged as a critical constraint, with certified artisan participation rates stagnating below one-third despite moderate progress in sanitation infrastructure modernization.

Figure 2
This is the Distribution of Rural Settlements in Various Regions Classified by Clustering Types



The dominant cluster, representing nearly three-quarters of sampled counties, exemplified synergistic advancements in housing safety and functional performance. Coastal regions within this typology demonstrated near-universal compliance with seismic codes alongside high penetration rates of renewable energy systems, achieving a 60% reduction in operational emissions relative to lagging counterparts. However, latent risks of technological lock-in persisted in early-adopting areas, where standardized yet thermally inefficient designs constrained further decarbonization. Northern subregions within this cluster faced unresolved challenges in phasing out coal-fired heating, underscoring the incomplete nature of energy transitions even in modernization-advanced contexts.

Inter-cluster comparisons revealed nonlinear relationships between governance efficacy and emission trajectories. Regions with robust regulatory frameworks exhibited 40% faster adoption of bioclimatic design principles, yet paradoxically demonstrated higher embodied carbon intensities due to material-intensive retrofitting practices. Transitional clusters displayed disproportional responsiveness to quality assurance interventions, where a 10% increase in artisan certification rates correlated with a 22% decline in construction-related emissions. These differential pathways necessitate context-sensitive policy instruments that reconcile immediate safety imperatives with long-term decarbonization goals, avoiding one-size-fits-all approaches that risk amplifying regional disparities.

The typological framework challenges deterministic models of rural development by demonstrating how historical policy legacies and localized governance capacities co-evolve with material conditions. Areas needing conservation demand combined solutions tackling building safety risks and energy accessibility challenges, while transitional corridors demand digitized compliance mechanisms to bridge procedural-formal divides. For modernization-advanced zones, circular economy principles must counterbalance the embodied carbon costs of prior infrastructure investments. By redefining housing systems as dynamic socio-technical networks rather than static physical assets, this stratification enables targeted resource allocation aligned with place-specific decarbonization leverage points.

Conclusions

The hierarchical classification framework developed in this investigation necessitates a paradigm shift in decarbonizing rural habitats, emphasizing the codependent evolution of vernacular material systems, institutional path dependencies, and spatially stratified emission trajectories. Conservation-priority zones, predominantly distributed across northern ecologically vulnerable territories, exemplify the compounding risks of fragmented retrofitting regimes where deferred structural upgrades perpetuate carbon-intensive adaptive behaviors while amplifying climate vulnerability. These regions demand integrative intervention protocols that synchronize bioclimatic retrofitting with distributed renewable microgrid deployment, leveraging fiscal instruments such as tiered subsidy mechanisms to overcome capital accessibility barriers while preserving vernacular architectural integrity. Transitional governance systems occupying economic corridors require institutional innovations transcending procedural compliance, necessitating blockchain-enabled quality tracing architectures to bridge persistent gaps between regulatory formalism and material performance benchmarks. Modernization-leading clusters confront the paradox of technological lock-in from early infrastructure investments, mandating phased transition roadmaps that integrate passive design retrofits with smart grid interoperability while operationalizing circular material flows to mitigate embodied carbon legacies.

This analytical framework challenges deterministic development models by demonstrating nonlinear emission reduction potentials across spatial hierarchies. Ecologically fragile zones exhibit disproportional decarbonization responsiveness to bioclimatic design interventions, whereas economically advanced regions achieve optimal mitigation through industrial symbiosis networks that repurpose agricultural byproducts into low-carbon construction biomaterials. The findings advocate for polycentric governance architectures that devolve technical standard adaptations to provincial authorities while maintaining national compliance baselines, thereby reconciling ecological imperatives with localized socio-cultural realities. Such paradigmatic shifts position rural housing systems as active socio-ecological negotiation processes rather than passive emission sources, transforming vernacular structures into dynamic sites of climate-responsive innovation.

Conceptual progress originates from redesigned emission accounting frameworks integrating institutional inertia dynamics—dimensions historically marginalized in conventional lifecycle assessment models. Practically, the diagnostic-prognostic framework empowers municipalities to prioritize context-specific interventions aligned with typological readiness levels, optimizing resource allocation across China's heterogeneous rural landscapes. Future investigations must address temporal dynamics of typological evolution, particularly rebound risks associated with energy-efficient modernization in advanced clusters and hysteresis effects retrofitting in conservation-priority systems. By synthesizing material institutional economics, this approach establishes a transferable paradigm for emerging economies navigating the dual imperatives of equitable progress and planetary boundary compliance, ultimately redefining rural habitats as living laboratories for transition.

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