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ARTICLE

Strategic Governance Models for Scaling Clean Energy Startups in Emerging Economies: A Multi-Stakeholder Systems Perspective

Tejinder Singh Lakhwani

School of Management and Entrepreneurship, IIT Jodhpur, Jodhpur, Rajasthan 342030, India

ABSTRACT

This study proposes a strategic governance framework to accelerate the scalable deployment of clean energy startups in emerging economies. Startups in solar, hydrogen, storage, and smart grid technologies play a vital role in advancing energy transitions. However, in regions such as India, Nigeria, and Brazil, these ventures face systemic barriers including fragmented policies, financing gaps, and limited institutional coordination. This research integrates stakeholder ecosystem mapping, multi-level governance theory, and innovation helix models with simulation-based scenario analysis to address these challenges. Using System Dynamics (SD) and Agent-Based Modeling (ABM), the study evaluates three governance scenarios: centralized, decentralized, and public–private partnership (PPP) across key performance indicators: startup survival rate, scaling velocity, policy responsiveness, and stakeholder alignment. Case insights inform the modeling logic and highlight trade-offs across governance types. Findings suggest that PPP-based models offer the most balanced performance, combining scalability with institutional adaptability, while decentralized models support local innovation but require stronger systemic integration. Centralized governance, though stable, risks stifling entrepreneurship. This research contributes to a simulation-informed governance framework that can guide clean energy policy design, startup ecosystem

*CORRESPONDING AUTHOR:
Tejinder Singh Lakhwani, School of Management and Entrepreneurship, IIT Jodhpur, Jodhpur, Rajasthan 342030, India;
Email: lakhwani.1@iitj.ac.in

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development, and adaptive regulation in resource-constrained settings. It also provides a transferable foundation for future empirical studies and potential application to climate-tech entrepreneurship and carbon credit systems.
Keywords: Clean Energy Startups; Governance Models; Emerging Economies; System Dynamics; Policy Simulation; Public–Private Partnerships

1. Introduction

The global energy transition has become a strategic imperative in response to escalating climate risks, energy insecurity, and the urgent need for decarbonization. In this context, clean energy startups that are typically agile, innovation-driven, and mission-focused are increasingly recognized as key enablers of sustainable energy innovation. They play a pivotal role in commercializing renewable technologies, expanding energy access, and building decentralized, climate-resilient systems [1–3]. By driving forward solutions in solar photovoltaics, green hydrogen, battery storage, and AI-integrated smart grids, these ventures are helping to reshape the energy landscape in both developed and developing regions [4,5].

However, many emerging economies remain significantly constrained by clean energy startups' scalability and long-term viability. Structural inefficiencies such as regulatory fragmentation, financing gaps, weak infrastructure, and limited institutional coordination pose substantial challenges to clean energy entrepreneurship [6,7]. Policy inconsistencies, bureaucratic inertia, and market volatility further hinder ecosystem stability, despite growing international commitments under frameworks such as COP26 and the Sustainable Development Goals [8–10]. In parallel, while platform-based innovation ecosystems offer new opportunities for collaboration and expansion, the absence of adaptive governance often results in stakeholder misalignment and fragmented deployment strategies [11,12]. To address these challenges, scholars and practitioners increasingly advocate for multi-level, multi-stakeholder governance models that align public, private, academic, and civil society actors. Theories like the Triple Helix and Quadruple Helix provide frameworks for understanding how universities, industries, governments, and communities co-produce innovation in complex systems [13,14].

Meanwhile, simulation-based methods such as system dynamics (SD) and agent-based modeling (ABM) are being explored to evaluate policy effectiveness, model institutional interactions, and visualize startup scaling under different regulatory environments [15,16]. To contribute to this evolving discourse, the present study seeks to develop and validate strategic governance frameworks that support the scaling of clean energy startups in emerging markets, particularly those grappling with institutional and infrastructural bottlenecks. To contribute to this evolving discourse, this study offers a novel hybrid framework combining stakeholder ecosystem mapping, governance modeling, and simulation-based scenario analysis to evaluate and optimize the scalability of clean energy startups in emerging markets. Unlike prior research that separately treats governance and innovation diffusion, this study integrates theory-driven design and system-level policy experimentation using simulation tools such as SD and ABM. The research specifically aims to:

- To understand their roles and interdependencies, map the stakeholder ecosystem, including governments, venture capitalists, development agencies, startups, NGOs, and local communities.
- Compare centralized versus decentralized governance models for their effectiveness in enabling clean energy innovation and policy alignment.
- Identify institutional, regulatory, financial, and operational barriers and enablers influencing the growth trajectories of clean energy startups in selected regions.
- Design strategic roadmaps and multi-actor partnership models, such as public–private partnerships (PPPs), mission-driven accelerators, and regional innovation hubs.
- Apply systems modeling techniques, including SD and ABM, to test policy interventions and governance

strategies under varying scenarios.

By integrating theoretical insights with simulation-based empirical analysis, this study offers conceptual contributions and actionable strategies for stakeholders seeking to drive clean energy transformation in the Global South.

2. Literature Review

2.1. Clean Energy Entrepreneurship in Emerging Economies

Clean energy entrepreneurship has become central to sustainable development in emerging economies, especially where centralized energy systems fail to meet decentralized demand [17]. In contrast, developed economies show evidence of non-linear effects between renewable energy adoption and carbon efficiency, underscoring the complexity of transition dynamics even in mature contexts [9]. Solar, wind, bioenergy, and hydrogen startups have been instrumental in expanding energy access, localizing innovation, and creating green jobs [18–20]. These ventures often operate under institutional fragility, infrastructure deficits, and limited access to patient capital, which sharply distinguish them from counterparts in industrialized economies [3,6,21]. Recent studies emphasize that, beyond technical capacity, entrepreneurial success is influenced by robust ecosystem factors such as policy stability, regulatory clarity, access to funding, and networks of trust and knowledge [19,20]. However, despite targeted initiatives by governments and development actors, startups frequently fail to scale beyond pilot phases due to bureaucratic inertia, fragmented policy landscapes, and inconsistent subsidies [22,23]. These patterns underscore the need for integrated governance frameworks beyond piecemeal interventions and foster long-term coordination, experimentation, and resilience [24].

