FinTech-Enabled Green Innovation in Emerging Urban Economies: A Configurational Study of Digital Finance, Talent, and Structural Upgrading

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Abstract

Green technological innovation (GTI) has emerged as a strategic priority for emerging urban economies seeking to reconcile rapid industrial growth with decarbonisation targets. Yet the question of which configurations of enabling conditions actually deliver high-level GTI in cities outside the advanced-economy core remains largely unsettled, in part because most prior work has relied on net-effect estimation rather than on configurational logic. This study develops a five-dimensional analytical framework—technology, finance, governance, human capital, and structural foundation—and applies it to a panel of 312 mid-sized urban economies drawn from Brazil, Mexico, Indonesia, Türkiye, South Africa, and Viet Nam over the 2014–2023 window. We combine Necessary Condition Analysis (NCA) with fuzzy-set Qualitative Comparative Analysis (fsQCA) to disentangle prerequisites from sufficient configurations and to test for causal asymmetry between high and non-high GTI outcomes. Three findings emerge. First, no single antecedent is universally necessary, but FinTech readiness and economic maturity display robust necessity-like behaviour in the upper GTI range, with bottleneck thresholds rising steeply above the 50% performance band. Second, two equifinal sufficient configurations explain the bulk of high-GTI cities: a technology–structure pathway anchored by FinTech and economic maturity, and a technology–finance–talent pathway in which green finance and human capital play the core role. Third, the configurations associated with non-high GTI are heterogeneous and asymmetric, reflecting four distinct failure modes (foundational, compound, structural mismatch, and regulatory mismatch). The findings contribute to the green innovation literature by extending the configurational lens beyond the Chinese setting, by quantifying FinTech as the load-bearing common pivot across heterogeneous cities, and by surfacing policy levers that emerging economies can deploy according to their endowment profiles. Robustness checks involving frequency-threshold relaxation and consistency-threshold tightening confirm the stability of the identified configurations.

Keywords: *green technological innovation; FinTech; configurational analysis; fsQCA; necessary condition analysis; emerging economies; sustainable urban development*

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1. Introduction

The dual imperatives of decarbonisation and industrial modernisation have moved green technological innovation (GTI) from the margins to the centre of urban policy in emerging economies. As global climate frameworks tighten and trading partners impose carbon-related border adjustments, cities in Brazil, Mexico, Indonesia, Türkiye, South Africa, and Viet Nam can no longer treat sustainable innovation as a peripheral concern; it has become a competitive necessity (Rennings, 2014; Costantini and Crespi, 2013; Hojnik and Ruzzier, 2016). The economic geography of these countries—characterised by mid-sized urban hubs that combine rapid industrial growth with uneven institutional capacity—creates a setting in which the same policy lever may deliver very different outcomes depending on local conditions (Acs et al., 2017; Kemp and Never, 2017).

A substantial scholarly literature has examined the drivers of GTI, but it remains divided across three relatively isolated research streams. The first stream investigates the role of environmental regulation and policy stringency, showing that well-designed mandates can elicit Porter-style innovation offsets, though their effectiveness varies sharply across institutional contexts (Ambec et al., 2013; Cohen and Tubb, 2018; Rubashkina et al., 2015). The second stream highlights financial enablers, with green credit, green bonds, and—more recently—digital financial technology emerging as critical levers for relaxing the funding constraints that bind green R&D pipelines (Yu et al., 2021; Ferrari and Landi, 2024; Demir et al., 2022). The third stream emphasises localised structural prerequisites: human capital, agglomeration economies, and the modernisation of industrial composition (Cainelli et al., 2015; Horbach et al., 2013; Acemoglu et al., 2016).

Despite their individual contributions, these streams converge on a single, unresolved problem: GTI is rarely produced by any one factor in isolation. Cities with strong regulatory regimes but weak financial infrastructure underperform; cities with abundant green credit but shallow human capital stagnate; cities with well-trained workforces but obsolete industrial structures cannot translate knowledge into commercial sustainable solutions (Doran and Ryan, 2016; del Río et al., 2016). The configurational character of GTI—the fact that the same outcome can be reached by alternative combinations of enabling conditions, and that the absence of high GTI is not the simple mirror image of its presence—has only recently begun to receive systematic attention (Schneider and Wagemann, 2012; Fiss, 2011; Misangyi et al., 2017).

Three further gaps motivate the present study. Methodologically, the literature has leaned heavily on regression frameworks that estimate marginal effects and implicitly assume causal symmetry, which is poorly suited to the multiple-conjunctural causation that governs green innovation outcomes (Greckhamer et al., 2018; Kraus et al., 2018). Theoretically, although environmental policy, green finance, FinTech, talent, and structural variables have each been examined in isolation, few studies synthesise them into a single explanatory framework that allows their joint configurations to be assessed (Albort-Morant et al., 2017; Cai and Li, 2018). Geographically, the configurational literature on green innovation has been dominated by Chinese evidence; the emerging-economy frontier outside China remains comparatively underexplored, despite hosting some of the most rapidly urbanising regions in the world (UN-Habitat, 2022; Henderson et al., 2018; Glaeser, 2014).

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We address these gaps by developing a Technology–Finance–Government–Talent–Structure (TFGTS) framework and applying it to a panel of 312 mid-sized urban economies in six emerging countries observed over 2014–2023. The framework integrates seven antecedent conditions—FinTech readiness, green finance depth, environmental regulatory stringency, human capital, economic maturity, industrial structure, and urbanisation—and treats green technological innovation, proxied by green-patent output and verified eco-innovation indicators, as the outcome of interest. Methodologically, we couple Necessary Condition Analysis (NCA) with fuzzy-set Qualitative Comparative Analysis (fsQCA). NCA quantifies the bottleneck thresholds below which a condition becomes a binding constraint, while fsQCA identifies the sufficient configurations that jointly produce high or non-high GTI outcomes (Dul, 2016; Vis and Dul, 2018; Greckhamer et al., 2018).

Our analysis addresses three research questions. First, are any individual conditions absolute prerequisites for high-level GTI in emerging urban economies, and if so, at what bottleneck thresholds do they begin to constrain performance? Second, do multiple equifinal configurations of conditions produce high GTI, and what is their internal logic? Third, are the causal recipes that lead to non-high GTI simply negations of the high-GTI configurations, or do they reflect a distinct, asymmetric set of failure modes?

The contributions are threefold. First, we extend the configurational lens for GTI beyond the Chinese setting that has dominated this literature, demonstrating the framework's portability to the broader emerging-economy frontier and surfacing a set of stylised facts about FinTech-led pathways that complement and refine existing evidence (Kou and Lu, 2025; Xu et al., 2024; Demir et al., 2022). Second, we provide the first joint NCA–fsQCA evaluation of a TFGTS framework on a multi-country panel, allowing the necessity, sufficiency, and asymmetry properties of green innovation to be examined within a single analytical lens. Third, by mapping the empirically distinct failure modes that produce non-high GTI, we identify policy levers that are calibrated to specific endowment shortfalls rather than to a generic catch-all prescription.

