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# When Structural Synergy Does Not Translate into Resilience: Governance and Functional Insularity in Island Systems

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**Abstract**

Interconnected territorial systems may benefit from cross-sectoral synergies, yet greater integration does not necessarily translate into greater resilience. This study develops a conceptual and mathematical framework for examining how institutional conditions modulate the contribution of structural synergy to systemic resilience. It introduces Functional Insularity as an operational state in which a territory must sustain essential functions under constrained access to external support, and proposes the Composite Resilience Index (CRI) to represent the interaction between baseline structural capacity, latent cross-sectoral synergy, and institutional transmission. The framework is operationalized using Sustainable Development Goal indicators for five island jurisdictions: Malta, the Dominican Republic, Cuba, Fiji, and Haiti. A sensitivity analysis explores how alternative assumptions about structural capacity, synergy, and institutional conditions affect modelled resilience. A comparison using the World Bank's Worldwide Governance Indicators further examines the sensitivity of the resulting institutional profiles to alternative governance measures. The results illustrate contrasting modelled configurations, while the governance comparison reveals heterogeneous agreement across cases, highlighting the importance of measurement choices and model assumptions. The study contributes a framework for investigating why similar levels of structural integration may yield different resilience outcomes under different institutional conditions. Although the empirical application is conducted at the national level and does not directly measure urban resilience, the concept of Functional Insularity offers a basis for future research on urban systems whose essential services depend on interconnected infrastructures, resource flows, and institutional coordination. Further independent validation is required before the CRI can be used as a predictive or operational resilience indicator.

**Keywords:** Systemic resilience; Functional insularity; Composite Resilience Index (CRI); Institutional maturity; Socio-technical systems; Structural synergy

## 1. Introduction

The resilience of complex regional systems has traditionally been evaluated through the lens of external connectivity and redundant supply chains. Under this paradigm, systemic stability is contingent upon a region's integration into global networks of energy, resources, and data.

However, recent global disruptions (ranging from geopolitical fragmentation to extreme climatic events) have revealed that hyper-connectivity can function as a double-edged sword, facilitating the rapid propagation of cascading failures. This shift in the global risk landscape necessitates a fundamental reevaluation of systemic autonomy, leading to what this paper defines as "Functional Insularity."

Functional insularity represents a strategic state in which a system must maintain its operational integrity while decoupled from external support networks. While the conceptual foundations of socio-ecological resilience are well-established (Elmqvist et al., 2003), (Elmqvist et al., 2026), a significant gap persists in the quantitative assessment of internal system dynamics during periods of isolation. Current metrics predominantly focus on post-shock recovery (adaptive resilience) but fail to capture the internal strength derived from the synergistic interaction between socio-technical sectors. While resilience is primarily assessed using performance and recovery indicators, synergy is measured through interaction models. However, the reviewed literature highlights the lack of integrated metrics that simultaneously capture recovery dynamics and internal system interactions.

To address this gap, this research proposes a new resilience architecture embodied in the Composite Resilience Index (CRI), a multi-dimensional mathematical framework designed to quantify the resilience of autonomous systems. Rather than representing governance as an additional resilience dimension, the proposed framework models institutional maturity as the transmission mechanism governing the efficiency with which latent structural synergies become realized macro-systemic resilience. This distinction separates the proposed framework from conventional additive resilience indices, in which governance contributes directly to the resilience score rather than regulating the conversion of structural interactions into effective resilience. The framework evaluates the capacity for sectoral synergy by utilizing emergent socio-technical configurations (such as green hydrogen integration and circular biomass buffers) as illustrative examples of sectoral coupling. By decoupling a system's base capacity from its synergistic strength, the CRI provides a robust decision-support tool for planners and engineers to design regional architectures that are not merely resistant to external shocks, but inherently capable of self-sustenance under institutional constraints.

This research does not merely propose a new metric; it introduces a new resilience architecture, while Functional Insularity provides the conceptual paradigm within which that architecture becomes operational. By framing isolation not as a spatial constraint but as an operational state, the proposed framework is elevated from a case-specific index into a generalized analytical framework for autonomous socio-technical networks. By synthesizing the ecological resilience frameworks of Elmqvist,(Elmqvist et al., 2003) , (Elmqvist et al., 2026) the planetary constraints of Kronenberg (Kronenberg et al., 2024), and the economic trade-offs of Fertő (Fertő & Harangozó, 2025), the CRI transforms functional insularity from a passive vulnerability into a quantifiable, scalable benchmark for 21st-century systemic stability.

In addition, this study addresses three related questions: (1) how can the interaction between baseline structural capacity, cross-sectoral synergy, and institutional governance be represented in a unified resilience framework; (2) how sensitive are the resulting modelled resilience profiles to alternative assumptions and governance measures; and (3) what conceptual insights can this framework offer for the study of functionally bounded territorial systems? We address these questions by developing the Composite Resilience Index (CRI), operationalizing its components using SDG indicators, and examining five island jurisdictions with contrasting structural and institutional profiles. The empirical exercise is exploratory rather than a direct observation of resilience under realized disruption. Its contribution lies in formalizing a governance-modulated account of structural synergy and identifying the conditions under which this account warrants further empirical testing.

**2. Review toward unified metrics of resilience and synergy interrelation**

The evolution of resilience theory has transitioned from a focus on static stability toward a dynamic understanding of adaptive capacity. However, a prominent challenge remains: the lack of a standardized, universal metric. With over 70 competing definitions, cross-disciplinary communication remains fragmented (Fisher, 2015). Originally rooted in Holling's (1973), (Holling, 1973) seminal distinction between engineering resilience—defined by the speed of return to equilibrium—and ecological resilience, the field now emphasizes a system's ability to absorb shocks without collapsing into an undesirable state. This paradigm shift, advanced by scholars such as Scheffer et al. (2012) and Lenton et al. (2008) ( (Scheffer et al., 2012) (Lenton et al., 2008)) has successfully migrated from biological ecosystems to critical infrastructure and socio-economic frameworks, establishing resilience as a universal property of complex, interconnected systems.

A critical analysis of current literature reveals a persistent tension between theoretical robustness and operational precision. While early conceptual models established the groundwork for adaptive cycles, they often lacked the empirical metrics required for practical management. The drive toward quantitative indicators are significantly motivated by the methodological frameworks of Malaska et al. (1999), Luukkanen et al. (2012), and Lauraéus and Kaivo-oja (2022) ((Malaska et al., 1999) , (Luukkanen et al., 2012) , (Lauraéus & Kaivo-oja, 2022)). By pioneering synergy metrics and, decomposition analysis these authors elucidated how systemic performance can be mathematically deconstructed into its constituent drivers. Their work provides the quantitative rigor necessary to explain how component interactions generate collective behaviors that exceed the sum of their parts, effectively balancing the trade-offs between modularity and connectivity. However, they do not propose metrics to quantitatively capture resilience alongside the internal connections between systems.

Contemporary contributions by Biggeri et al. (2019) and Huan et al. (2026) ((Biggeri et al., 2019), (Huan et al., 2026)) have introduced advanced synergism and performance metrics. Nevertheless, resilience is frequently treated as an emergent property without a unified measurement framework. As Vlot et al. (2019) (Vlot et al., 2019), observe, formula selection

must be context-specific, as no single metric possesses universal applicability. Synergy offers a complementary structural perspective, capturing interaction effects often missed by traditional frameworks. Consequently, integrating resilience and synergy represents a promising frontier for enhancing system reliability under uncertainty.

Current trends reflect a shift toward systemic integration, particularly concerning the United Nations Sustainable Development Goals (Dang & Serajuddin, 2020), (Akhtar et al., 2023), and (Assubayeva & Marco, 2024). Researchers such as Pradhan et al. (2017) and Basu et al. (2024) ((Pradhan et al., 2017) (Basu et al., 2024)) argue that resilience cannot be studied in isolation but must be viewed through the lens of interdependencies. To operationalize this, recent methodologies (Huan et al., 2026) utilize empirical synergy analysis to map interactions directly within the SDG framework, identifying specific "accelerator" targets—such as quality education or climate action—that yield the highest systemic return on investment.

While the frontier of urban science has established a clear trajectory toward regeneration and self-sufficiency ((Elmqvist et al., 2026); (Bai et al., 2025) ), current literature faces a significant operational gap: the absence of a framework that quantitatively integrates cross-sectoral structural dynamics with institutional complexity. Although multisectoral integration is widely recognized as a global imperative for sustainability, there remains a lack of models capable of diagnosing why systems with high synergistic potential often falter in their transition toward true operational autonomy. This limitation stems not only from the absence of institutional variables, but also from the prevailing practice of representing governance as one additional resilience dimension rather than as the mechanism regulating the efficiency with which structural synergies become operational resilience. This methodological void underscores the critical need for a new framework—one capable of translating institutional friction into an evaluative parameter, thereby evolving the resilience paradigm into a framework for sovereign operational stability in an increasingly fragmented global landscape.