2.2. Governance Frameworks in Energy Transitions: Models and Gaps

Governance is increasingly recognized as a foundational element in facilitating energy transitions, particularly in contexts with limited institutional capacity and heterogeneous stakeholder landscapes [25]. Despite their value, these frameworks often remain siloed. Few studies attempt to integrate them into operational governance models that can be tailored to the fluid and resource-constrained realities of emerging market startups [26]. Key Governance Theories are:

1. Network Governance emphasizes horizontal, trust-based collaboration among public, private, and civic actors. It enables flexible problem-solving in fragmented institutional settings [11,12] and is particularly relevant in contexts where formal regulatory institutions are weak or underdeveloped [26].
2. Multi-Level Governance (MLG) explores vertical coordination across municipal, national, and supranational scales, especially crucial for aligning decentralized technologies with transnational financing and policy frameworks [7]. The case of Germany's energy transition illustrates how national objectives can be effectively balanced with sub-national implementation responsibilities [27].
3. Adaptive Governance promotes iterative, learning-based approaches that adjust to uncertainty and promote policy feedback loops, experimentation, and stakeholder responsiveness [8,14]. Emerging technologies such as green hydrogen also demand flexible, cross-sectoral governance to ensure alignment between technological viability and economic integration, especially in resource-constrained settings [28].
4. Triple and Quadruple Helix Models expand governance to include universities, industries, governments, and civil society actors as co-creators in innovation ecosystems [13,14].

Despite their value, these frameworks often remain tailored to emerging market startups' attempt to integrate them into operational governance tailored to the fluid and resource-constrained realities of emerging market startups [2]. Three major research gaps persist:

- Limited Inclusion of Non-State Actors: Most policy frameworks overlook local entrepreneurs, NGOs, and grassroots innovators, despite their pivotal role in informal or semi-formal energy transitions [13,18]. This lack of inclusion has also been highlighted in energy justice literature, which stresses the importance of

procedural equity and distributed agency [25].
- Under-theorization of Policy Volatility: There is insufficient exploration of how fluctuating policy regimes, inconsistent incentives, and regulatory instability impede venture scaling and investor confidence [1,23]. Institutional analyses suggest that transitions often stall when governance structures fail to adapt to uncertainty and actor diversity [26].
- Absence of Simulation-Ready Frameworks: While governance theories are well established, there is limited application of SD and ABM to simulate policy alternatives and institutional dynamics in clean energy ecosystems [15,16].

This study addresses the aforementioned gaps by integrating governance theories with simulation-based modeling to develop and evaluate strategic governance configurations suited for clean energy startup ecosystems. Prior research often treats policy formulation, stakeholder coordination, and innovation diffusion as separate domains. In contrast, this study operationalizes governance as a dynamic and interdependent system comprising actor behaviors, institutional feedback, and adaptive mechanisms.

Table 1 presents four foundational governance theories Network Governance, Multi-Level Governance, Adaptive Governance, and Helix Models commonly applied in energy transition and innovation literature. For each, the table outlines the core theoretical assumptions, key limitations identified in prior studies, and how the present research advances them through simulation-based modeling. The table demonstrates how these models are operationalized to assess clean energy startup scalability in emerging markets.

The selected governance theories Network Governance, Multi-Level Governance, Adaptive Governance, and the Helix Model are widely cited in the sustainability transitions, innovation ecosystem, and clean energy policy literature [1,14]. Together, they capture critical dimensions of governance: horizontal coordination, vertical policy integration, adaptive capacity, and stakeholder cocreation. Other theories, such as Principal–Agent models or Transaction Cost Economics, are more limited in scope and focus primarily on contractual dynamics at the firm level, making them less suitable for system-wide policy modeling.

By embedding these theoretical lenses into a simulation-ready policy experimentation framework, this research contributes a practical toolkit and conceptual advancement for designing resilient governance configurations tailored to the realities of clean energy entrepreneurship in the Global South.

Table 1. Governance models and their relevance.

Governance Theory	Core Assumptions	Limitations in Literature	How This Study Advances It
Network Governance	Trust-based horizontal coordination; stakeholder interdependence	Lacks formal policy levers in highly bureaucratic contexts	Integrated with ABM to simulate actor coordination
Multi-Level Governance	Coordination across scales of authority	Often descriptive, lacks a mechanism for design	Modeled in SD to explore vertical policy flows
Adaptive Governance	Policy learning, system feedback, iterative adjustments	Difficult to apply in rigid regulatory structures	Embedded in scenario testing logic
Helix Models	Innovation co-production by universities, government, industry, and civil society	Rarely operationalized in emerging market contexts	Translated into stakeholder mapping for simulation

3. Research Methodology

This study adopts a mixed-methods research design integrating qualitative case studies with simulation-based modeling to investigate and validate governance frameworks for scaling clean energy startups in emerging economies. The methodological framework addresses the empirical complexity of multi-stakeholder environments and the need for dynamic policy experimentation under uncertainty.

3.1. Qualitative Case Studies and Stakeholder Interviews

This study proposes a comparative qualitative case study approach as part of a conceptual framework to explore how different governance structures impact the scalability of clean energy startups across diverse emerging market contexts. The selection of cases is based on three countries, India, Nigeria, and Brazil, representing varied institutional configurations, policy dynamics, and levels of ecosystem maturity in the clean energy sector. **Table 2** outlines the comparative case study design involving India, Nigeria, and Brazil. For each country, it highlights the core focus areas (rooftop solar, mini-grids), the dominant governance models observed (PPPs, decentralized, hybrid), and the rationale for their selection. These cases were chosen to represent varying institutional capacities, governance maturity, and energy transition strategies across emerging economies, serving as contextual inputs for the simulation framework.

Table 2. Proposed case study design and focus areas.