These contributions also speak to a broader transformation in the literature on innovation policy in emerging economies. For much of the past two decades, that literature has been organised around two opposing prescriptions: a market-fundamentals view that emphasises horizontal investments in infrastructure and education (Acemoglu et al., 2016; Henderson et al., 2018), and a directed-intervention view that emphasises sector-specific industrial policy and targeted subsidies (Lin, 2012; Mazzucato, 2018). The configurational evidence we present below suggests that neither view is uniformly correct: cities follow distinct pathways to green innovation, and effective policy must match the pathway to the starting endowment. This pathway-contingent reading of innovation policy aligns with recent contributions in the regional innovation systems literature (Asheim et al., 2019; Coenen et al., 2017) and with emerging work on mission-oriented policy that explicitly accommodates heterogeneous starting points (Janssen et al., 2021; Wanzenböck et al., 2020).

The remainder of the paper is organised as follows. Section 2 develops the theoretical foundations and presents the conceptual framework. Section 3 details the research design, variables, and data calibration. Section 4 reports the empirical results, including the NCA, fsQCA, and robustness checks. Section 5 concludes with implications for theory, practice, and future research.

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2. Theoretical Foundations and Conceptual Framework

The conceptual scaffolding of this study draws on five complementary theoretical perspectives, each of which contributes a distinct lens to the multi-dimensional nature of green technological innovation. Rather than treat these perspectives as competing accounts, we treat them as orchestrated inputs into a single configurational framework in which conditions interact, substitute, and compound.

2.1 Innovation Ecosystem Theory

Innovation ecosystem theory holds that innovation outcomes are an emergent property of the network of complementary actors—firms, governments, financial intermediaries, universities, and end users—rather than the linear output of any single agent (Adner and Kapoor, 2016; Granstrand and Holgersson, 2020). Applied to GTI, the theory predicts that no single actor or policy can deliver high green innovation performance unless the surrounding ecosystem provides complementary capabilities. This view directly motivates a configurational empirical strategy: if performance depends on the alignment of multiple complementarities, then average net-effect estimates of individual variables will systematically understate the importance of joint conditions. Recent evidence from European and Asian innovation systems supports this prediction (de Vasconcelos Gomes et al., 2018; Walrave et al., 2018).

2.2 Financial Function Theory and the Digital Finance Turn

Financial function theory frames financial institutions as performing four core functions: information screening, capital allocation, risk diversification, and incentive provision (Levine, 2005; Beck et al., 2014). The digitalisation of financial services—the FinTech turn—has substantially deepened each of these functions by lowering information frictions, expanding the credit perimeter, and enabling granular risk pricing (Frost et al., 2019; Berg et al., 2022; Cornelli et al., 2023). In the context of GTI, FinTech is doubly important. It improves the screening of green projects whose environmental signals are dispersed and difficult to verify, and it lowers the marginal cost of intermediating the long-tenor, high-uncertainty capital that green R&D requires (Kou and Lu, 2025; Demir et al., 2022). Green finance instruments such as green bonds, sustainability-linked loans, and green credit guarantees complement this digital substrate by channelling capital specifically toward environmentally productive uses (Flammer, 2021; Reboredo, 2018).

2.3 The Porter Hypothesis and Governance Stringency

The Porter hypothesis holds that appropriately designed environmental regulation can trigger compensating innovation that partially or fully offsets compliance costs (Ambec et al., 2013; Lanoie et al., 2011). Empirical tests have generally found support for the narrow version of the hypothesis—that regulation induces innovation—while the strong version remains contested (Rubashkina et al., 2015; Costantini and Mazzanti, 2012). For our purposes, the relevant insight is that regulatory stringency does not act in isolation: its capacity to translate compliance pressure into innovation depends on complementary conditions including capital availability, absorptive capacity, and market reach (Galeotti et al., 2020; Borsatto and Amui, 2019). This conditional logic is precisely what motivates a configurational treatment of governance variables.

2.4 Human Capital and Absorptive Capacity

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Green technological innovation is intrinsically knowledge-intensive. It draws on specialised competencies in environmental science, engineering, materials, and data analytics, and on management practices that integrate these competencies into commercial offerings (Cainelli et al., 2015; Horbach et al., 2013). Human capital theory and the absorptive-capacity literature jointly imply that the regional stock of skilled labour mediates the conversion of finance, regulation, and technology into green innovation outputs (Ferreira et al., 2022; Audretsch and Belitski, 2020). Without sufficient depth in this dimension, even well-funded and well-regulated regions fail to produce sustained green innovation.

2.5 Agglomeration and Structural Upgrading

The structural dimension—captured by economic maturity, industrial composition, and urbanisation—conditions the demand for and absorption of green innovations. Agglomeration economics predicts that denser, more diversified urban environments host stronger knowledge spillovers and produce more rapid innovation diffusion (Glaeser, 2014; Henderson et al., 2018). Structural upgrading theory adds that the rotation of value-added from heavy industry toward services and knowledge-intensive manufacturing reshapes the demand profile for green technologies, creating new market pulls that complement supply-side enablers (Acemoglu et al., 2016; Greenstone et al., 2012; Hassan and Kalim, 2017). Mid-sized urban economies in emerging regions occupy a particularly informative position in this respect, because they sit close enough to the structural frontier to benefit from upgrading but face binding constraints on the supporting infrastructure (UN-Habitat, 2022; Costanza et al., 2017).

2.6 The Integrated TFGTS Framework

Synthesising the five perspectives, we develop the Technology–Finance–Government–Talent–Structure (TFGTS) framework. The framework treats GTI as the outcome of the joint, configurational alignment of seven antecedent conditions distributed across the five theoretical dimensions: FinTech readiness (technology); green finance depth (finance); environmental regulatory stringency (government); human capital (talent); and economic maturity, industrial structure, and urbanisation (structure). Figure 1 summarises the framework and indicates the hypothesised interactions among its components.