This state-of-the-art review illuminates a definitive transition from conceptual exploration toward methodological consolidation. While the historical evolution from ecological stability to dynamic adaptation is well-documented, the current frontier lies in the empirical integration of structural synergy with temporal resilience. The literature suggests that while multi-sectoral metrics and SDG-based "accelerators" have provided sophisticated tools for navigating volatility, the field remains fragmented by domain-specific silos. Therefore, the future of the discipline hinges on bridging the gap between high-level mathematical abstractions and actionable, site-specific implementation. This synthesis underscores the urgent need for unified, hybrid frameworks like the one proposed in this study, which can operationalize the resilience-synergy nexus and transform theoretical insights into robust decision-support strategies for an increasingly interconnected world.

## 3. **Theoretical Framework and Methodology**

### 3.1. Conceptualizing Sectoral Synergy and Interaction

The mathematical definition of synergy in this study draws upon the interaction models proposed by (Luukkanen et al., 2012). In a time-invariant system, the output $z$ can be determined by the interaction of inputs $x$ and $y$ through the expression:

$$z = ax + by + cxy + d \quad (1)$$

In this formulation, while the coefficients $a$ and $b$ represent the impact of individual inputs, the term $cxy$ represents the explicit interaction. Synergy is thus defined as a desired combined multiplicative effect where the cross-interaction leads to an increase in total output. Conversely, a negative interaction ($c < 0$) signifies a "trade-off," where the coupling of sectors diminishes the system's overall performance.

To evaluate the depth of sectoral integration within the selected island systems, this study transcends traditional economic models of market concentration. While conventional tools such as the Herfindahl-Hirschman Index (HHI) (Augustinaitis et al., 2022) are highly effective at identifying internal dominance and asset distribution within a single, isolated sector, they are fundamentally ill-equipped to map the complex, multidimensional interdependencies between distinct sectors. To bridge this methodological gap, we utilize the Lauraéus and Kaivo-oja (LKI) framework (Lauraéus & Kaivo-oja, 2022) Unlike the node-centric HHI, the LKI framework enables a nuanced quantitative assessment of functional cross-sectoral dependencies. By weighting these multi-sectoral interactions according to their strategic systemic importance, the LKI approach provides a holistic mathematical representation of structural coupling. Crucially, within this framework, complex systems can be evaluated by deploying illustrative configurations—such as a conceptual energy-transportation-food nexus in the hydrogen economy—to demonstrate how integrated sectors function as a unified socio-technical whole rather than as an aggregate of isolated silos.

### 3.2. Resilience as an Emergent Systemic Property

A critical departure from traditional linear indices is the treatment of Systemic Resilience ($R$) as an emergent property rather than a simple aggregate. Resilience is driven not only by sectoral efficiency but by the density and quality of functional integrations—the "circularity" of the system.

Without loss of generality, one may posit a model relating systemic resilience to both baseline sectoral performance and cross-sectoral integration effects. However, given the inherently interdependent and non-linear nature of these factors, resilience cannot be interpreted as a simple additive combination. Instead, integration effects actively modulate performance itself, generating feedback loops that amplify system-wide outcomes. Consequently, a generalized macro-formulation of systemic resilience ($R(t)$), is a function of a baseline capacity and its integration effects.

Therefore:

$$R(t) = f(Performance, Integration\ Effects) \quad (2)$$

where $f(.)$ represents a potentially non-linear function capturing the interactions, feedbacks, and emergent properties arising from the baseline capacity ($B$), structural synergy ($S$), and institutional transmission ($\kappa$). This formulation reflects the core tenets of Complex Adaptive Systems (CAS), where resilience arises from the quality, intensity, and structure of interconnections, enabling adaptive, self-reinforcing dynamics over time.

3.3. The Resilience-Synergy Model

To formalize these relationships into an operational framework, we introduce a model where the marginal effect of sectoral synergy on total resilience is directly proportional to the system's baseline performance ($B$), modulated by an institutional transmission filter. We define this relationship through the following partial derivative:

$$\frac{\partial R}{\partial S} = \kappa B \qquad (3)$$

Where $\kappa$ represents the sensitivity or transmission coefficient of the system to synergistic configurations. By integrating this differential expression with respect to $S$ and applying the boundary condition that resilience must equal baseline capacity in the absence of interaction ($R = B$ *when* $S = 0$) we derive the complete formulation for the Composite Resilience Index (CRI) as equation (4).

$$R = B(1 + \kappa S) \qquad (4)$$

This specification allows for a robust, mathematically structured interpretation of system dynamics across different governance and technical regimes, as detailed in Table 1.

Table 1. Interpretation of system dynamics according to synergistic sensitivity coefficient $\kappa$

| **When:** | **Effect:** |
|---|---|
| $\boldsymbol{\kappa = 1}$ | The marginal effect of synergy is linear and unitary; system resilience scales proportionally with the direct interaction of baseline assets ($B$) and structural coupling ($S$). |
| $\boldsymbol{\kappa > 1}$ | The system exhibits high synergistic amplification, where institutional maturity optimizes transmission, yielding accelerating, non-linear gains in operational resilience. |
| $\boldsymbol{\kappa < 1}$ Including $\boldsymbol{\kappa < 0}$ | The system faces diminishing returns or "trade-offs," where sectoral coupling may introduce vulnerabilities or inefficiencies. |
| $\boldsymbol{\kappa = 0}$ | Resilience is strictly additive ($R = B$), implying a fragmented system with no emergent properties. |

The proposed formulation (equation 4), serves as a quantitative framework for capturing systemic resilience as an emergent property. Traditional approaches to resilience often rely on simple linear aggregation, assuming that the performance of a system is merely the sum of its sectoral components. Such methods, however, fail to account for the amplification effect inherent in interconnected systems.

We justify the use of a multiplicative structure based on the theory of systems integration. In this model, baseline performance ($B$) represents the system's capacity in a "vacuum"—its intrinsic potential. However, in a real-world complex system, sectoral interactions do not merely add to the baseline; they provide a structural environment that either amplifies or suppresses this potential.

By defining $R = B(1 + \kappa S)$, we explicitly treat resilience as an interaction effect. If a system has high baseline performance but zero functional connections ($S = 0$), resilience is limited to the baseline (no synergy). As connectivity increases, the synergy term $\kappa BS$ acts as a catalyst, scaling the entire system output. This reflects the reality that a well-integrated system is more than the sum of its parts—it is a system capable of collective adaptation. We consider this model has both, non-linearity and emergence property.

The inclusion of the sensitivity parameter $\kappa$ allows the model to capture the dynamic responsiveness of the system. While $S$ represents the *structural potential* for synergy, $\kappa$ represents the *efficiency* with which the system architecture translates those connections into resilience gains. This distinction could be valuable also for foresight studies. It allows policymakers to identify not only where new connections are needed (increasing synergy $S$) but also where institutional or technical barriers exist that hinder the conversion ($\kappa$) of those connections into actual resilience ($S$). So, sensitivity ($\kappa$) is modelled as a dynamic driver.

In addition, this model maintains the principle of parsimony. It reduces complex inter-sectoral dynamics to a first-order approximation that is both mathematically tractable and theoretically intuitive. It provides a formal bridge between static structural indices (like the HHI and LKI) and the dynamic requirements of resilience modeling.

The derivation of $R$ from the partial derivative $\frac{\partial R}{\partial S} = \kappa B$ underscores that the marginal contribution of any new functional connection is intrinsically tied to the existing system capacity. This aligns with empirical observations in complex systems theory stating that the "value" of an additional link between sectors is higher when the sectors themselves are robust.

From a conceptual standpoint, this internal coupling echoes the qualitative framework of Wijesekara (2025) (Wijesekara, 2025), who utilizes the notation 1+1≠2 to illustrate synergetic dynamics. Although Wijesekara's formulation functions as a theoretical metaphor rather than a literal mathematical constraint, it shares a profound conceptual alignment with the non-linear architecture of our proposed model. Beyond the guaranteed mathematical accuracy, the proposed model captures a positive feedback loop where systemic resilience emerges from the synergy of interconnected capacities rather than from the isolated performance of individual subsystems.

The proposed model interprets resilience as an emergent structural property arising from the interaction between systemic connectivity and institutional regulation. In this framework, synergy does not inherently increase resilience; rather, its effect depends on the sensitivity parameter $\kappa$, which governs whether internal flows are stabilized, accumulated, or

destabilized. Consequently, excessive connectivity under weak sensitivity parameter may amplify systemic fragility by facilitating cascading failures across sectors.

Consequently, our model provides a superior heuristic for simulating future pathways, as it allows researchers to explore scenarios where policy interventions target either the baseline capacity of sectors or the effectiveness of their functional coupling. Nevertheless, this model still is “conceptual” without current and contrastable data that can convert into resilience and synergy metrics. Accordingly, the next step will be necessary the operationalization of variables.

3.4. The Reference Operationalization Scenario: The Green Hydrogen Economy as a Sectoral Coupling Archetype.

To transition the abstract mathematical relationships defined in the Resilience-Synergy Model (Section 3.3) into an operational diagnostic tool, the system's potential intersectoral synergy ($S$) must be grounded in a specific technological configuration. In this framework, the deployment of a green hydrogen ($e - H_2$) economy is selected purely as a conceptual reference archetype—an illustrative heuristic case rather than an empirical technical object of study. Within a boundary-closed system or a functional island—abstracted here as any regional socio-technical network experiencing acute logistical, economic, or political decoupling—the energy sector exerts a disproportionate, cascading influence on macro-systemic survival.