Country	Key Focus Area	Governance Dimension	Rationale for Selection
India	Solar incubators, rooftop solar (Gujarat, Karnataka)	Public–private partnerships, innovation ecosystems	Rapid growth in solar decentralized initiatives at the state level
Nigeria	Off-grid and mini-grid solutions	Donor-supported PPPs, community energy models	Energy access gap, strong donor/startup collaboration
Brazil	Ethanol–hydrogen innovation hubs	Hybrid governance in clean fuels policy	Leading biofuel ecosystem; emerging hydrogen integration efforts

Note: At this stage, the interview protocol remains conceptual and has not yet been implemented. It is intended as a future research extension following preliminary model validation. A sample interview guide and proposed coding themes are provided in **Appendix A** to facilitate replication and future empirical application.

Each case will be examined using secondary data sources, including national and subnational energy policies, government program documents, international donor reports, and startup accelerator case studies. These documents will provide insight into institutional frameworks, policy instruments, and stakeholder alignments. To extend the empirical depth in future research applications, this study proposes a structured protocol for conducting semi-structured interviews with key stakeholder groups in each ecosystem. These stakeholders are expected to represent government, industry, finance, and civil society, each contributing distinct perspectives on barriers, enablers, and coordination mechanisms within the clean energy governance landscape. **Table 3** categorizes the primary stakeholders identified for semi-structured interviews across the three case study countries. It outlines each stakeholder group's expected contributions to the research, such as policy insight, financial ecosystem understanding, regulatory perspectives, or on-the-ground entrepreneurial challenges. These stakeholder inputs are intended to inform model calibration, validate scenario assumptions, and ensure contextual relevance of governance strategies.

Table 3. Key stakeholders for proposed interviews and their roles.

Stakeholder Group	Examples	Expected Contribution
Government & Regulators	Energy ministries, state regulators	Policy intent, regulatory bottlenecks, incentive structures
Startup Founders/Executives	Solar/hydrogen entrepreneurs	Operational barriers, innovation needs, and scaling challenges
Venture Capital & Development Finance	DFIs, green investors, angel networks	Investment risks, funding gaps, expectations
NGOs & Community Leaders	Rural energy NGOs, cooperatives	Equity concerns, local engagement, and trust-building

Qualitative data from these interviews would be coded using grounded theory principles, employing qualitative analysis tools such as NVivo or Atlas.ti. This would allow inductive identification of themes related to governance coordination, stakeholder misalignment, and innovation bottlenecks across the three contexts. The insights derived from this phase are intended to inform the development of simulation models in the next research stage. They will serve as empirical anchors for proposing context-sensitive, multi-actor governance frameworks to scale clean energy ventures in the Global South. These stakeholder categories interact in complex and interdependent ways to influence the growth trajectory of clean energy startups. **Figure 1** map depicts the multi-level and multi-actor governance ecosystem that shapes the scalability of clean energy startups in emerging economies. It illustrates the dynamic, bi-directional flows of influence, capital, trust, and regulatory feedback among key stakeholders government agencies, private investors, startups, civil society, and local communities. The diagram highlights coordination mechanisms and systemic interdependencies that drive innovation, policy responsiveness, and institutional resilience.

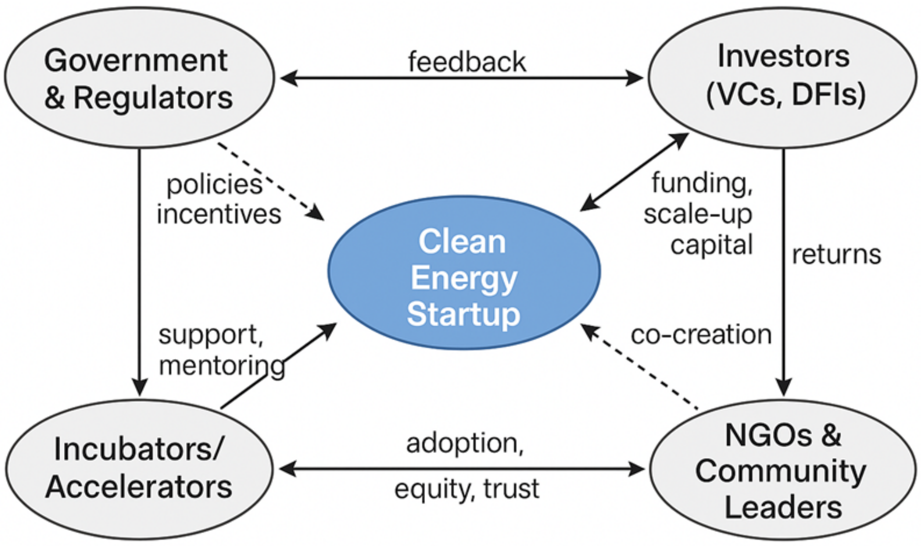

Figure 1. Governance ecosystem for clean energy startups.

3.2. Simulation-Based Modeling of Governance Scenarios

This study adopts a hybrid methodology combining simulation-based modeling and theory-driven analysis to complement the qualitative case analysis. The goal is to evaluate and visualize the performance of alternative governance strategies for scaling clean energy startups under complex, resource-constrained conditions. While the current study does not implement live simulations, it lays out a simulation-ready framework supported by theoretical models from the governance literature, validated using illustrative case insights drawn from India, Nigeria, and Brazil. Depending on the structure of stakeholder interactions and the dominant governance mechanisms identified in each case, the modeling approach may adopt either SD or ABM. To improve accessibility and ensure clarity for interdisciplinary readers, the simulation framework is designed as a conceptual testing tool rather than a full empirical implementation. It visualizes how different governance structures might influence startup growth, stakeholder coordination, and responsiveness to policy shocks. This approach supports "what-if" experimentation across contrasting institutional contexts.

- SD is appropriate for modeling aggregated behavior over time, particularly in contexts where policy cycles, resource allocation, and institutional inertia play central roles. This approach enables feedback loop representation and long-term scenario testing[15]. This is especially suitable for contexts with centralized governance, such as India's state-level solar programs or Brazil's biofuel strategy, where institutional inertia and long-term funding cycles are key drivers of change.
- ABM suits environments characterized by stake-

holder heterogeneity, localized decisions, and decentralized coordination. ABM is particularly useful for modeling contexts like Nigeria's decentralized mini-grid ecosystems. NGOs, local communities, and donor-funded startups interact through localized decision-making, trust-building, and variable regulation. ABM allows for simulating interactions among autonomous actors such as startups, government agencies, community representatives, and investors, with the ability to observe emergent governance patterns [16].