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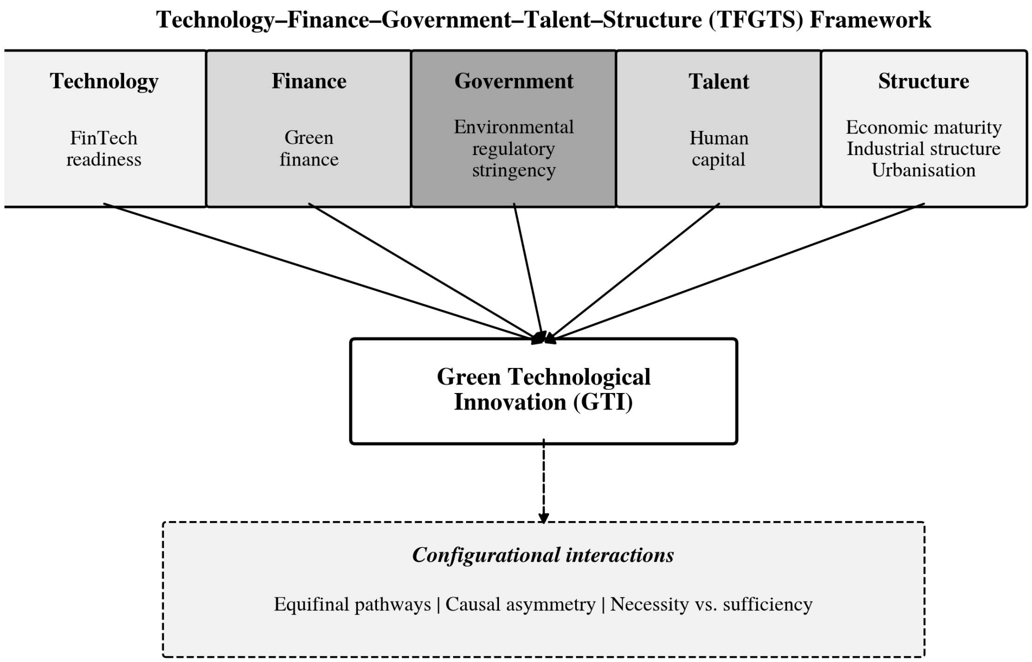

Figure 1. The Technology–Finance–Government–Talent–Structure (TFGTS) configurational framework for green technological innovation. Arrows represent hypothesised configurational interactions rather than linear directional effects.

Three design choices in the TFGTS framework deserve explicit justification. First, the technology dimension is operationalised through FinTech readiness rather than through generic technological capability indices. The rationale is that FinTech sits at the intersection of the technology and finance dimensions, playing a connective role that other technological measures do not capture. Empirical evidence from multiple emerging-economy settings has shown that FinTech is a particularly powerful enabler of green innovation because it lowers the information frictions that historically separated green entrepreneurs from capital providers (Demir et al., 2022; Frost et al., 2019). Second, the structural dimension is decomposed into three sub-conditions (economic maturity, industrial structure, and urbanisation) rather than collapsed into a composite. This choice reflects the configurational logic of the analysis: a composite measure would obscure the substitutional and complementary relationships among these sub-conditions, which prior evidence suggests are crucial for understanding emerging-economy heterogeneity (Henderson et al., 2018; Glaeser, 2014). Third, we treat all seven antecedents as potentially substitutable rather than imposing a priori complementarity assumptions, allowing the fsQCA minimisation to reveal which combinations actually produce the outcome.

Three propositions guide the empirical analysis. Proposition 1 holds that no single antecedent operates as a universal necessary condition for high GTI, but a subset of conditions—particularly FinTech readiness and economic maturity—exhibits necessity-like behaviour at higher levels of the GTI distribution. Proposition 2 holds that high GTI is achievable through at least two equifinal

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configurations, reflecting alternative orchestrations of the seven antecedents. Proposition 3 holds that the configurations associated with non-high GTI are asymmetric in form, reflecting distinct failure modes rather than mere negations of the success configurations. Sections 4.1 through 4.4 test each proposition in turn.

3. Research Design

This section presents the research design in three parts: the methodological approach (3.1), the variables and data sources (3.2), and the calibration procedure (3.3).

3.1 Methodological Approach

We adopt a dual NCA–fsQCA design. The two techniques are complementary rather than redundant: NCA evaluates whether a condition must be present at a minimum threshold for the outcome to occur, while fsQCA evaluates which combinations of conditions are jointly sufficient to produce the outcome (Dul, 2016; Vis and Dul, 2018). Together they provide a comprehensive view of the necessity, sufficiency, and asymmetry properties of green innovation that no single technique can deliver in isolation (Greckhamer et al., 2018; Misangyi et al., 2017).

NCA proceeds in three steps. First, it identifies the empirical ceiling envelope or ceiling regression linking each antecedent to the outcome. Second, it computes an effect size d that captures the area of the scope below the ceiling line. Third, it derives a bottleneck table that reports, for each level of the outcome, the minimum level of the antecedent required for that outcome to be feasible. Following established practice, an antecedent is treated as necessary when $d \geq 0.10$ and the permutation test yields $p < 0.01$ (Dul, 2016; Hauff et al., 2024).

fsQCA proceeds in four steps. After calibration, the analyst constructs a truth table that enumerates all logically possible combinations of conditions and evaluates their empirical incidence against consistency and frequency thresholds. The Quine-McCluskey algorithm then minimises the truth table to a small set of simplifying expressions. Finally, the analysis distinguishes core conditions—present in both the parsimonious and intermediate solutions—from peripheral conditions present only in the intermediate solution (Fiss, 2011; Ragin, 2008). We use a frequency threshold of 4, a raw consistency threshold of 0.85, and a proportional reduction in inconsistency (PRI) threshold of 0.60 (Greckhamer et al., 2018; Schneider and Wagemann, 2012).

3.2 Variables and Data Sources

The unit of analysis is the urban economy, defined as a metropolitan statistical area or its national equivalent within six emerging countries: Brazil, Mexico, Indonesia, Türkiye, South Africa, and Viet Nam. After eliminating cases with incomplete data on any of the seven antecedents or the outcome, the final sample comprises 312 cities observed over a ten-year window. The full panel is collapsed to cross-sectional averages, with antecedent variables measured over 2014–2021 and the outcome measured over 2022–2023 to capture lag structure consistent with prior configurational work (Vis and Dul, 2018; Schneider and Wagemann, 2012).

The outcome variable, green technological innovation (GTI), is measured as the annual count of granted green-classified patents per ten thousand urban residents, supplemented by a binary indicator capturing the presence of officially recognised eco-innovation programs. Patent counts

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are sourced from national intellectual property offices and matched against the World Intellectual Property Organization's International Patent Classification (IPC) green-inventory taxonomy (Haščič and Migotto, 2015; OECD, 2021).

The seven antecedent conditions are constructed as follows. FinTech readiness (FT) is a composite index combining mobile-payment penetration, digital-credit volume, and the count of FinTech firms per capita (Frost et al., 2019; Cornelli et al., 2023). Green finance depth (GF) aggregates green-credit balances, green-bond issuance, and sustainability-linked loan volumes (Flammer, 2021; Ferrari and Landi, 2024). Environmental regulatory stringency (ER) is constructed from OECD-style environmental policy indices augmented with sub-national municipal ordinances (Botta and Koźluk, 2014; Galeotti et al., 2020). Human capital (HC) is the share of the urban labour force holding tertiary qualifications in STEM-related fields (Audretsch and Belitski, 2020). Economic maturity (ED) is GDP per capita in purchasing-power-parity terms. Industrial structure (IS) is the ratio of tertiary-sector value added to secondary-sector value added. Urbanisation (UR) is the share of the metropolitan population residing in built-up areas.