Under these conditions, green hydrogen transcends its conventional categorization as a secondary fuel or localized storage solution; it could operate as a systemic energy vector—defined here as a physical medium that transfers and transforms energy across distinct sectoral boundaries. Through this role, it structurally bridges primary clean power generation with deep-decarbonization pathways and hard-to-abate sectors traditionally dependent on external fossil fuel supply chains (Maka & Mehmood, 2024). As schematically outlined in the conceptual macro-topology in Figure 1, the green hydrogen configuration establishes a cross-sectoral nexus that directly links clean energy infrastructure, heavy transportation networks, and agricultural primary production.

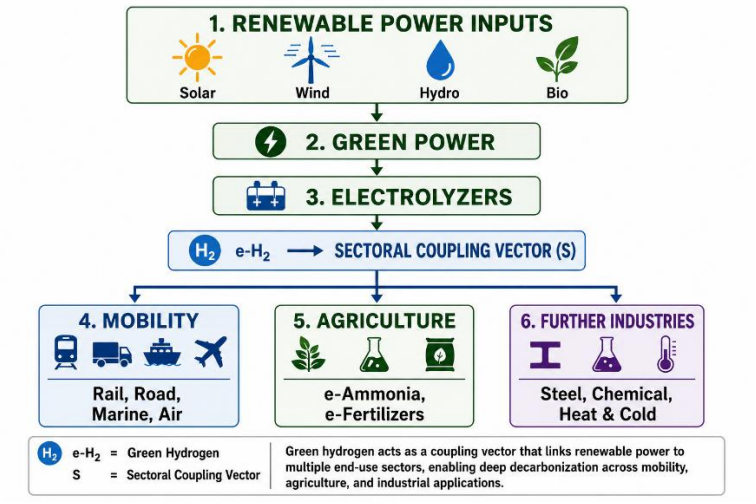

Figure. 1. Green hydrogen sectoral coupling implication.

It is critical to emphasize that this framework does not simulate the physical, chemical, or thermodynamic mass-energy balances of hydrogen infrastructure. Instead, the hydrogen vector is deployed as a high-visibility structural baseline to justify why and how distinct socio-technical sectors interact. As illustrated in the comprehensive topological architecture of green hydrogen sectoral coupling in Figure 1, the $e - H_2$ vector acts as the core metabolic hub of the system, initiating an energetic phase transition where primary electrical exergy—harvested from domestic solar, wind, hydro, or biomass inputs—is converted via automated electrolyzers into chemical energy carriers. This centralized vector directly drives multi-sectoral integration by dynamically linking the clean electrical grid to the critical pillars of the territory's metabolic baseline ($B$).

Specifically, this systemic link enables the multi-modal electrification of heavy transport networks—including rail, road, and marine systems—through fuel cells and synthetic e-fuels, thereby securing internal logistics when liquid fuel imports are abruptly disrupted. Simultaneously, this systemic link extends into the primary sector to strengthen localized food security by providing the necessary inputs for domestic e-ammonia and fertilizer production, ensuring that agricultural systems remain operationally viable without reliance on foreign petrochemical supply chains. Finally, this cross-sectoral integration connects directly to regional infrastructure by delivering clean energy and essential industrial inputs for residential networks and localized manufacturing sites.

By establishing these closed-loop dependencies, the green hydrogen economy transforms isolated technical capacities into a unified, self-sustaining metabolic engine. While its ultimate environmental objective remains aligned with a long-term zero-emissions trajectory, its immediate systemic implication within the CRI framework is purely evaluative, providing the qualitative and structural rationale required to parameterize the core pillars of sovereign operational capacity ($R$) under functional isolation

### 3.5. Data Sourcing Strategy and the Boundaries of Functional Insularity

To operationalize the macro-sectoral baseline proxies (energy, agriculture, transportation), this framework deliberately adopts the standardized indicators from the Sustainable Development Report (Sachs et al., 2025) matrix as its primary empirical anchor. The selection of this international reporting architecture represents a pragmatic baseline choice. Utilizing a unified, peer-reviewed global matrix facilitates cross-territorial comparison, mitigating the accounting discrepancies and methodological asymmetries often encountered when evaluating socio-technically disparate jurisdictions. The UN SDG dataset provides a mathematically homogeneous, pre-normalized domain where diverse territorial metrics are subjected to uniform reporting protocols, serving as a consistent foundation for the initial calibration and proof-of-concept testing of the Resilience-Synergy model.

Crucially, this data sourcing strategy is designed as a scalable, temporary scaffolding rather than a definitive operational ceiling, providing a conceptual basis for analyzing diverse typologies of functional insularity. While traditional models often restrict insularity to permanent geographic characteristics (such as oceanic islands), this framework conceptualizes insularity through a topology of systemic isolation. Consequently, the model could be extended to territories experiencing induced functional insularity triggered by climate shocks, sudden infrastructure failures, or severe geopolitical disruptions. In such scenarios, a landlocked or connected region can suffer rapid, multi-sectoral decoupling from broader supply networks, temporarily operating as a functionally isolated system.

Territories experiencing acute crises or operational isolation often suffer from localized data fragmentation, which inherently limits the availability of high-fidelity metrics. To address this constraint, the proposed framework shifts the analytical focus toward cross-sectoral interfaces and the sensitivity coefficient ($\kappa$) rather than internal sectoral minutiae. Consequently, this flexible architecture allows future iterations to substitute the standardized global baseline for granular, localized empirical datasets as they become verifiable, without altering the underlying mathematical structure or its replicability.

### 3.6. Standardized Operationalization and Methodological Justification of Model Variables $B$, $S$, $and \kappa$

To minimize subjective weighting biases and enhance cross-country comparability, the macro-systemic architecture is operationalized as a non-parametric, coupled network. All raw inputs are sourced from the Sustainable Development Report and linearly rescaled from their native [0, 100] interval to a normalized domain [0, 1] prior to model injection.

The baseline performance ($B$) represents the uncoupled socio-technical capacity of the territory across its core infrastructure nodes. The selection of an unweighted arithmetic means to calculate $B$ reflects a parsimonious systemic assumption: under acute insularity or structural decoupling, affordable energy, food security, and logistics/industrial infrastructure hold equal operational priority. Because these three sectors form a non-hierarchical survival triad, a deficit in any single node destabilizes the entire baseline capacity, justifying their equal mathematical weight:

$$B = \frac{1}{3}\left(\frac{SDG\ 2}{100} + \frac{SDG\ 7}{100} + \frac{SDG\ 9}{100}\right) \qquad (5)$$

Adopting an unweighted arithmetic mean introduces an inevitable trade-off between universal standardization and regional contextualization. In non-crisis settings, regions naturally exhibit structural asymmetries, often prioritizing investments in their dominant economic sectors. However, within the framework of functional insularity, macro-systemic resilience operates under the principle of the weakest link, drawing from Liebig's Law of the Minimum. In a decoupled scenario, a highly developed agricultural sector becomes functionally useless if the domestic transportation network or energy grid collapses, as resources cannot be processed

or distributed. Consequently, equal weighting acts as an intentional mathematical penalty against structural imbalances, asserting that absolute resilience cannot be achieved by subsidizing a failing critical sector with the surplus of another. Retaining a non-parametric equal weight at this stage is methodologically necessary to establish an objective, cross-territorial comparative baseline, even though future policy-simulation iterations may integrate localized weight customization such as the Analytical Hierarchy Process (AHP).

The potential structural synergy activated by this alternative energy carrier is mapped through the territory's techno-environmental enabling environment. Here, $SDG_{12}$ (Responsible Consumption and Production) and $SDG_{13}$ (Climate Action) are selected as specific empirical proxies because a green hydrogen transition cannot materialize in a vacuum; it fundamentally requires a dual structural alignment consisting of circular industrial/waste cycles ($SDG_{12}$) and strict carbon-mitigation regulatory frameworks ($SDG_{13}$). Operationalizing $S$ (equation 6) through a simple arithmetic mean ensures that the capacity for cross-sectoral synergy is modeled as co-dependent, relying equally on technological market readiness and institutional decarbonization momentum:

$$S = \frac{1}{2}\left(\frac{SDG\ 12}{100} + \frac{SDG\ 13}{100}\right) \qquad (6)$$

Advanced physical infrastructure cannot achieve cross-sectoral integration under regulatory paralysis or institutional corruption; therefore, the transmission of techno-environmental synergies into actual macro-resilience is fundamentally mediated by governance quality and administrative capacity. To operationalize this relationship, we first define the Institutional Maturity Index ($I_m$) as the normalized baseline score of Peace, Justice, and Strong Institutions ($SDG_{16}$), where $I_m \in [0,1]$. The transmission gatekeeper coefficient ($\kappa$) is subsequently computed as a non-linear function of this institutional index, as formalized in Section 3.6.1. This specific sigmoidal architecture is mathematically necessary to model threshold friction and asymptotic saturation, ensuring that sub-standard governance acts as an entropic drain ($\kappa < 0$) while highly mature administrations accelerate synergy without violating physical efficiency limits. By introducing the $\kappa$ parameter, this framework separates structural network configurations ($S$) from dynamic institutional responsiveness ($\kappa$). Unlike traditional additive composite indices, this multiplicative structure ensures that resilience ($R$) emerges from the non-linear amplification of baseline capacity through interdependencies, providing an explicit quantitative tool potentially useful for foresight scenario simulation.