The simulation model is structured to test the impact of three governance scenarios:

- **Scenario A**: Centralized regulatory control with limited local engagement
- **Scenario B**: Decentralized governance with strong community and local actor participation
- **Scenario C**: Hybrid public–private partnership models with shared decision-making

The model is conceptualized to test a series of governance configurations, such as:

- Centralized regulatory frameworks vs. decentralized local governance
- Active public-private partnership

The literature and empirical case insights inform these assumptionsnity engagement and bottom-up coordination.

Each configuration will be evaluated using performance indicators that reflect both innovation and governance outcomes:

- Startup survival rate
- Scaling velocity (time to reach commercial viability or geographic expansion)
- Policy responsiveness (measured by adaptation speed to external shocks)
- Stakeholder alignment (consensus and coordination across actors)

To operationalize this structure, the model defines agents such as startups, government regulators, investors, and communities, each with their own behavioral rules. For instance, startups adjust scaling based on investment flow and local adoption; government agents respond to feedback signals; and communities influence the legitimacy and uptake of technologies. The literature and empirical case insights inform these assumptions, and their interactions are simulated over a ten-year horizon. A simplified version of the agent behavior and policy response logic is outlined in **Appendix B** to support transparency and future reproducibility. These scenarios are informed by theoretical concepts such as multi-level governance, adaptive regulation, and innovation ecosystem resilience. **Figure 2** outlines the dual-layered simulation structure that integrates qualitative case inputs with system-based modeling (SD and ABM). The framework links governance configurations (centralized, decentralized, hybrid) to policy levers, stakeholder dynamics, and outcome metrics such as scalability, responsiveness, and equity. It demonstrates how empirical case insights from India, Nigeria, and Brazil inform model parameterization, allowing for comparative scenario testing and future real-world implementation. **Table 4** presents the key governance configurations tested within the simulation framework Scenario A (centralized), Scenario B (decentralized), and Scenario C (public–private partnerships). Each configuration is evaluated across four metrics: Startup Survival Rate, Scaling Velocity, Stakeholder Alignment, and Policy Responsiveness. The table also outlines the theoretical foundations of each scenario and expected outcomes, providing a structured basis for scenario comparison. SD and ABM were selected due to their ability to simulate dynamic feedback and heterogeneous stakeholder behaviors, which are central to governance in energy transitions. Unlike econometric models, which require extensive historical data, or qualitative scenario planning, which lacks formal behavioral rules, SD and ABM offer the capacity to model emergent patterns, path dependence, and policy feedback loops in environments characterized by uncertainty and interdependence [15,17]. This is particularly appropriate given the lack of stable longitudinal data across the chosen countries and the exploratory nature of policy design in emerging contexts.

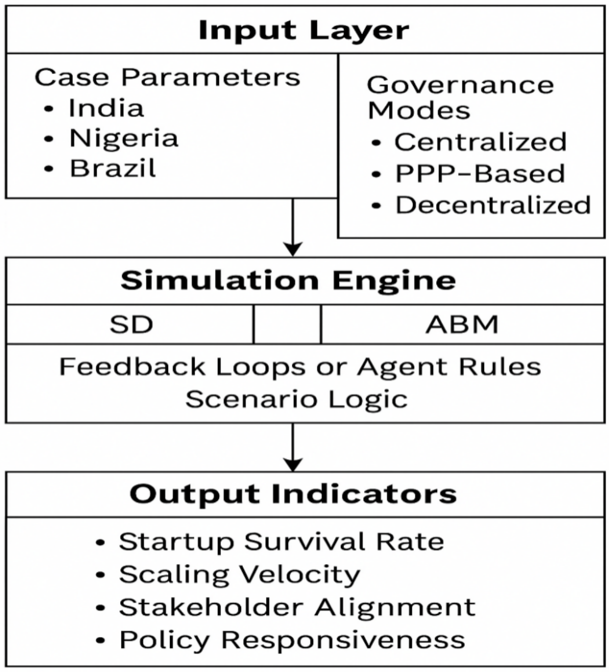

Figure 2. Conceptual simulation framework for governance scenario analysis.

Findings from the phases will be triangulated to design a strategic governance roadmap that reflects empirical realities and modeled foresight. This roadmap will identify actionable policy, financial, organizational, and institutional levers for fostering scalable and resilient clean energy startup ecosystems.

The integrated methodology enables theoretical development (by extending governance models) and practical applicability (by offering validated tools for policy experimentation). The mixed-methods approach addresses the clean energy transitions' multidimensional, evolving nature in emerging markets. **Appendix B** includes a pseudocode overview and schematic diagram describing agent rules, interaction triggers, time-step events (ABM), and feedback equations (SD) to ensure future replicability and model development.

Table 4. Simulated governance scenarios and evaluation metrics.

Scenario	Governance Type	Key Characteristics	Evaluation Metrics
Scenario A	Centralized Regulation	Top-down policymaking, limited local autonomy	Moderate survival, slow scaling, weak responsiveness
Scenario B	Decentralized Governance	Community engagement, local innovation, and bottom-up coordination	High alignment, variable survival, context-sensitive responsiveness
Scenario C	Public–Private Partnerships (PPP)	Shared decision-making, joint financing, mixed regulatory oversight	Fast scaling, moderate survival, strong adaptability

4. Case-based Discussion

The conceptual simulation framework developed in earlier sections is grounded in governance theories such as Multi-Level Governance, Adaptive Governance, and innovation helix models. These theoretical constructs manifest in practice by applying them to three case contexts: India, Nigeria, and Brazil. Each case is linked to one of the simulated governance scenarios (A, B, or C), enabling us to bridge abstract modeling with grounded, empirical insights. It applies the proposed governance framework to three illustrative cases: India, Nigeria, and Brazil, using publicly available data, secondary literature, and policy reports. The analysis combines governance typologies, identified enablers and barriers, and proposed roadmaps to evaluate the strategic environment for scaling clean energy startups.