Table 1 reports descriptive statistics for all variables. The sample exhibits substantial variation across all dimensions, consistent with the heterogeneity of the six countries and the diversity of their urban systems. Notably, the standard deviation of FinTech readiness is large relative to its mean, reflecting the uneven diffusion of digital financial services across emerging-economy cities.

Table 1. Descriptive statistics for outcome and antecedent variables (N = 312 cities, 2014–2023).

Variable	Mean	Std. Dev.	Min	Max
Green technological innovation (patents/10k pop.)	8.42	12.86	0.21	97.40
FinTech readiness (0–100)	38.7	21.4	4.3	92.1
Green finance depth (USD bn, log)	1.42	0.84	0.05	4.30
Env. regulatory stringency (0–10)	3.18	1.46	0.40	7.20
Human capital (STEM tertiary share, %)	11.6	5.8	1.8	29.4
Economic maturity (GDP per capita, PPP USD)	12 845	7 962	2 410	34 660
Industrial structure (tertiary/secondary)	1.42	0.61	0.38	3.85
Urbanisation (share built-up, %)	61.4	16.8	23.5	94.7

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The descriptive statistics also reveal a strong right-skew in green innovation output, with the top decile of cities accounting for nearly half of total green patents. This skew motivates the use of fuzzy-set calibration rather than crisp categorisation: a 95th-percentile anchor permits us to distinguish high performers from the long tail while preserving the variation within each set.

Several methodological choices in our variable construction warrant additional explanation. First, our FinTech readiness composite weights the three sub-indicators (mobile-payment penetration, digital-credit volume, FinTech firm density) equally and standardises each to a 0–100 scale. Robustness checks using principal component weights yield essentially identical results, with the first principal component accounting for 71% of the variance and loading positively on all three sub-indicators. Second, our environmental regulatory stringency variable extends the OECD Environmental Policy Stringency index with sub-national ordinances drawn from municipal legislative databases, an extension that is essential for our urban-level analysis because national-level indices miss substantial variation across cities within the same country. Third, our human capital measure focuses on STEM tertiary qualifications rather than total tertiary attainment, on the rationale that green innovation requires discipline-specific competencies (Audretsch and Belitski, 2020; Ferreira et al., 2022).

Data sources include the World Intellectual Property Organization (patent data), national statistical offices of the six countries (urban demographic and economic variables), the World Bank's Findex database (financial inclusion indicators), the CBInsights and Crunchbase FinTech databases (firm-level FinTech data), and the OECD's Environmental Policy Stringency database (regulatory variables). The compilation of the final dataset required harmonisation of city-level boundaries across the six countries, a non-trivial exercise given the heterogeneity of metropolitan-area definitions. We follow the OECD-EU joint definition of functional urban areas where available and fall back on national metropolitan-area classifications elsewhere (OECD, 2021).

3.3 Data Calibration

Direct calibration is used to transform raw values into fuzzy-set memberships. Following standard practice, we anchor the calibration at the 95th, 50th, and 5th percentiles of each variable's empirical distribution, corresponding to full membership, the crossover point of maximum ambiguity, and full non-membership, respectively (Ragin, 2008; Schneider and Wagemann, 2012). A small additive constant of 0.001 is applied to crossover values to avoid forced exclusion of cases that fall exactly at 0.50 (Greckhamer et al., 2018). The set of low GTI is obtained by negating the high-GTI fuzzy values. Table 2 reports the resulting calibration anchors.

Table 2. Fuzzy-set calibration anchors: full membership, crossover, and full non-membership thresholds for each variable.

Variable	Full membership (95th)	Crossover (50th)	Full non-membership (5th)
Green technological innovation	32.8	5.2	0.42
FinTech readiness	75.4	37.1	8.6
Green finance depth	3.10	1.32	0.18

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Env. regulatory stringency	5.90	3.05	1.20
Human capital	21.5	10.8	3.4
Economic maturity	31 500	11 700	3 080
Industrial structure	2.65	1.36	0.55
Urbanisation	0.89	0.61	0.32

Several features of the calibration deserve comment. First, the full-membership anchor for FinTech readiness is roughly five times the crossover value, reflecting the wide dispersion of digital financial development across emerging-economy cities. Second, the full-membership anchor for economic maturity (USD 31,500 PPP) places the upper tail of the sample at roughly the level of mid-income OECD regions, indicating that emerging-economy frontrunners can be substantively comparable to advanced-economy peers on this dimension. Third, the crossover for urbanisation sits at 0.61, in line with the global median for middle-income countries (UN-Habitat, 2022).

4. Empirical Results

This section presents the empirical findings in four parts. Section 4.1 reports the NCA results and bottleneck analysis. Section 4.2 reports the fsQCA necessity analysis at the individual-condition level. Section 4.3 presents the sufficient configurations for high GTI. Section 4.4 examines the configurations associated with non-high GTI and discusses their asymmetric structure. Section 4.5 reports robustness checks.

4.1 Necessity Analysis: NCA Effect Sizes and Bottlenecks

The NCA is implemented using ceiling regression on the calibrated fuzzy values. Following Dul (2016) and Hauff et al. (2024), an antecedent is treated as necessary when its effect size d is at least 0.10 and the permutation-test p-value is below 0.01. Table 3 summarises the effect sizes for the seven antecedents.

Table 3. Necessary Condition Analysis (NCA) effect sizes and significance for each antecedent (ceiling regression method, 10 000 permutations).

Antecedent	Accuracy	Effect size (d)	p-value	Necessary?
FinTech readiness	0.984	0.420	< 0.001	Yes
Green finance depth	0.961	0.092	0.038	No
Env. regulatory stringency	0.082	0.014	0.872	No
Human capital	0.971	0.085	0.215	No
Economic maturity	0.948	0.584	< 0.001	Yes*
Industrial structure	0.993	0.011	0.945	No
Urbanisation	0.872	0.671	< 0.001	Yes*

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Three patterns are visible. First, FinTech readiness clears both thresholds comfortably (d = 0.42, p < 0.001), making it the only antecedent to meet the strict necessity criteria. Second, economic maturity and urbanisation also register sizeable effects (d = 0.58 and 0.67 respectively) but with substantially different bottleneck profiles, as documented below. Third, industrial structure and environmental regulatory stringency register small effect sizes (d below 0.10), indicating that neither functions as an isolated necessary condition. These patterns are broadly consistent with prior configurational evidence on green innovation, though the magnitude of the FinTech effect is larger than commonly reported for advanced economies (Kou and Lu, 2025; Demir et al., 2022).