*3.6.1. Determination of the synergistic sensitivity coefficient (κ)*

The structural resilience of an island system is an emergent property governed by the quality of its internal governance, rather than merely a function of its technical capacity. To capture this non-linear relationship, we introduce the synergistic sensitivity coefficient ($\kappa$) a modulating factor derived through a hyperbolic tangent (tanh) transfer function.

This sigmoidal architecture is intentionally selected over alternative linear or exponential modeling paradigms. A linear interaction formulation erroneously implies constant returns to scale, assuming that an incremental governance improvement yields the identical resilience dividend regardless of the baseline system state. Conversely, unbounded exponential models fail to account for physical carrying capacities, projecting unrealistic, runaway growth. The hyperbolic tangent transfer function resolves these structural distortions by mathematically parameterizing systemic friction at the lower asymptotic boundary and capturing diminishing marginal returns at the upper saturation limit where $\kappa \to 1$. This choice aligns with long-standing transition literature confirming that technological and infrastructure diffusion dynamics inherently follow non-linear (Geels, 2011), sigmoidal trajectories rather than constant linear pathways (Grübler et al., 1999).

Employing this specific mathematical architecture allows the model to capture two critical systemic phenomena: threshold friction and asymptotic saturation. Specifically, $\kappa$ accounts for the institutional friction that can hinder technological integration in fragile states, while simultaneously recognizing that even in highly mature systems, the marginal gains in resilience from synergy are subject to clear operational and organizational limits. By utilizing a sigmoid-shaped curve, the model reflects a realistic "break-even" point where a system transitions from a state of resource cannibalization to one of productive synergistic acceleration.

To operationalize this factor with empirical rigor, we propose the use of Sustainable Development Goal 16 (SDG 16: Peace, Justice, and Strong Institutions) (Sachs et al., 2025) as the primary proxy for institutional maturity. As a globally standardized metric, the SDG 16 score provides a multi-dimensional assessment of a state's legal framework, corruption levels, and administrative efficiency—all of which are decisive for the long-term viability of complex alternative energy carrier infrastructures. Normalizing the SDG 16 index into a $[0,1]$ domain and mapping it through the $\tanh()$ function, the model translates qualitative governance indicators into a quantitative modulator, thereby ensuring that the resulting CRI ($R$) is grounded in the socio-political reality of the territory under study.

The synergistic sensitivity coefficient ($\kappa$) is explicitly modeled as a non-linear function of the normalized governance index ($I_m \in [0,1]$ representing the scaled score of SDG 16), operating as the fundamental socio-political enabler that modulates resource-nexus synergy. To model phase transitions, saturation limits, and threshold dynamics, the system sensitivity coefficient to synergistic effects $\kappa$ is formalized as an adaptive, country-specific sigmoidal architecture, represented by Equation 7, and graphically in Figure 2.

$$\kappa = A_s * \tanh(P_s * (I_m - 0{,}5)) \qquad (7)$$

The empirical calibration and operational boundaries conditions of the governing parameters are defined by the sigmoid amplitude ($A_s$) the sigmoid slope ($P_s$) and the institutional maturity index ($I_m$).

The parameter $A_s$ acts as a dimensionless scaling factor dictating the systemic upper boundary of the system. It asserts that, under an ideal institutional configuration, intersectoral synergy can amplify the system's baseline resilience by a maximum threshold determined by $A_s * 100\%$. Bounding $A_s$ at 1.5, for instance, establishes a strict socio-technical saturation ceiling. This boundary condition mathematically reflects the law of diminishing returns, demonstrating that intersectoral synergy cannot amplify macro-resilience beyond a definitive 150% threshold above the baseline capacity, regardless of further institutional perfection or governance inputs.

Operating as a dynamic calibration parameter, $P_s$ dictates the mathematical slope of the phase transition—conceptually representing the institutional elasticity or catalytic velocity of the territory. Rather than being treated as a static constant across the entire global cohort, $P_s$ scales dynamically according to each nation's intrinsic state of socio-economic and structural development. By adjusting $P_s$ based on empirical national developmental baselines, the model captures a fundamental systemic reality: nations with higher structural friction or lower baseline development possess a lower $P_s$ (a flattened trajectory), meaning they convert potential intersectoral synergy into operational resilience at a slower rate. Conversely, territories undergoing optimized development exhibit a higher $P_s$ (a compressed, steep trajectory; e.g., a calibrated baseline value of $P_s = 3$), configuring a high-gain sigmoidal transition region where minor institutional anti-corruption or regulatory milestones trigger rapid, non-linear system stabilization.

The constant 0.5 in the mathematical expression (equation 7) establishes a strict operational threshold. It specifies that a territory must score at least 50 out of 100 on the normalized SDG 16 index for cross-sectoral synergies to overcome internal administrative friction and begin to exert a net-positive amplification effect on macro-resilience ($\kappa > 0$). Crucially, when $I_m < 0.5$, the function naturally yields a negative $\kappa$, mathematically demonstrating that under negligent or corrupt institutional mediums, advanced technological deployments turn into an entropic or operational burden that actively drains and degrades the baseline resources of the system ($R < B$).

The figure 2 shows the nonlinear relationship determined by the equation 7.

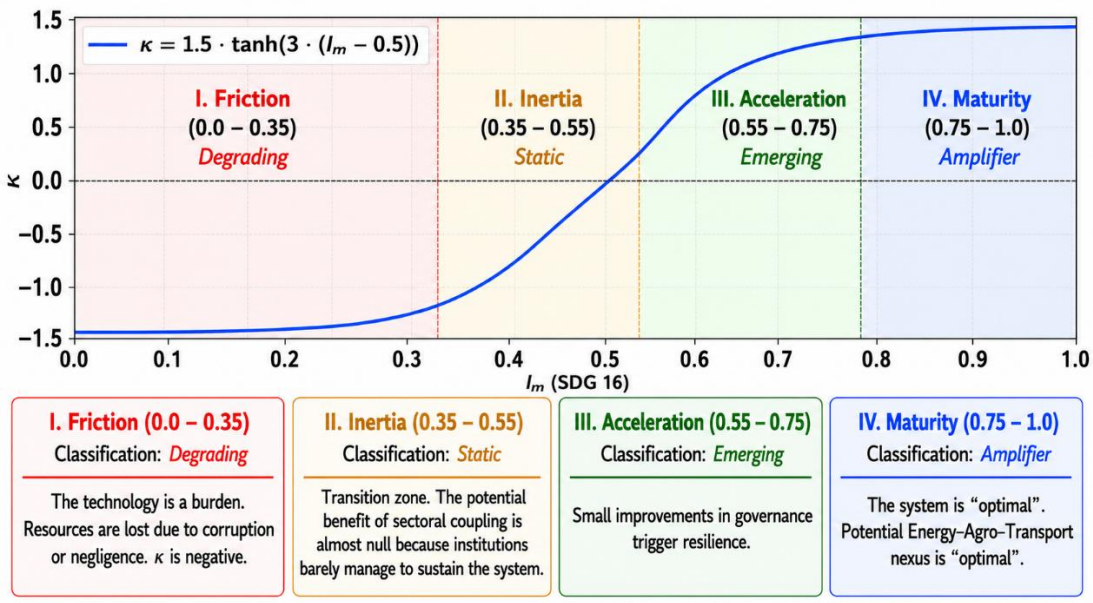


Figure 2. Graphical representation of the s*ynergistic sensitivity coefficient, and classification*.

The S-shaped curve captures a transition from "trade-off" to "synergy" system performance as governance quality improves. Four distinct regimes are highlighted along the $I_m$ axis. In the Friction zone (0.0–0.35), the system exhibits degrading behavior, where weak institutions lead to inefficiencies and negative outcomes ($\kappa < 0$). This is followed by the Inertia zone (0.35–0.55), a transitional regime in which improvements in governance yield minimal gains, and system performance remains near neutral. As $I_m$ increases further, the system enters the Acceleration zone (0.55–0.75), where incremental institutional improvements produce disproportionately positive effects, reflecting an emerging and increasingly resilient system. Finally, in the Maturity zone (0.75–1.0), the curve saturates, indicating that the system has reached an optimal state in which performance stabilizes at its maximum level. Overall, this sigmoidal mathematical architecture emphasizes the critical, non-linear role of institutional quality in enabling or throttling the translation of technical synergy into actual macro-systemic resilience.

### *3.7. Formal Derivation and Mathematical Consistency of the Synergistic Sensitivity Coefficient*

Rather than postulating $\kappa$ as an additional model parameter this section derives it as the natural first-order generalization of the baseline resilience architecture. The objective is to establish the mathematical consistency of the proposed synergistic sensitivity coefficient while preserving the classical interaction model as a particular limiting case. The following derivation is not intended to construct a complete physical theory of macro-resilience; rather, it demonstrates that the proposed coefficient emerges as the simplest mathematically consistent extension of the classical interaction architecture while retaining analytical tractability and physical interpretability.