4.1. Application of the Proposed Governance Framework

India: Rooftop Solar and Incubator Ecosystem (PPP-Oriented Governance): India's clean energy ecosystem reflects a hybrid governance configuration aligned with Scenario C (PPP-based governance) in the simulation framework. This structure resonates with the Triple and Quadruple Helix models, where governments, industries, research institutions, and civil society co-produce innovation and coordinate implementation. The PPP model enables shared decision-making, blended financing, and adaptive regulatory design, key traits of institutional resilience outlined in the theoretical foundations. India's rooftop solar program, particularly in states such as Gujarat and Karnataka, presents a hybrid governance model characterized by public–private partnerships (PPPs), innovation clusters, and targeted policy instruments. The Gujarat Solar Park initiative and Solar City Program demonstrate how regional governments, startup accelerators, and financial institutions can collaborate to incubate cleantech ventures and facilitate deployment. To enhance transparency in how the case illustrations were constructed, the key data sources consulted for each country. As this is a conceptually oriented study relying primarily on secondary materials, the case insights for India, Nigeria, and Brazil are drawn from a curated set of academic studies, government documents, and international project reports. These sources inform the interpretation of governance models and institutional dynamics relevant to clean energy startups. **Table 5** outlines the primary focus areas, source types, and specific references used per country to support traceability and replicability of insights. India, Nigeria, and Brazil were selected for contrasting positions along the governance maturity spectrum. India offers examples of structured public–private partnerships and innovation clusters. Nigeria presents a decentralized, donor-influenced landscape with off-grid energy solutions. Brazil illustrates hybrid federal governance with an active ethanol-to-hydrogen transition. Together, they capture geographic diversity, governance variability, and relevant startup ecosystems, making them suitable proxies for other Global South contexts. Applying Scenario C (PPP-based governance) from the simulation typology, India's case shows:

- High policy responsiveness through state-level subsidies, viability gap funding, and accelerated approval processes.
- Moderate startup survival is supported by incubators (CEED, TBI-IIT Madras) but is hindered by uneven policy implementation across states.
- Fast scaling velocity in early adopters (Gujarat, Telangana) but slower diffusion in less industrialized regions.
- Stakeholder alignment is moderately high, with visible coordination between government, startups, and multilateral finance agencies (IREDA, ADB).

Nigeria: Mini-Grids and Donor-Led Ecosystems (Decentralized Governance): Nigeria's clean energy startups primarily operate in an off-grid context supported by donor-driven programs like the Nigeria Electrification Project (NEP) and community energy cooperatives. The governance model aligns closely with Scenario B (decentralized governance), featuring bottom-up project initiation, flexible regulation, and community financing models. Simulation-based logic suggests:

- High stakeholder alignment, particularly locally through village energy committees and NGO involvement.
- Variable startup survival, as dependence on grants and pilot funding creates instability.
- Slow but steady scaling velocity, hindered by bureaucratic hurdles and customs delays.
- Policy responsiveness is weak at the federal level but adaptive at the community level.

Brazil: Ethanol–Hydrogen Clusters (Hybrid Governance): Brazil's energy innovation centers around biofuels and emerging hydrogen integration, governed by a polycentric system combining federal policy, private investment, and research institutes. The governance model overlaps Scenarios A and C, reflecting hybrid central-local governance. Key observations are:

- Policy stability is relatively high, especially in ethanol regulation, but emerging hydrogen policy remains fragmented.
- Startup scaling in the hydrogen sector is slow due to

infrastructural gaps and a lack of venture capital engagement.
- IP protection and technology transfer mechanisms remain underdeveloped, discouraging university–startup spinouts.
- Cross-sector alliances exist between petrochemical firms, academic labs, and federal energy bodies, but coordination is inconsistent.

Table 5. Country-level data sources for case illustrations.

Country	Primary Focus Area	Source Type	Specific References Used
India	Rooftop solar, PPP incubators, innovation clusters	Government reports, academic case studies	[5,11,14,18]
Nigeria	Off-grid mini-grids, donor-supported PPPs, and community energy	International project reports, development agency white papers	[10,17,21,27]
Brazil	Ethanol–hydrogen clusters, hybrid governance, R&D ecosystems	Federal policy reports, innovation agency reports, and academic literature	[1,3,9,29]

4.2. Key Governance Gaps Identified

Across the three cases, several common governance bottlenecks were observed, as stated in **Table 6**. It provides a transparent summary of primary data sources, government programs, and academic studies used to derive country-specific insights. These include rooftop solar pilot projects in India [5], donor-led mini-grids in Nigeria [21], and innovation finance programs in Brazil [23]:

Table 6. Governance barriers across case contexts.

Barrier	Evidence from Cases
Policy Inconsistency	State-level variation in India; lack of clarity in Nigeria's federal grid integration
IP and Innovation Transfer Gaps	Startups do not efficiently commercialize Brazil's hydrogen and bioethanol R&D
Infrastructure Weakness	Nigeria: mini-grid hardware logistics; Brazil: hydrogen transport; India: urban slums
Investor Access & Risk Aversion	All three markets show insufficient venture capital or derisking instruments.

4.3. Synthesized Outcomes Across Case Illustrations

Using the simulation-informed framework, **Table 7** summarizes the governance typologies observed in each country, highlighting key institutional barriers (policy volatility, funding fragmentation), enabling factors (PPP ecosystems, community engagement), and context-specific strategies recommended for scaling clean energy startups. The insights are derived from case-based interpretation and simulation-informed scenario analysis:

Table 7. Comparative insights across governance models.

Country	Governance Type	Dominant Barriers	Key Enablers	Recommended Roadmap
India	PPP-based Hybrid	Policy inconsistency, urban equity gaps	State subsidies, solar incubators	Cluster-based accelerators, mission-driven PPPs
Nigeria	Decentralized, Community	Funding volatility, regulatory gaps	Community ownership, NGO partnerships	Innovation sandboxes, local energy co-ops
Brazil	Polycentric Hybrid	IP barriers, slow R&D commercialization	Biofuel stability, academic–industry links	Tech-transfer platforms, federal startup grants

The results demonstrate that no single governance model is universally optimal. Instead, the successful scaling of clean energy startups depends on context-specific combinations of governance structures, stakeholder configurations, and adaptive policy instruments. Public–private partnerships offer fast scalability but require strong coordination; decentObservingusion but may lack stability; hybrid systinvestor agents ems thrive with aligned institutional logic. These insights provide a foundation for designing simulation-ready policy scenarios and adaptive governance roadmaps to support energy innovation in resource-constrained settings.