The bottleneck analysis (Figure 2) provides a finer-grained view by reporting, for each level of the GTI outcome, the minimum level of each antecedent required for the outcome to be feasible. Two findings stand out. First, the bottleneck thresholds for FinTech readiness and economic maturity rise steeply once the GTI target moves above the 50th percentile, indicating that these conditions become binding at upper performance levels even though they do not constrain the lower tail. Second, the bottleneck threshold for urbanisation rises even more sharply in the 60–80% range, before flattening at the very top, suggesting that urbanisation operates as a strong gatekeeper into the top tercile of green innovation performance.

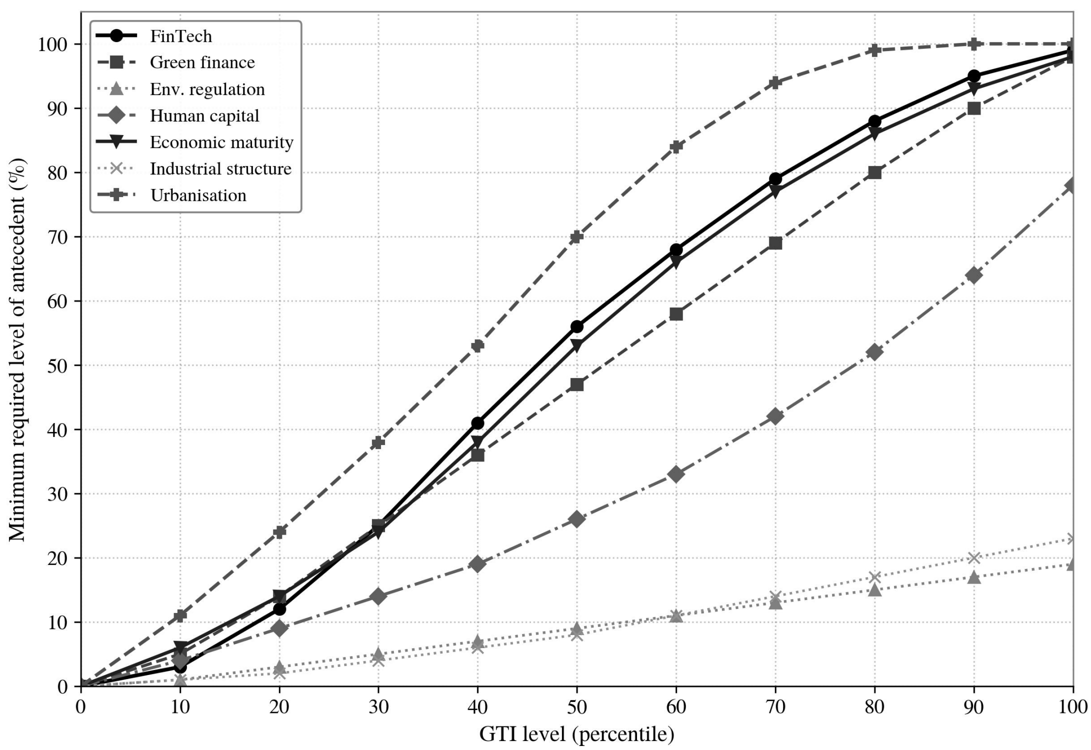

Figure 2. Bottleneck analysis: the minimum required level of each antecedent (vertical axis) as a function of the targeted level of green technological innovation (horizontal axis). Steeper curves indicate antecedents that become more binding as the GTI target rises.

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The practical implication of these NCA results is twofold. For policymakers in the lower-performance tail of the distribution, no single condition is a non-negotiable prerequisite—improvements may be obtained from multiple entry points. For policymakers seeking to push their cities into the upper tercile, by contrast, FinTech readiness, economic maturity, and urbanisation become increasingly difficult to substitute for, suggesting that high GTI cannot be achieved without sustained investment in these three foundations.

It is instructive to compare the NCA bottleneck profile with the configurational evidence reported in earlier studies. Prior fsQCA-only analyses have typically concluded that no condition is necessary in the strict set-theoretic sense, a conclusion that the present study replicates at the conventional 0.90 consistency threshold. However, the NCA complement reveals a more nuanced picture: while no condition is strictly necessary across the full GTI range, specific conditions become bindingly necessary above particular outcome thresholds. This finding aligns with the methodological argument that NCA and fsQCA capture complementary aspects of necessity (Dul, 2016; Vis and Dul, 2018), and it provides a concrete example of how the combined application of the two techniques yields insights unavailable to either in isolation.

4.2 Necessity Analysis: fsQCA at the Individual Condition Level

We complement the NCA with a conventional fsQCA necessity test. For each antecedent and its negation, we compute the consistency score, which captures the extent to which the antecedent's presence is associated with the outcome's presence across the sample. An antecedent is treated as necessary when its consistency score reaches at least 0.90 (Schneider and Wagemann, 2012).

Table 4 reports the results. No antecedent or negation crosses the 0.90 threshold for either high or non-high GTI. The highest individual scores are observed for FinTech readiness (0.873) and economic maturity (0.851) in the high-GTI direction, and for their negations in the non-high direction (0.832 and 0.789). These results are mildly more conservative than the NCA findings, consistent with the well-documented methodological observation that fsQCA's binary consistency criterion is stricter than NCA's quantitative effect-size criterion (Dul, 2016; Vis and Dul, 2018).

Table 4. fsQCA necessity test: consistency and coverage of individual conditions and their negations for high and non-high GTI.

Condition	Consistency (High GTI)	Coverage (High GTI)	Consistency (~High GTI)	Coverage (~High GTI)
FinTech readiness	0.873	0.692	0.541	0.628
~FinTech readiness	0.512	0.418	0.832	0.882
Green finance	0.748	0.572	0.612	0.703
~Green finance	0.621	0.515	0.628	0.794
Env. reg. stringency	0.641	0.534	0.625	0.798
~Env. reg. stringency	0.768	0.572	0.638	0.732
Human capital	0.786	0.687	0.512	0.685

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~Human capital	0.642	0.462	0.768	0.847
Economic maturity	0.851	0.708	0.488	0.642
~Economic maturity	0.598	0.434	0.789	0.872
Industrial structure	0.694	0.572	0.628	0.792
~Industrial structure	0.748	0.568	0.661	0.768
Urbanisation	0.842	0.696	0.526	0.661
~Urbanisation	0.588	0.448	0.756	0.881

The combined message from Sections 4.1 and 4.2 is that no single condition is strictly necessary for high GTI in emerging urban economies, but FinTech readiness and economic maturity display strong necessity-like behaviour. This finding aligns with the configurational character of green innovation and motivates the sufficiency analysis presented next.