Let the composite macro-resilience of a territory, $R$, be defined as a function of its baseline capacity, $B$, and its potential structural synergies, $S$. Under a conventional unmodulated coupling architecture, resilience increases linearly with structural synergy, implying that the

marginal contribution of $S$ remains constant and is entirely determined by the territory's baseline structural capacity. This relationship is expressed as:

$$\frac{\partial R}{\partial S} = B \qquad (8)$$

Equation (8) implies that each additional unit of structural synergy contributes exactly $B$ units of macro-resilience, irrespective of institutional quality or governance conditions. Consequently, the system assumes a rigid one-to-one coupling between technical synergies and resilience outcomes, leaving no mechanism through which institutional environments can either amplify or suppress the effectiveness of those synergies.

To account for institutional modulation while preserving the simplicity of the original formulation, the constant marginal sensitivity is generalized through a bounded synergistic sensitivity coefficient, $\kappa$. A first-order multiplicative modulation is adopted because it represents the simplest extension that simultaneously preserves linearity, dimensional consistency, and exact recoverability of the classical model when $\kappa = 1$. Under this assumption, the generalized marginal relationship becomes in the form of equation 9.

$$\frac{\partial R}{\partial S} = \kappa B \qquad (9)$$

where $\kappa$ represents the effective sensitivity of macro-resilience to structural synergy under a given institutional environment. Rather than modifying the available structural capacity itself, $\kappa$ regulates the efficiency with which potential structural synergies are converted into realized macro-systemic resilience. Notably, $\kappa$ does not constitute an additional source of resilience. Instead, it governs the transmission efficiency through which existing structural synergies are transformed into effective macro-systemic resilience. Consequently, institutional maturity modifies the effectiveness of synergistic interactions rather than the quantity of structural resources available to the system.

Integrating Equation 9 with respect to $S$, and imposing the physically meaningful boundary condition that macro-resilience equals baseline capacity when no structural synergies are active, ($R = B$ when $S = 0$) analytically yields the generalized resilience architecture adopted throughout this work, represented by Equation 10.

$$R = B + \kappa BS = B(1 + \kappa S) \qquad (10)$$

Equation 10 introduces a fundamental conceptual distinction from conventional composite resilience indices. Rather than incorporating institutional maturity as an additional weighted resilience component, the proposed architecture assigns it a fundamentally different functional role: κ governs the efficiency with which latent structural synergies are translated into realized macro-systemic resilience. Consequently, institutional maturity cannot generate resilience independently in the absence of structural assets or cross-sectoral synergies; conversely, abundant technical synergies remain largely unrealized when institutional transmission efficiency is low. Governance is therefore interpreted as the transmission

mechanism of resilience rather than as an independent resilience resource. This multiplicative architecture therefore departs fundamentally from conventional composite indices, where governance contributes as an independent weighted component rather than as the mechanism regulating system-wide synergy conversion. The internal consistency of the formulation is immediately verified by differentiating Equation 10, as follows:

$$\frac{\partial R}{\partial S} = \left(\frac{\partial B}{\partial S} + \frac{\partial \kappa BS}{\partial S}\right) = (0 + \kappa B) = \kappa B \qquad (11)$$

Thereby recovering Equation 9 exactly.

This derivation demonstrates that the proposed formulation is a mathematically consistent first-order generalization of the classical interaction model. When $\kappa = 1$, the original unmodulated architecture is recovered exactly as a limiting case. Values of $\kappa > 1$ describe institutional environments that amplify the marginal returns of structural synergies, whereas $0 < \kappa <1$ represents partial attenuation of those returns. Finally, $\kappa < 0$ characterizes entropic institutional regimes in which additional structural coupling becomes counterproductive, reducing rather than increasing composite macro-resilience. Consequently, $\kappa$ should not be interpreted as an empirical adjustment parameter or an additional resilience dimension, but as a mathematically derived transmission coefficient that quantifies the system-dependent efficiency with which latent structural synergies are converted into realized macro-systemic resilience.

**4.0. Analytical Framework for Case Study Selection and State Variables**

This study focuses on small island jurisdictions, as a case studies, due to their acute exposure to compounding energy, economic, and environmental vulnerabilities. Small Island Developing States (SIDS) constitute a distinct cohort of 39 States and 18 Associate Members of United Nations regional commissions, characterized by structural insularity, limited domestic markets, and high import dependencies.

To evaluate the operational boundaries of the Composite Resilience Index ($R$), we employ a purposeful, non-random typological selection strategy designed to capture maximum structural and institutional variation. The analytical cohort comprises four SIDS members—the Dominican Republic, Haiti, Cuba, and Fiji—supplemented by Malta, a non-SIDS developed island economy, which serves as an external baseline for advanced structural comparison.

4.1. Empirical Case Selection and Regime Archetypes

To empirically validate the non-linear dynamics and threshold behaviors governed by the Composite Resilience Index (CRI) framework, this study utilizes a purposeful, comparative case-selection strategy. Rather than evaluating a homogeneous cohort, we select three distinct Small Island Developing States (SIDS)—Cuba, the Dominican Republic, and Fiji—that function as structural archetypes for the different operational regimes of the sigmoidal transfer function mapped in Figure 2. These territories exhibit highly divergent institutional maturity baselines ($I_m$), allowing us to test how the same conceptual sectoral coupling vector yields

entirely different macro-resilience outcomes depending on the underlying governance medium.

The operational choice of SDG 16 as the primary proxy for institutional maturity ($I_m$), is consistent with the macro-structural perspective emerging in contemporary sustainability literature. Rather than treating governance as an isolated socio-political objective, empirical consensus positions strong, effective, and transparent institutions as a fundamental, necessary enabling condition for successfully scaling and anchoring sustainable energy-resource nexuses (Fuso Nerini et al., 2017),(Sachs et al., 2019). By operationalizing SDG 16 within the CRI architecture, this model directly tests the theoretical premise that institutional capacity acts as a key enabling mechanism—or bottleneck—determining whether localized technical synergies can be successfully translated into macro-systemic resilience.

The selection of Cuba provides the empirical baseline for the "Inertia" Regime, anchoring the model at its critical zero-crossing inflection point (where $I_m \approx 0.5$). Cuba presents a compelling socio-technical paradox: it possesses a robust legacy of physical baseline assets ($B$) and deep domestic technical expertise born from decades of forced economic isolation. However, under the CRI framework, its rigid institutional framework and centralized administrative friction neutralize the synergistic sensitivity coefficient ($\kappa$). This positions Cuba as the ideal case study to model how systemic inertia can entirely decouple localized sector-coupling potentials ($S$) from actual macro-resilience dividends ($R$), leaving the system structurally trapped within its baseline boundaries.

In stark contrast, the Dominican Republic is selected to populate the "Acceleration" Regime, mapping directly onto the high-gain, maximum-sensitivity zone of the sigmoidal curve where the first derivative ($\frac{d\kappa}{dI_m}$) reaches its peak. Boasting a highly dynamic and evolving policy landscape, this territory represents an emerging framework where the institutional elasticity and catalytic velocity are highly reactive. The Dominican Republic serves as an ideal exploratory laboratory to demonstrate how incremental regulatory overhauls and targeted institutional optimizations can trigger exponential, non-linear returns, rapidly unlocking the cross-sectoral synergies ($S$) required to scale domestic energy and resource autonomy.

Finally, Fiji is integrated as the systemic benchmark, populating the upper asymptotic boundary of the maturity regime where $I_m$ approaches its maximum values. Fiji represents a mature institutional ecosystem that has successfully transitioned toward comprehensive cross-sectoral governance, epitomized by its highly integrated policy frameworks linking energy, sustainable agriculture, and climate adaptation networks. By mapping Fiji within the upper saturation zone where the sensitivity coefficient approaches its maximum theoretical limit ($\kappa \to 1.0$), the model can empirically define the optimal performance ceiling of the resource-energy nexus under geographic isolation, providing a concrete baseline against which the transition trajectories of alternative functional islands can be algorithmically computed.

*4.2. Epistemological Justification for Utilizing the SDG Framework as State Variables*

A persistent challenge in modeling socio-ecological systems (SES) is the dimensionality problem and data asymmetry across heterogeneous domains (e.g., matching physical energy flows with qualitative governance indexes). This framework resolves this by repurposing the United Nations Sustainable Development Goals (SDGs) not as mere political targets, but as standardized, normalized state variables within a complex systems architecture.

Utilizing the global SDG indicator database provides three indispensable methodological advantages. Structural Harmonization (1). It transforms disparate socio-political, economic, and biophysical datasets into a bounded, dimensionless domain ([0, 100] or [0, 1]), eliminating scaling biases. Global Portability (2): The standardized nature of UN metadata guarantees that the model remains invariant and scalable. A framework calibrated on Small Island Developing States (SIDS) can be mapped directly onto any isolated region, municipality, or microgrid worldwide. Reduction of Arbitrary Weighting (3): By utilizing pre-validated, peer-reviewed global indicator frameworks, the model avoids the subjective biases inherent in localized, ad-hoc indexing.

The macro-scale resilience ($R$) of a territorial system under isolation or boundary-closed scenarios is formalized as a non-linear, modulated linear amplification system, visually conceptualized in Figure 3.