5. Simulation Model-based findings

It presents a simulation-based demonstration of how different governance configurations influence clean energy startup scalability. The simulations are built conceptually using benchmark parameters from literature and case-based heuristics, allowing for comparative scenario evaluation without relying on real-time primary data. The goal is to analyze "what-if" dynamics across governance types, especially under uncertainty and policy stress.

5.1. Simulation Setup and Scenarios

The framework integrates SD and ABM elements. While SD captures systemic variables like funding cycles and policy feedback, ABM simulates the behavior of autonomous actors such as startups, government agencies, investors, and NGOs. The model is calibrated using stylized inputs drawn from literature [15,16,30]. To illustrate the internal logic of the simulation, consider a scenario in which the government actor in Scenario C (PPP model) increases the subsidy level for clean energy startups. In the ABM layer, this change reduces the capital threshold startup agents require, increasing their survival probability during early-stage operations. As more startups survive and scale, community adoption rates rise due to lower costs, improving trust and uptake among community agents. Observing improved survival and adoption signals, investor agents increase their funding flows, creating a positive feedback loop. Simultaneously, in the SD layer, this policy change increases the inflow rate in the startup pipeline stock and reduces attrition in the survival flow. It also improves the stakeholder alignment score, as more agents (startups, government, investors, and communities) exhibit converging behaviors. Over time, the policy responsiveness index rises due to stronger feedback mechanisms and adaptive learning encoded in the governance model. **Table 8** summarizes these three governance types, outlining the core rules and coordination logics modeled in each scenario. Agents are:

- Startups: Modeled with traits for risk tolerance, capital availability, and technology readiness
- Government Actors: Implement policies with varying degrees of adaptability and subsidy strength
- Investors: Differentiated by risk appetite and green portfolio share
- Communities: Influence adoption rates and governance preferences

Table 8. Simulated governance scenarios.

Scenario	Governance Type	Key Rules Modeled
Scenario A	Centralized Regulation	High bureaucracy, slow feedback loops, and limited local autonomy
Scenario B	Decentralized Local Governance	Adaptive response, local resource control, varied actor behavior
Scenario C	PPP-Based Hybrid Governance	Shared decision-making, moderate adaptability, and co-investment

Each simulation: high0 years and outputs system-level metrics.

5.2. Governance Scenario Outcomes

Simulated results (based on benchmark trajectories) are summarized below across four key indicators. The reported metrics (**Table 9**) state the conceptual simulation runs based on stylized agent behavior and literature-calibrated parameters. While not empirically validated through primary data, they reflect comparative scenario dynamics under controlled governance configurations.

Table 9. Simulated performance metrics by governance scenario.

Indicator	Scenario A: Centralized	Scenario B: Decentralized	Scenario C: PPP-Based Hybrid
Startup Survival Rate (%)	48	63	72
Avg. Scaling Time (Years)	6.2	7.8	4.9
Stakeholder Alignment Score*	0.42	0.68	0.74
Policy Responsiveness Index†	0.35	0.82	0.71

* Score from 0 (misalignment) to 1 (full consensus); † Index from 0 (slow response) to 1 (highly adaptive).

Key Observations are:

- Scenario A (Centralized) shows low responsiveness and slower diffusion due to rigid policy structures.
- Scenario B performs well in adaptability and alignment but suffers from inconsistent survival due to weak capital networks.
- Scenario C outperforms startup survival and scaling velocity, balancing state support with private agility.

To complement the tabulated comparison, **Figure 3** normalized radar chart compares the three simulated governance scenarios (A: Centralized, B: Decentralized, C: Public–Private Partnership) across four key performance dimensions: Startup Survival Rate, Scaling Velocity (inverse of failure rate), Stakeholder Alignment, and Policy Responsiveness. Scenario C emerges as the most balanced, offering high responsiveness and stakeholder synergy. Scenario B scores high on community alignment but shows inconsistent scalability. Scenario A underperforms across most metrics, highlighting the limitations of rigid, top-down governance structures.

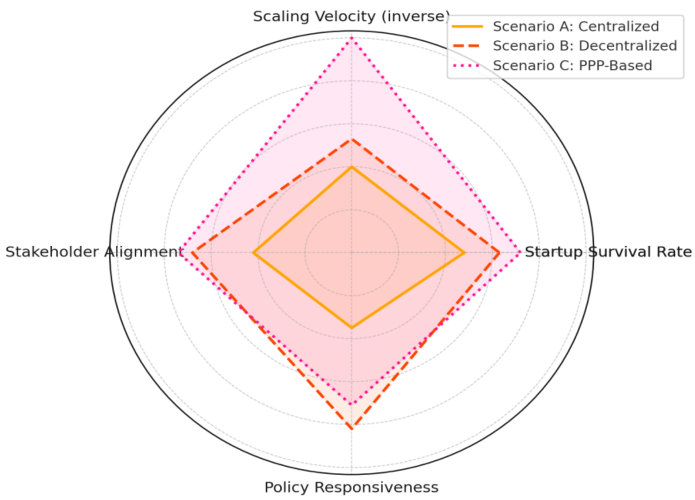

Figure 3. Comparative performance of governance scenarios across evaluation metrics.

5.3. Policy Implications from Simulated Scenarios

The comparative simulation analysis reveals several governance-specific insights relevant to policymakers, investors, and ecosystem enablers across emerging economies. Aligning the simulation findings with the case-based observations from India, Nigeria, and Brazil offers a synthesized interpretation of what governance strategies work best and where.