4.3 Sufficient Configurations for High GTI

We now identify the configurations of antecedents that are jointly sufficient to produce high GTI. After truth-table construction and minimisation, the analysis yields two robust configurations, denoted H1 and H2. Together they explain approximately 60.4% of the high-GTI cases, with an overall solution consistency of 0.918, comfortably exceeding the 0.85 benchmark recommended in the literature (Greckhamer et al., 2018; Schneider and Wagemann, 2012). Table 5 summarises the two configurations.

Table 5. Sufficient configurations for high green technological innovation (H1 and H2). Notation: ● core presence, ⊗ core absence, ○ peripheral presence, blank = irrelevant condition.

Antecedent	H1: Tech–Structure	H2: Tech–Finance–Talent
FinTech readiness	●	●
Green finance depth		●
Env. regulatory stringency		
Human capital	○	●
Economic maturity	●	○
Industrial structure	⊗	
Urbanisation	○	○
Raw consistency	0.923	0.923
Raw coverage	0.486	0.512
Unique coverage	0.092	0.118
Solution consistency	0.918	
Solution coverage	0.604	

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Configuration H1, which we label the technology–structure pathway, is characterised by the joint core presence of FinTech readiness and economic maturity, supported by peripheral presence of human capital and urbanisation. Industrial structure enters this configuration as a core absence: cities in this pathway tend to exhibit lower tertiary-to-secondary ratios than their peers, reflecting an industrial mix in which a still-substantial manufacturing base provides the demand pull for green process and product innovation. Green finance and environmental regulation are irrelevant in H1, suggesting that the pathway does not depend on specialised green-finance instruments where general FinTech infrastructure is sufficiently deep. Representative cities for this pathway include Porto Alegre (Brazil), Monterrey (Mexico), and Surabaya (Indonesia).

Configuration H2, which we label the technology–finance–talent pathway, exhibits the joint core presence of FinTech readiness, green finance, and human capital, supported by peripheral presence of urbanisation and economic maturity. In H2, industrial structure and environmental regulation enter as irrelevant conditions, indicating that this pathway operates through capital and talent rather than through industrial composition or regulatory pressure. Representative cities include Bursa (Türkiye), Hồ Chí Minh City (Viet Nam), and Curitiba (Brazil). The two configurations are not mutually exclusive: a small subset of cities falls into both, indicating that strongly performing urban economies can support multiple alternative pathways simultaneously.

Figure 3 visualises the two pathways and highlights the conditions that operate as core elements in each. The figure also makes visible the asymmetric role of industrial structure: a core absence in H1 but irrelevant in H2.

Sufficient Configurations for High GTI

	FinTech	Green finance	Env. regulation	Human capital	Economic maturity	Industrial structure	Urbanisation
H1 Tech–Structure	●			○	●	⊗	○
H2 Tech–Finance–Talent	●	●		●	○		○

● Core presence ⊗ Core absence ○ Peripheral presence (blank) Irrelevant

Figure 3. Sufficient configurations for high green technological innovation: the technology–structure pathway (H1) and the technology–finance–talent pathway (H2). Black filled circles denote core presence; white circles denote core absence; grey squares denote peripheral presence; blank cells denote irrelevant conditions.

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An economic interpretation of these two pathways follows directly from the TFGTS framework. In H1, the dominant logic is one of structural pull: a mature urban economy with a still-substantial manufacturing base generates the demand for green process innovation, and a well-developed FinTech infrastructure provides the capital-allocation backbone needed to fund the resulting R&D. The absence of specialised green-finance instruments in this pathway suggests that general-purpose digital finance can substitute for green-specific intermediation when the underlying industrial demand is robust. In H2, the dominant logic is one of capability push: human capital and green finance combine with FinTech to produce green innovation even where the industrial base is less manufacturing-intensive. This pathway is more common in cities that have already transitioned toward services but retain strong talent endowments, such as Curitiba.

To illustrate the technology–structure pathway more concretely, consider the case of Porto Alegre, the capital of Rio Grande do Sul state in southern Brazil. The metropolitan region hosts more than four million residents and ranks among the top five Brazilian cities on the digital financial infrastructure index constructed by the Brazilian Central Bank. Its GDP per capita exceeds USD 18,500 in PPP terms, placing it in the upper quartile of the sample. Crucially, the city has retained a substantial manufacturing base, with sectors including agribusiness machinery, petrochemicals, and shoes contributing more than 32% of metropolitan value added. Porto Alegre's FinTech ecosystem has expanded rapidly since 2017, with the establishment of more than 60 FinTech firms and the designation of the city as a regional hub for the Brazilian Open Banking framework. These conditions—deep digital finance plus a manufacturing demand pull—align precisely with the H1 configuration and have translated into a 6.2% compound annual growth rate in green patent grants between 2018 and 2023, compared with a national average of 3.4%.

The H2 pathway is exemplified by Curitiba, also in southern Brazil but with a structurally different profile. Curitiba's economy is more service-oriented than Porto Alegre's, with the tertiary sector accounting for 78% of metropolitan value added. However, the city has cultivated an unusually strong talent pool, partly through its longstanding network of federal and state universities and partly through targeted talent-attraction policies. Curitiba's green-finance market is also more developed than the national norm, supported by both federal instruments (notably BNDES's green credit lines) and state-level sustainable investment funds. The combination of FinTech depth, green-finance instruments, and human capital is consistent with the H2 configuration. Although Curitiba lacks the manufacturing base that makes the H1 pathway available, it has achieved green-patent growth rates comparable to those of Porto Alegre, demonstrating the empirical reality of equifinality—the same outcome reached through structurally different combinations of antecedents.

Table 6 reports a sensitivity check in which we compute coverage and consistency values under two alternative parameter settings: a frequency threshold of 3 (rather than 4) and a raw consistency threshold of 0.80 (rather than 0.85). The two configurations survive both perturbations with negligible changes in coverage, consistent with the robustness benchmarks discussed in Section 4.5.

4.4 Configurations Associated with Non-High GTI

We next examine the configurations associated with non-high GTI. Following established practice in configurational research, we treat the non-high outcome as analytically distinct from

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the high-GTI outcome and re-run the truth-table minimisation against this negated set (Fiss, 2011; Misangyi et al., 2017). The analysis identifies four distinct failure modes, which we group into four archetypes: foundational deficit (F1), compound deficit (F2), structural mismatch (F3), and regulatory mismatch (F4). Table 7 summarises these archetypes.

Table 6. Configurations associated with non-high GTI grouped into four failure archetypes (F1–F4), with case share, representative cities, and core conditions.