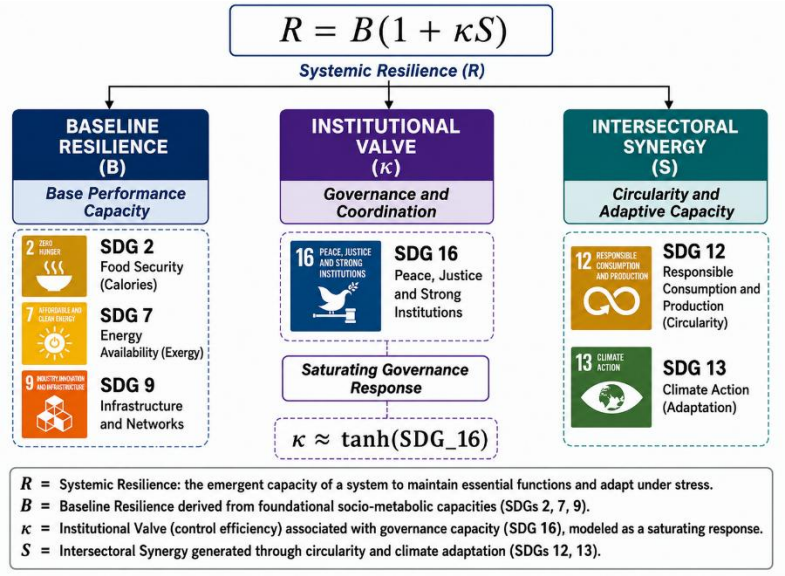


Figure 3. Experiment methodology design for the emerging resilience model validation.

Figure 3 shows the experiment methodology design presented. The 17 UN SDGs have been selected as inputs for the model. The key indicators for each SDG have been taken from a Sustainable Development Report 2025 (Sachs et al., 2025).

The baseline performance ($B$) establishes the system's structural minimum—the absolute baseline capacity to maintain organizational integrity and avert systemic collapse when completely decoupled from external nodes. This requires the simultaneous convergence of three infrastructural pillars: SDG 2 (Zero Hunger) dictates the internal caloric and agricultural

supply required to sustain the population; SDG 7 (Affordable and Clean Energy) represents the available primary exergy required to execute physical work within the boundary; and SDG 9 (Industry, Innovation, and Infrastructure) represents the topological network capacity (logistics, transport, and physical distribution channels) needed to internalize supply chains. Without a functioning baseline, the system faces immediate collapse, configuring $B$ as the structural hardware of the isolated state.

The potential structural synergy ($S$) represents the potential efficiency of the resource-energy nexus, capturing how effectively the system optimizes resource loops and buffers external disruptions. SDG 12 (Responsible Consumption and Production) operates as a metric for internal circularity, indexing the minimization of raw material throughput. SDG 13 (Climate Action) measures the adaptive capacity of the territory to withstand and absorb external environmental shocks. Here, $S$ represents the "software" potential of the system—its capacity for cross-sectoral cascading (e.g., utilizing hydrogen sectoral coupling). However, this technical potential, cannot manifest in isolation; it must be structurally modulated by the governance medium.

The institutional sensitivity coefficient ($\kappa$), derived from SDG 16 (Peace, Justice, and Strong Institutions), acts as the systemic regulator or valve. Accordingly, SDG16 is intentionally excluded from the structural asset stock (B) and from the latent synergy state (S). Its function is not to increase either quantity directly, but to regulate the efficiency with which the interaction between them produces realized macro-resilience. This distinction is essential because it assigns governance a functional rather than additive role within the CRI architecture. This functional interpretation departs from the dominant paradigm adopted by most composite resilience indices, where governance is typically incorporated as one additional weighted dimension alongside infrastructure, economy, or environmental performance. Within the CRI framework, institutional maturity is instead conceptualized as the operational mechanism that governs the efficiency with which latent structural synergies become realized macro-systemic resilience. Consequently, governance is interpreted as a system-level transmission process rather than as an independent resilience asset.

Governance is modeled here as the operational medium through which physical resource flows are directed. Although a high technical synergy ($S$) may be available, it remains functionally dormant if the institutional medium introduces severe administrative friction, corruption, or regulatory paralysis. Therefore, $\kappa$ enters the equation strictly as a multiplier of $S$, dictating the extraction efficiency of the system's potential.

The selection of Sustainable Development Goals (SDGs) as inputs for the CRI model is a pragmatic choice driven by the need for a universally harmonized dataset across the diverse cohort of selected study cases. The robustness of the CRI model is contingent upon the quality of its inputs. In accordance with principles of systemic modeling, we acknowledge that the reliability of the system's output is inherently bounded by the fidelity of the provided input data (input-output fidelity constraint). As SDG metrics are utilized as proxy indicators, this research

explicitly addresses potential input biases by employing non-linear scaling functions, ensuring that the resulting assessments reflect systemic trends.

*4.3. Endogeneity, Structural Independence, and Phenomenological Bounding*

Although the inherent interdependencies among the UN SDGs are widely acknowledged, utilizing them as state variables within a macro-resilience framework requires a careful epistemological delineation. A potential structural concern arises from the fact that institutional maturity ($I_m$/ SDG 16) historically influences both baseline infrastructure development ($B$ / SDGs 2, 7, 9) and the adoption of circular synergies ($S$/ SDGs 12, 13). This cross-domain influence could theoretically introduce simultaneous causality or endogeneity biases into a standard statistical specification.

To resolve this potential dimensionality, overlap without altering the mathematical formulation of the core framework, the model operates under a stock-flow framework that decouples these variables across distinct temporal scales and physical dimensions. Baseline resilience ($B$) is conceptualized strictly as a socio-technical material asset stock—a multi-decadal physical legacy of power grids, logistical networks, and agricultural topsoil that exhibits significant temporal inertia. In contrast, the institutional sensitivity coefficient ($\kappa$) operates as an instantaneous operational flow representing real-time regulatory throughput efficiency, whereas the potential structural synergy ($S$) is defined as a latent state configuration of the system's resource loops. Under this specification, $S$ and $\kappa$ function as fast-dynamic operational variables, whereas $S$ represents the slow-dynamic physical asset base.

This functional separation becomes critically evident during acute territorial shocks. If a jurisdiction experiences an abrupt institutional collapse, its physical infrastructure stock comprising $S$ remains physically intact in the short term. Instead, the real-time operational capacity of the governance medium ($\kappa$) to coordinate, couple, and extract utility from those assets through a designated alternative energy carrier vector is immediately compromised.

This functional separation becomes critically evident during acute territorial shocks: if a nation experiences an abrupt institutional collapse, its physical hardware—the infrastructure stock comprising $B$—does not instantly evaporate. Instead, what is immediately compromised is the systemic software—the real-time capacity of the governance medium ($\kappa$) to coordinate, couple, and extract utility from those assets through a designated sectoral coupling vector.

By defining the components through this physical partition, the core relationship ($R = B(1 + \kappa S)$) functions as an instantaneous phenomenological equation of state rather than a causal, structural econometric model. The framework deliberately avoids mapping the historical socio-political pathways that originally generated the territory's asset matrix. Instead, it diagnoses the net, cross-sectional sovereign operational capacity of a boundary-closed system at a specific timestamp.

Although the equation operates as a static diagnostic tool at a single point in time, its mathematical architecture remains fully compatible with foresight scenario simulation. Foresight capabilities are achieved through parametric perturbation of the fast-dynamic operational variables ($\kappa$ and $S$) across hypothetical regulatory or technological pathways while holding the physical asset stock ($S$) constant. This approach isolates the index from double-counting and endogeneity errors common in static statistical specifications, providing a mathematical foundation for comparative institutional policy analysis.

## 5. Results Analysis and Discussion

The empirical application of the Composite Resilience Index ($R$) framework reveals a significant structural divergence in the potential capacity of isolated jurisdictions to absorb alternative energy carrier integration. By utilizing standardized Sustainable Development Goal (SDG) metrics as state variables, the model demonstrates that techno-environmental synergy does not operate as an independent determinant of macro-resilience. Instead, its capacity to amplify systemic performance functions as a multiplicative dividend that remains strictly contingent upon the baseline structural robustness of the territory and the throughput efficiency of its institutional framework.

Consequently, this framework does not track the empirical deployment of operational hydrogen infrastructure; rather, it evaluates the latent systemic readiness of each jurisdiction to exploit the cross-sectoral linkages provided by such alternative energy vectors. Table 2 presents the calculated values for the core components of the model across the selected jurisdictions. The interaction of these variables is evaluated under a baseline institutional inflection threshold configured at $I_m$= 0.50, corresponding to a normalized score of 50 on the SDG 16 index.

Table 2. Emerging resilience model calculations and classification by each study case.

| Country | Code | $B$ | $I_m$ | $\kappa$ | $S$ | $R$ | Classification |
|---|---|---|---|---|---|---|---|
| **Malta** | MLT | 0.75 | 0.70 | 0.81 | 0.73 | 1.20 | Amplifier |
| **Dominican Republic** | DOM | 0.63 | 0.63 | 0.55 | 0.85 | 0.93 | Accelerator |
| **Cuba** | CUB | 0.60 | 0.65 | 0.64 | 0.93 | 0.95 | Inertia |
| **Fiji** | FJI | 0.65 | 0.77 | 1.0 | 0.90 | 1.24 | Synergistic Amplifier |
| **Haiti** | HTI | 0.30 | 0.25 | -0.97 | 0.96 | 0.02 | Friction |

### 5.1. Divergence in Resilience Amplification

The findings compiled in Table 2 demonstrate that the potential impact of alternative energy vectors is strictly modulated by the synergistic sensitivity coefficient ($\kappa$), Rather than producing a uniform or linear response across the cohort, the model maps distinct structural trajectories. Based on the quantitative interactions between baseline physical capacities ($B$) latent cross-

sectoral synergy ($S$), and institutional maturity ($I_m$), the five analyzed states are categorized into distinct systemic archetypes.