(i) PPP Models Offer Balanced Strengths (Scenario C): India's rooftop solar and startup incubator ecosystems exemplify Scenario C a PPP-based governance model that balances scalability, responsiveness, and moderate stakeholder alignment. This hybrid structure supports:

- Innovation sandboxes for piloting regulatory reforms,
- Co-financed startup accelerators to attract blended capital, and
- Flexibility corridors enabling iterative, state-led policy experimentation.

PPP models have proven successful where state governments are proactive and innovation clusters serve as intermediaries between finance, policy, and technology.

(ii) Decentralization Enhances Adaptability (Scenario B): Nigeria's off-grid mini-grid ecosystem demonstrates the strengths of decentralized governance: strong stakeholder alignment and local legitimacy. However, institutional fragmentation and limited financial coordination constrain its scalability. To strengthen this model:

- Capital mobilization tools such as green sovereign funds and donor consortia should be institutionalized.

- Intellectual property regimes and scale-up pathways must be formalized to encourage long-term investment.

Decentralized models work best where community engagement is strong but must be complemented by supportive national infrastructure.

(iii) Centralized Models Inhibit Innovation (Scenario A): Brazil's centralized approach to ethanol regulation reflects Scenario A. While effective for ensuring energy stability, it limits the diffusion of newer technologies (hydrogen clusters). Centralized governance can still be suitable in:

- High-capacity states with strong enforcement and mission-oriented policy coherence,
- Sectors requiring regulatory control, such as grid security or biofuel compliance.

However, these models risk inhibiting entrepreneurial experimentation and cross-sectoral coordination.

(iv) Systemic Trade-Offs Are Unavoidable: The simulations underscore that governance involves unavoidable trade-offs:

- Rapid scaling (Scenario C) may limit local inclusivity.
- High adaptability (Scenario B) can reduce national coherence.
- Strong control (Scenario A) supports compliance but may deter innovation.

Therefore, governance design must be context-sensitive, iterative, and actor-aware, rather than a universal template. **Table 10** presents a regional strategy matrix, mapping each country's aligned governance scenario, key strengths, policy gaps, and recommended instruments.

These findings confirm the utility of the simulation framework as a flexible tool for ex-ante policy experimentation.

Table 10. Regional governance strategy matrix: case-specific policy pathways.

Country	Aligned Scenario	Effective Elements	Required Enhancements	Recommended Instruments
India	Scenario C (PPP)	State subsidies, incubators, and policy responsiveness	Inter-state coordination, last-mile access	Viability gap funding, mission-driven PPPs, green bonds
Nigeria	Scenario B (Decentralized)	Community ownership, NGO partnerships	Stable funding, national innovation platforms	Innovation sandboxes, sovereign guarantees, and rural IP registry
Brazil	Scenario A/C Hybrid	Policy stability (ethanol), federal R&D links	Technology transfer mechanisms, venture capital incentives	Tech transfer offices, federal grant schemes, and hydrogen consortia

6. Conclusions

This study proposed and conceptually demonstrated a hybrid framework for evaluating strategic governance models that support the scaling of clean energy startups in emerging economies. The research contributes to the academic discourse and practical policy design for sustainable energy transitions by integrating insights from innovation governance theory with simulation-based scenario analysis.

6.1. Theoretical Contributions

This study contributes to the theoretical advancement of governance research in sustainability transitions by developing a structured framework that integrates multi-level governance, innovation ecosystems, and adaptive regulation. It emphasizes the central role of heterogeneous actors, including startups, government bodies, investors, and community stakeholders, in shaping the trajectory of clean energy transitions. The framework provides a nuanced understanding of governance diversity in emerging markets by exploring the dynamic trade-offs between centralized control, decentralized innovation, and hybrid public–private partnerships. Unlike existing studies focusing primarily on technology diffusion, this work applies simulation logic using SD and ABM to strategic governance configurations. In doing so, it addresses a critical gap in the literature: the lack of integrative, scalable governance models that can inform decision-making under institutional uncertainty and resource constraints.

6.2. Practical Implications

The study offers several actionable insights for stakeholders engaged in clean energy transitions within resource-constrained environments. Policymakers can leverage the proposed governance typologies and simulation-based indicators to evaluate "what-if" scenarios and anticipate the systemic impacts of policy reforms before implementation. For investors and incubators, the framework highlights the conditions under which startup survival rates and scaling velocity are optimized, enabling more informed decisions about ecosystem engagement and risk allocation. Regional planners can apply the findings to design localized interventions such as innovation sandboxes, public–private partnership (PPP) accelerators, and cluster-based hubs that reflect the specific dynamics of local stakeholders. Importantly, the comparative analysis of India, Nigeria, and Brazil illustrates no universally optimal governance configuration. Instead, governance strategies that are contextually grounded, particularly those that emphasize stakeholder alignment and adaptive policy response, are most likely to foster sustainable, scalable energy entrepreneurship.

6.3. Transferability and Contextual Limitations

While the proposed simulation-ready governance framework is grounded in case insights from India, Nigeria, and Brazil, its underlying structure is designed to be adaptable across other Global South contexts. Regions such as Southeast Asia, Latin America, and the Middle East and North Africa (MENA) share several structural challenges, including institutional fragmentation, financing gaps, and variable regulatory environments that affect the scalability of clean energy startups. However, the transferability of the framework is subject to important contextual limitations. Factors such as political stability, strength of civic institutions, public trust in governance, and maturity of innovation ecosystems vary considerably across countries. For example, while community-driven models may be suitable in parts of Sub-Saharan Africa or Southeast Asia, they may require different assumptions in highly centralized or security-sensitive MENA contexts.

Additionally, implementation would require localized calibration of model parameters such as subsidy thresholds, risk perception, and actor behavior based on empirical data and stakeholder feedback. Therefore, this study presents a flexible architecture for governance experimentation but emphasizes that future applications must be adapted to the target context's unique socio-political and institutional dynamics.

6.4. Future Work

Future research may extend this framework in several directions:

- Empirical implementation using real-world stakeholder interviews and quantitative model calibration across emerging economies.
- Application to climate-tech domains, such as carbon capture, electric mobility, and urban resilience, where governance challenges mirror those in clean energy startups.
- Integration with carbon credit ecosystems, exploring how governance design influences transparency, certification integrity, and market participation in carbon offset platforms.