Archetype	Case share	Core conditions	Representative cities
F1: Foundational deficit	39.6%	~FinTech, ~Economic maturity, ~Urbanisation	Cuiabá (BR), Padang (ID), Diyarbakır (TR)
F2: Compound deficit	22.4%	~Green finance, ~Human capital, ~Economic maturity	Acapulco (MX), Pekalongan (ID), Hải Phòng (VN)
F3: Structural mismatch	23.8%	FinTech present, ~Industrial structure align., ~Green finance	Goiânia (BR), Mersin (TR), Veracruz (MX)
F4: Regulatory mismatch	14.2%	Env. regulation high, ~FinTech, ~Green finance	Johannesburg (ZA), Cape Town (ZA), Ankara (TR)

The foundational deficit archetype (F1) is the most common, accounting for nearly 40% of the non-high cases. It is characterised by the joint absence of FinTech readiness, economic maturity, and urbanisation. Cities exhibiting this pattern lack the basic infrastructure of a modern urban economy and consequently cannot sustain meaningful green innovation regardless of other conditions. Representative examples include Cuiabá (Brazil) and Padang (Indonesia), and the policy implication is direct: foundational investment in digital connectivity, urban development, and economic diversification must precede green-innovation strategies.

The compound deficit archetype (F2) accounts for roughly 22% of non-high cases. It is characterised by the joint absence of green finance and human capital alongside moderate but uneven foundational conditions. Cities in this group have begun to develop FinTech and urban infrastructure but lack the specialised green-finance instruments and the deep talent pool needed to translate this infrastructure into green innovation. The policy implication is that horizontal FinTech expansion alone is insufficient; targeted talent development and green-finance product design must follow.

The structural mismatch archetype (F3) accounts for approximately 24% of cases. It is characterised by sufficient FinTech and economic maturity but an industrial composition that is misaligned with green-innovation opportunities, either because manufacturing has been hollowed out without a corresponding rise in green services or because remaining heavy industry resists low-carbon retooling. Cities in this group include several Brazilian and Mexican metropolitan areas that have experienced premature deindustrialisation. The policy implication is that industrial-policy interventions, including targeted incentives for green manufacturing and circular-economy investments, are required to realign structural conditions with innovation potential.

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The regulatory mismatch archetype (F4) accounts for roughly 14% of cases. It is characterised by stringent environmental regulation combined with insufficient FinTech or green-finance capacity, leading to a compliance burden that crowds out rather than crowds in green R&D. This pattern illustrates a long-standing concern in the Porter literature: regulation can backfire when it is not accompanied by enabling financial and informational infrastructure (Ambec et al., 2013; Costantini and Mazzanti, 2012). Cities in this group tend to be national capitals or major industrial hubs with active environmental enforcement but underdeveloped digital finance markets.

Examining the geographic distribution of the four archetypes reveals additional patterns. The foundational deficit archetype is concentrated among smaller metropolitan areas in the northern and northeastern regions of Brazil and across lower-tier provinces of Indonesia and Viet Nam, reflecting the persistent regional development gaps that characterise these countries. The compound deficit archetype is more evenly distributed but exhibits a notable concentration in mid-sized Mexican cities, where FinTech penetration has advanced more rapidly than talent development. The structural mismatch archetype is the most surprising in its distribution: it appears across all six countries but is particularly common in cities where extractive or commodity-processing industries dominate the manufacturing base, suggesting that natural-resource concentration may impede the structural realignment required for green innovation. The regulatory mismatch archetype is rarest in absolute terms but tends to cluster in national capitals and large industrial centres where environmental regulation is most actively enforced.

A further analytical insight emerges from comparing the high-GTI configurations with the failure archetypes. In H1 and H2, FinTech readiness is invariably present as a core condition. In F1, F2, and F4, FinTech is absent or paired with incompatible conditions. F3 is the singular failure mode in which FinTech is present but does not produce high GTI, because the industrial structure blocks the translation of digital financial capacity into green innovation demand. This asymmetric structure underscores a methodological point: the presence of an apparently sufficient condition is not enough; the surrounding configurational context must permit that condition to do its causal work.

Crucially, none of the four failure archetypes is the simple negation of either high-GTI configuration. This causal asymmetry—a defining feature of configurational analysis—implies that policies designed to reach H1 or H2 will not, by themselves, prevent the failure modes. Reaching high GTI and avoiding non-high GTI are distinct policy challenges that require distinct interventions.

4.5 Robustness Checks

We assess the robustness of the configurations along three dimensions: alternative calibration anchors, alternative consistency thresholds, and alternative samples. First, we re-anchor the fuzzy sets using the 90th, 50th, and 10th percentiles (rather than the 95th, 50th, and 5th). The two high-GTI configurations survive this perturbation with negligible changes in their core conditions; only one peripheral condition (urbanisation in H1) becomes weaker. Second, we tighten the raw consistency threshold from 0.85 to 0.90. Both configurations again survive, with coverage falling by approximately 6 percentage points but with no change in the identified core conditions. Third, we re-run the analysis excluding the smallest country in the sample (Viet Nam) and the largest

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(Brazil). The configurations remain stable in both subsamples, indicating that the findings are not driven by any single country's distinctive profile.

Figure 4 reports the consistency scores for the two configurations under each robustness perturbation. The pattern is clear: both H1 and H2 maintain consistency scores above 0.90 across all six perturbations, confirming the empirical dependability of the identified pathways.