Malta: characterized as "Amplifiers," these states have successfully surpassed the critical institutional friction threshold ($I_m$ > 0.5). Malta ($B$ = 0.75, $\kappa$ = 0.81) illustrates a trajectory where a mature initial governance baseline allows the system to efficiently translate a potential sectoral synergy of $S$ = 0.73 into an amplified macro-resilience score of ($R$ = 1.20). In this case, the simulated introduction of an alternative energy carrier acts as a potential catalyst capable of driving interconnected optimization across pre-existing logistics and infrastructure networks.

Fiji: as a "Synergistic Amplifier", Fiji represents a unique and highly efficient archetype where the Institutional Maturity Index ($I_m$ = 0.77) yields a perfect unitary sensitivity coefficient ($\kappa$ = 1.0). Despite operating from a lower absolute baseline capacity ($B$ = 0.65) than its European counterparts, Fiji's institutional architecture ensures zero frictional attenuation. Consequently, the system leverages its high coupling potential ($S$ = 0.90) to achieve the highest systemic resilience in the cohort ($R$ = 1.24), validating the hypothesis that institutional alignment can outperform raw infrastructural scale in isolated systems.

The Dominican Republic presents a high-potential strategic positioning scenario characterized by a solid baseline performance ($B$ = 0.63) and a positive, upward-trending sensitivity coefficient ($\kappa$ = 0.55). With an integration potential of $S$ = 0.85, the country achieves an improved resilience score of $R$ = 0.93. Positioned on the steep, responsive slope ("Accelerator") of the hyperbolic tangent curve showed in Figure 2, the model suggests that marginal investments in institutional efficiency (SDG 16) would yield exponentially higher returns on resilience than the mere expansion of physical infrastructure assets, such as electrolysis facilities—thereby utilizing the simulated vector of hydrogen sectoral coupling capability as an illustrative proxy.

Cuba presents a paradoxical profile, showing an archetype of "Inertia". Despite possessing a stable baseline performance ($B$ = 0.60) and the second highest structural coupling potential in the study ($S$ = 0.93), its final resilience is heavily capped at $R$ = 0.95. This plateau occurs because its institutional coefficient ($\kappa$ = 0.64), while positive, acts as a flow limiter. The theoretical benefits of the energy-food-transport nexus are largely absorbed by structural and bureaucratic rigidities, confining advanced technology to isolated innovation clusters with marginalized macroeconomic impact.

In Haiti study case, the model delivers a critical diagnostic for states residing below the critical governance threshold $I_m < 0.5$. Then, Haiti has an extremely low $I_m$= 0.25. With a heavily negative sensitivity coefficient ($\kappa$ = -0.97), Haiti's projected systemic resilience collapses to $R$ = 0.02. In this regime of severe institutional fragility, the high technological complexity of a green hydrogen vector could behave as a "resource sink" rather than an asset. This "friction" archetype represents unsustainable maintenance costs and security risks, suggesting that the

strategic priority must be the reinforcement of the institutional base before the implementation of advanced energy vectors.

Although the final systemic resilience values for Cuba ($R$=0.95) and the Dominican Republic (0.93) are numerically comparable, the systemic classification reflects a fundamental divergence in their synergy conversion efficiency as shown in Figure 4. Cuba exhibits an "Inertia"' archetype because, despite possessing the second highest sectoral coupling potential in the cohort $S$ (= 0.93), its resilience is constrained by a "ceiling" effect. This suggests that structural and bureaucratic rigidities act as a bottleneck, preventing the system from translating its high potential into proportional resilience gains. In contrast, the Dominican Republic is classified as a "Accelerator." Its systemic architecture is currently in a responsive regime where the institutional environment facilitates the conversion of sectoral synergies into systemic outcomes as figure 4 b) shows. Consequently, the Dominican Republic demonstrates a higher marginal return on institutional improvement, indicating a system with lower internal friction capable of effectively scaling the benefits of the energy transition.

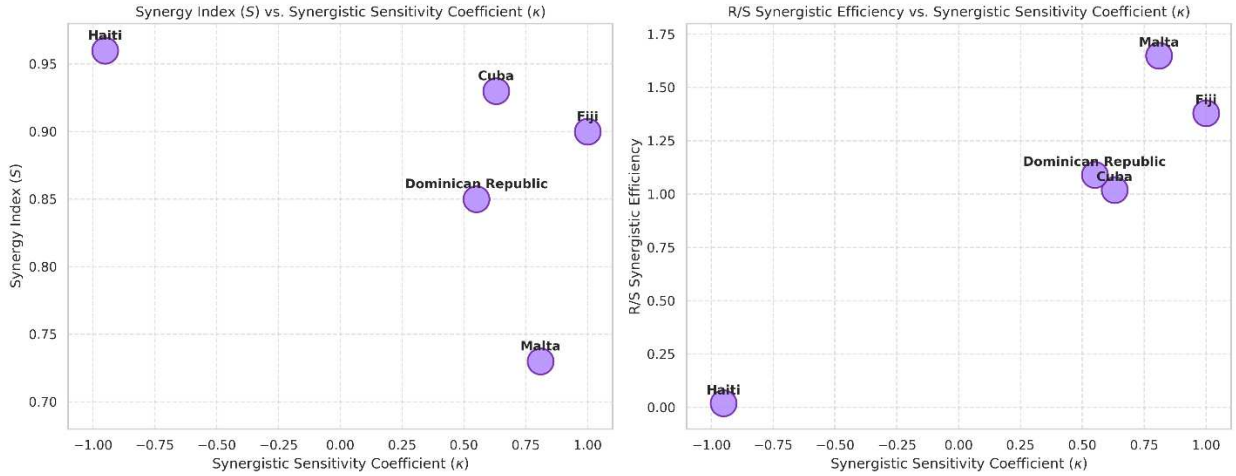


Figure 4. Synergy index ($S$) and synergistic efficiency ($R/S$) *VS* Synergistic Sensitivity coefficient ($\kappa$).

The empirical findings indicate that the systemic impact of green hydrogen is strictly conditioned by the Institutional (SDG 16) Synergistic Sensitivity Coefficient ($\kappa$), which acts as a modulator for the baseline performance ($B$). Although the final systemic resilience ($R$) values for Cuba (0.95) and the Dominican Republic (0.93) are numerically comparable, the systemic classification reflects a fundamental divergence in their synergy conversion efficiency.

Furthermore, these results highlight a critical distinction between environmental ambition and operational capacity. While countries like Cuba and Haiti may demonstrate robust commitments to sustainability frameworks—such as those reflected in SDG 12 and 13—the model reveals that these assets remain latent without the necessary institutional maturity. This reinforces the central thesis of this study: resilience is not merely a function of general climate-oriented objectives, but rather a "thermodynamic" outcome of an institution's ability to operationalize technological complexity. Without a stable governance foundation (as

represented by the SDG 16 threshold), even high-potential synergy ($S$) remains uncoupled from the systemic resilience ($R$) required for sovereign autonomy.

While these findings establish a clear systemic archetype for each state, one must consider whether this static snapshot fully captures the intricate, non-linear dynamics inherent in sovereign systems. Indeed, a critical question emerges: to what extent does this model remain robust when subjected to the inherent volatility of policy and technological shifts? By introducing marginal perturbations to our core parameters, we test whether these classifications are stable properties of the system or merely transient outcomes of our current data set.

5.2. Modell Sensitivity and Systemic Elasticity

To assess the robustness of the model, we performed a sensitivity analysis by perturbing the input variables. The sensitivity analysis simulates responsiveness to a 10% fluctuation in technological synergy ($S$) and baseline capacity ($B$), alongside a 5% marginal shift in institutional maturity ($I_m$). The latter is propagated through the system via the sigmoidal transfer function detailed in Equation 7. We deliberately selected a more conservative threshold for $I_m$ (5%) compared to the other parameters (10%) to reflect the concept of institutional viscosity—the structural inertia and slower pace characteristic of governance reforms.

Table 3 presents the systemic elasticity of the model through a structured perturbation analysis to demonstrate the system's dynamic responsiveness to marginal changes. The first column lists the country codes, and the second reports the baseline Composite Resilience Index ($R$) derived from the unperturbed SDG 16 data. The remaining columns of Table 3 are structured into three distinct sections, each comprising a variable-impact pair: the first column in each section identifies the parameter subject to perturbation—technological synergy ($S$), baseline capacity ($B$), and the modulated sensitivity coefficient ($\kappa$)—while the second column quantifies the resulting value of $R$.