This study provides a scalable foundation for navigating the complex, actor-rich, and policy-volatile terrain of clean energy entrepreneurship in the Global South by offering a conceptual roadmap and simulation-ready toolkit.

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Data Availability Statement

The data supporting the findings of this study are not publicly available due to privacy and ethical restrictions.

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Conflicts of Interest

The authors declare no conflict of interest.

Appendix A

Sample Interview Protocol and Coding Themes

This appendix provides a conceptual template for stakeholder interviews to be conducted in future phases of the research. The aim is to capture diverse perspectives on governance, innovation barriers, and stakeholder coordination within clean energy startup ecosystems in emerging economies. These interview questions and thematic codes are designed to guide data collection and analysis using grounded theory principles.

Table A1. Sample semi-structured interview questions.

Stakeholder Group	Sample Interview Questions
Government & Regulators	- What policies or regulatory incentives currently support clean energy startups in your jurisdiction? - What challenges do you face in coordinating across different government levels or departments? - How responsive is your policy framework to new startup models or technologies?
Startup Founders/Executives	- What are the major regulatory or operational hurdles you face in scaling your startup? - How would you describe your interactions with government agencies, incubators, and investors? - What governance or partnership models have helped you grow?
Venture Capital & DFIs	- What factors influence your decision to invest in clean energy startups in emerging economies? - What types of governance or de-risking mechanisms improve investor confidence? - How do you assess scalability potential in different regulatory contexts?
NGOs & Community Leaders	- How are local communities involved in clean energy initiatives? - What governance barriers affect community acceptance or participation? - What strategies have worked to bridge trust between startups and local users?

Table A2. Preliminary coding themes for qualitative analysis.

Code Category	Example Codes
Governance Structures	Top-down policymaking, decentralized coordination, PPP dynamics
Policy Instruments	Subsidies, tax incentives, feed-in tariffs, licensing speed, and approval delays
Stakeholder Coordination	Multi-agency overlap, cross-level friction, vertical alignment
Startup Barriers	Grid integration, infrastructure delays, IP issues, and policy inconsistency
Investment Conditions	Risk appetite, co-investment logic, and green finance access
Community Engagement	Awareness programs, co-design practices, local ownership, trust-building
Adaptability & Feedback	Policy iteration, feedback loops, sandboxing, agile reform

These codes are aligned with grounded theory principles and will be refined iteratively based on data collected.

This protocol is a foundational input for future empirical data collection and model calibration. Interview transcripts coded using these themes can support the refinement of agent behaviors in the simulation models and validate the performance metrics across governance scenarios.

Appendix B

Simulation Logic and Pseudocode Framework

This appendix provides a conceptual structure and pseudocode logic for the simulation model proposed in Section 3.2. It integrates SD for aggregated policy feedback loops and ABM for decentralized actor interactions. The design is suitable for implementation in simulation platforms such as AnyLogic, NetLogo, or Python (Mesa).

This appendix provides the simulation logic that underpins the conceptual governance scenarios analyzed in the study. The model integrates SD to capture policy feedback and resource flows, and ABM simulates interactions among startups, government actors, investors, NGOs, and communities. The logic described here will support future empirical calibration and simulation implementation in platforms such as AnyLogic, NetLogo, or Mesa (Python).

Table A3. Agent-based model (ABM) structure.

Agent Type	Key Attributes
Startup	Capital level, tech readiness, survival probability, risk tolerance
Government	Policy adaptability, subsidy level, regulation delay, and feedback rules
Investor	Risk appetite, green finance portfolio share, and co-investment behavior
Community	Trust level, energy need index, adoption propensity, equity feedback
NGO	Facilitation score, local engagement index, awareness campaign impact

```
Interaction Rules (Pseudocode):
for t in range(1, T_max):
  for startup in startups:
    startup.evaluate_regulatory_burden(government)
    startup.seek_investment(investors)
    startup.evaluate_adoption_rate(community)
    startup.update_survival_status()

  for government in governments:
    government.receive_feedback(startups, communities)
    government.update_policy_if_feedback_threshold()

  for investor in investors:
    investor.adjust_investment_strategy(government)
    investor.fund_startups(startups)

  for community in communities:
    community.evaluate_trust(government, startups)
    community.update_adoption()

  log_simulation_metrics(t)
```

Table A4. System dynamics (SD) loop.

Stock	Flow In/Out
Startup Pipeline	+ Incubation, – Attrition (regulated by risk + capital)
Policy Responsiveness	+ Feedback adaptation, – Bureaucratic delay
Funding Availability	+ Green investment inflow, – Disbursement to startups
Stakeholder Alignment	+ Coordination efforts, – Miscommunication incidents

Used to model aggregate policy inertia, scaling delays, funding cycles, and systemic feedback.

Core Stocks and Flows.

Equations:

- Startup Survival Rate:

$$\begin{aligned} \text{Survival}(t) = \text{Survival}(t-1) + \\ \alpha_1 * \text{Funding}(t) - \beta_1 * \text{Risk}(t) \end{aligned} \tag{1}$$

- Policy Responsiveness (with Delay):

$$\begin{aligned} \text{Response}(t) = \text{Response}(t-1) + \\ \gamma * (\text{Feedback Input} - \text{Threshold}) \end{aligned} \tag{2}$$

- Scaling Velocity (Time to Diffusion):

$$\begin{aligned} \text{Scale}(t) = \delta * \text{Survival}(t)\text{Policy Lag}(t) + \\ \text{Infrastructure Delay}(t) \end{aligned} \tag{3}$$

Table A5. Scenario encoding.

Scenario	Key Parameter Overrides
A	Low policy adaptability, high bureaucratic delay, and no community interaction
B	High community feedback sensitivity, decentralized investment behavior, variable risk sharing
C	Moderate delay, adaptive feedback, co-financed decision-making (PPP logic)

These parameter values can be calibrated iteratively during live simulation runs using empirical data or exploratory sensitivity analysis. This simulation logic is designed to offer flexibility and modularity, enabling it to be extended for related domains (carbon markets, electric mobility) or adapted for empirical calibration using stakeholder input data in future fieldwork phases.

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