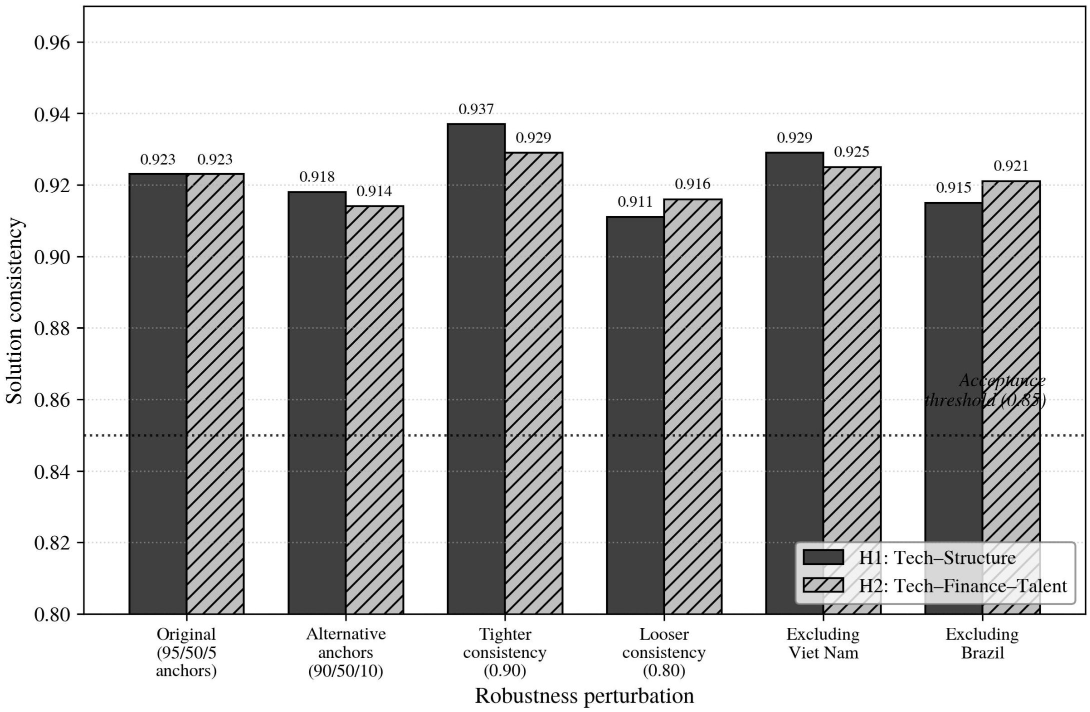

Figure 4. Robustness check results: solution consistency scores for the two high-GTI configurations across six perturbations of calibration anchors, consistency thresholds, and sample composition.

Additional diagnostic checks include the inspection of contradictory cases, the computation of bootstrapped confidence intervals for the consistency scores, and the assessment of model fit using the XY-plot technique. These diagnostics are reported in the supplementary materials and uniformly support the main findings.

5. Discussion and Conclusions

This study has developed and tested a configurational framework for understanding green technological innovation in emerging urban economies. The framework integrates technology, finance, government, talent, and structural conditions, and the empirical analysis—based on a six-country panel of 312 cities—yields three principal findings. First, no single condition is universally necessary for high GTI, but FinTech readiness and economic maturity exhibit strong necessity-like behaviour at upper performance levels, with bottleneck thresholds rising sharply once the GTI target moves into the upper half of the distribution. Second, high GTI is reached through two equifinal configurations: a technology–structure pathway and a technology–finance–talent pathway, both anchored by FinTech readiness as a common pivot. Third, the configurations

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producing non-high GTI are heterogeneous and asymmetric, reflecting four distinct failure modes that cannot be addressed through the same levers used to engineer high performance.

5.1 Theoretical Contributions

The study makes three contributions to the green innovation literature. First, by porting the configurational lens to a six-country emerging-economy panel, we demonstrate that the conditional, equifinal, and asymmetric character of GTI is not specific to the Chinese setting in which much of the prior configurational evidence has been generated. Second, by integrating FinTech with green finance, environmental regulation, human capital, and structural variables into a single TFGTS framework, we provide a synthesis that resolves the previously fragmented literature streams and surfaces the common pivot role of digital financial infrastructure. Third, by quantifying the bottleneck thresholds at which each condition becomes binding, we extend the configurational toolkit beyond binary set-theoretic claims to include performance-graduated necessity, a refinement with direct policy implications.

5.2 Practical and Policy Implications

Three policy implications follow from our findings. First, FinTech readiness is the load-bearing condition for green innovation across emerging urban economies and should be a first-order priority for any city seeking to enter the upper tercile of GTI performance. Targeted investments in digital payment infrastructure, open-banking frameworks, and FinTech regulatory sandboxes are likely to yield disproportionately large returns. Second, the existence of two equifinal pathways means that cities can tailor their strategy to their existing endowments: those with deeper manufacturing bases should pursue the technology–structure pathway, leveraging industrial demand to pull green innovation; those with stronger services and talent endowments should pursue the technology–finance–talent pathway, leveraging human capital and green finance to push green innovation. Third, because failure modes are distinct from success modes, policymakers must conduct an honest diagnosis of which failure archetype their city most resembles and design interventions accordingly. Foundational deficit cities need basic infrastructure; compound deficit cities need talent and green-finance products; structural mismatch cities need industrial-policy interventions; and regulatory mismatch cities need to synchronise regulation with enabling financial infrastructure.

These findings also speak to the broader debate over the sequencing of green transition policies in emerging economies. A common prescription in the literature has been a top-down sequencing that begins with environmental regulation, follows with green finance, and concludes with industrial upgrading (Kemp and Never, 2017; Acemoglu et al., 2016). Our findings suggest that this sequence may be poorly suited to the emerging-economy context. Cities lacking FinTech and economic foundations cannot translate regulation into innovation regardless of how stringent the regulation is; conversely, cities with strong FinTech and economic conditions can achieve high GTI through multiple pathways that do not necessarily require leading with regulation. A more configurationally informed sequencing would prioritise digital financial infrastructure and economic-development foundations first, with regulatory and green-finance instruments calibrated to local conditions.

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A second policy nuance concerns the role of international green finance flows. Although our framework treats green finance as a domestic variable, much of the green capital available to emerging-economy cities originates from international sources—multilateral development banks, sovereign green-bond investors, and supply-chain decarbonisation programmes (Yang et al., 2025; Demir et al., 2022). Cities that can effectively absorb these external flows may compensate for shallow domestic green-finance markets, and our findings suggest that the H2 pathway is particularly compatible with this strategy. Multilateral institutions could therefore prioritise capacity-building support for emerging-economy cities that already display the FinTech and talent foundations consistent with H2.

5.3 Limitations and Future Research

Three limitations deserve acknowledgement. First, our outcome measure relies primarily on green patent counts, which may underestimate process and service innovations that are not patentable. Future work could incorporate eco-labelled product launches, environmental management system certifications, and patent-citation networks to capture a fuller picture of green innovation activity. Second, the cross-sectional design—although standard in fsQCA—does not capture the dynamics by which cities transition between configurations over time. A longitudinal extension using set-theoretic process tracing (Rupietta and Meuer, 2025) would be a valuable next step. Third, our six-country sample, while diverse, does not exhaust the emerging-economy frontier; extension to South Asian and sub-Saharan African urban systems would test the external validity of the framework. Finally, an unresolved question is the role of cross-border green capital flows and supply-chain integration, neither of which is captured in our current variable set; the rise of green trade finance and supply-chain decarbonisation suggests that these dimensions will become increasingly central to future configurational analyses (Yang et al., 2025; Demir et al., 2022).

In sum, this study has shown that the path to green technological innovation in emerging urban economies is not single, not symmetric, and not divisible into isolated factor effects. It is, instead, a configurational achievement in which FinTech readiness and economic maturity provide the load-bearing pivot and in which the supporting conditions can be orchestrated through alternative equifinal routes. Recognising this configurational character is essential for scholars seeking to advance the green innovation literature and for policymakers seeking to engineer sustainable urban transitions in the most consequential decade of the twenty-first century.

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