Table 3. Sensitivity analysis (Impact of 10% change in $S$, $B$ and 5% in $\kappa$ on Resilience $R$).

| **Country Codes** | $\boldsymbol{R}$ | Sensitivity to $\Delta\boldsymbol{S}$ (10%) | | Sensitivity to $\Delta\boldsymbol{B}$ (10%) | | Sensitivity to $\Delta\boldsymbol{\kappa}$ (5%) | |
|---|---|---|---|---|---|---|---|
| | | $\Delta S$ (10%) | $R_{\Delta S\ (10\%)}$ | $\Delta B$ (10%) | $R_{\Delta B\ (10\%)}$ | $\Delta\kappa$ (5%) | $R_{\Delta\kappa\ (5\%)}$ |
| **MLT** | 1.20 | 0.80 | 1.24 | 0.83 | 1.31 | 0.92 | 1.25 |
| **DOM** | 0.93 | 0.94 | 0.96 | 0.69 | 1.02 | 0.67 | 0.99 |
| **CUB** | 0.95 | 1.02 | 0.99 | 0.66 | 1.05 | 0.75 | 1.02 |
| **FJI** | 1.24 | 0.99 | 1.30 | 0.72 | 1.37 | 1.09 | 1.29 |
| **HTI** | 0.02 | 1.06 | -0.01 | 0.33 | 0.02 | -0.93 | 0.03 |

The results reveal a clear divergence in how sovereign systems respond to exogenous fluctuations. Countries such as Malta (MLT), and Fiji (FJI) demonstrate high elasticity across all perturbed parameters, showing consistent positive growth in resilience. Conversely, the model identifies significant systemic inelasticity in regimes such as Haiti (HTI), where the resilience index remains largely stagnant and severely depressed ($R < 0$) despite targeted improvements

in synergy or institutional maturity. This stark contrast suggests that the return on investment for technological or capacity scaling is non-linearly conditioned by the system's baseline institutional state. Furthermore, the comparative sensitivity between the 10% variations in $S$ and $B$ and the 5% marginal shift in $\kappa$ underscores the high leverage of governance as a systemic multiplier.

In archetypes operating near non-linear transition zones, such as Cuba (CUB) and the Dominican Republic (DOM), the model highlights that resilience is not merely a function of resource accumulation, but is heavily dependent on the efficiency with which those resources are integrated into the existing institutional framework. Consequently, this diagnostic confirms that policy interventions must be calibrated according to the specific operational regime of each state, as identical investments in technological synergy yield vastly different resilience trajectories depending on the prevailing institutional friction

Although the initial findings provide a coherent diagnostic, it is necessary to determine whether the observed archetypes are an artifact of the specific governance framework provided by the SDG 16. To test the robustness of this classification, we introduce a comparative analysis using the World Bank's Worldwide Governance Indicators (WGI)(World-Bank, 2025). It is essential to distinguish between the nature of these metrics: SDG 16 acts as a performance-based index, quantifying objective outcomes and structural achievements, whereas the WGI functions as a perception-based index, aggregating expert assessments and stakeholder subjective evaluations of institutional quality. By performing a cross-validation using WGI, this exercise serves as a robust stress test: if the systemic resilience patterns remain consistent across these disparate frameworks—one grounded in empirical performance and the other in institutional perception—we can be confident that the CRI model is capturing a fundamental systemic property rather than a measurement-dependent outcome

5.3. Robustness and Measurement Sensitivity of Institutional Transmission

To eliminate potential indicator bias, we cross-validated the system's institutional metrics using the World Bank's Worldwide Governance Indicators (WGI). To justify the robustness of the classification presented in table 4, it is essential to interpret the systemic divergence typology not as numerical identity, but as the stability of the systemic diagnostic across disparate governance frameworks.

Table 4. Robustness check of the synergistic sensitivity coefficient ($\kappa$) across two governance frameworks.

| Country | $\kappa$ (via SDG 16) | $\kappa$ (via WGI) | Systemic Divergence Typology |
|---|---|---|---|
| **MLT** | 0.81 | 0.90 | Convergent Institutional Maturity |
| **DOM** | 0.55 | 0.45 | Emergent Alignment |
| **CUB** | 0.64 | -0.65 | Structural Decoupling |
| **FJI** | 1.00 | 0.54 | Asymmetric Adaptive Stability |
| **HTI** | -0.96 | -0.64 | Convergent Systemic Fragility |

The consistency levels observed across institutional archetypes reflect the stability of the model's diagnostic power regardless of the governance proxy employed. High consistency — observed in the "Amplifier" and "Friction" archetypes — indicates that both outcome-based (SDG 16) and perception-based (WGI) frameworks converge on the same systemic categorization, confirming that these archetypes represent fundamental structural states rather than methodological artifacts. Specifically, the persistence of a negative sensitivity coefficient ($\kappa$) for the "Friction" archetype (Haiti) despite variations in absolute values between -0.96 and -0.97, serves as a robust indicator of systemic instability that transcends specific measurement scales. Conversely, the lower consistency observed in the "Inertia" archetype (Cuba) highlights nuanced cases where the gap between institutional output and public perception remains wide, suggesting that while the system's underlying dynamics are captured, the transition state is highly sensitive to the nature of the governance indicator utilized. This variation is not a limitation but rather an additional analytical layer that exposes the divergence between objective performance and institutional perception within transitioning economies. The cross-methodological alignment confirms that the institutional sensitivity coefficient ($\kappa$) is an emergent property of the system rather than a statistical artifact of indicator selection. Whether operationalized via perception-based metrics (WGI) or outcome-oriented frameworks (SDG 16), the institutional threshold ($I_m \approx 0{,}5$) remains the critical inflection point governing composite resilience.

The data reveal a "Sovereignty Paradox" in which absolute baseline capacity serves as a necessary condition, yet institutional efficiency remains the decisive multiplier for functional insularity. This is exemplified by the divergent systemic paths of Cuba and the Dominican Republic. Despite their numerical proximity in composite resilience scores, their underlying dynamics are polar opposites; Cuba's configuration suggests that bureaucratic rigidities prevent the system from capitalizing on its high sectoral coupling potential, whereas the Dominican Republic operates within a responsive regime where institutional reforms effectively catalyze resilience. Furthermore, the model identifies Haiti as a critical case where institutional stabilization must strictly precede any large-scale technological intervention. Ultimately, this quantitative framework transforms sustainability from a vague policy goal into a rigorous diagnostic tool, enabling sovereign states to determine whether their primary bottleneck necessitates infrastructural investment or fundamental institutional re-engineering.

The framework demonstrates high analytical sensitivity by capturing the phenomenon of structural decoupling within Cuba's institutional matrix. Under the formal lens of SDG 16, Cuba exhibits the centralized state capacity and regulatory frameworks necessary to dictate systemic transitions, yielding a positive sensitivity coefficient ($\kappa$ = 0.64). However, when evaluated through the Worldwide Governance Indicators (WGI), which reflect de facto operational risks and expert perceptions, the sensitivity coefficient undergoes a critical phase transition into negative territory ($\kappa$ = -0.65). This sharp divergence does not imply model instability; rather, it uncovers a latent institutional friction. In a real-world insularity or crisis

scenario, Cuba's physical infrastructure ($B$) would operate far below its theoretical synergy potential, as formal planning mechanisms are throttled by real-world operational rigidity. This systemic bottleneck perfectly contextualizes the systemic inelasticity observed in the marginal perturbation analysis, wherein technological stimuli ($\Delta S$) fail to yield meaningful resilience gains due to institutional dissipation.

Fiji emerges as the most structurally robust cohort member when subjected to institutional matrix alterations, demonstrating a remarkable capacity for adaptive elasticity. While external expert metrics (WGI) introduce a more conservative appraisal of small island developing states—compressing Fiji's sensitivity coefficient to 0.54—the system successfully resists cascading into a negative friction regime, stabilizing firmly within "Acceleration" zone. This behavior reveals that Fiji's systemic resilience is not an ephemeral artifact dependent on international perception; its core de jure institutional foundation ($\kappa = 1$ via SDG 16) acts as an exogenous buffer. This structural buffer ensures that the nation maintains high resource-to-resilience transmission efficiency even under stringent global evaluation criteria. This cross-matrix stability heavily corroborates the highly elastic behavior documented in the sensitivity analysis, where marginal asset perturbations trigger exponential returns in functional insularity.

### 5.4. Hydrogen as the Missing Link Between SDGs

The discussion focuses on the capacity of the potential structural synergy ($S$) to facilitate simultaneous compliance with the UN 2030 Agenda. The model demonstrates that a simulated green hydrogen framework operates as a viable vector capable of coupling SDG 7 (Affordable and Clean Energy) with SDG 2 (Zero Hunger) and SDG 9 (Industry, Innovation, and Infrastructure) to optimize cross-sectoral efficiency within island contexts.

The transition from a linear economy characterized by import-consumption pathways to a circular framework encompassing generation, storage, and re-utilization cycles reduces vulnerability to external commodity price shocks—a critical factor for the stability of Small Island Developing States (SIDS). Consequently, while hydrogen functions as an internal sector-coupling mechanism, it simultaneously acts as a strategic buffer that decouples the domestic economy from international market volatility. In addition, the empirical outcomes further elucidate the operational dynamics of the previously identified sovereignty paradox. The analysis of Cuba and Haiti warns that pursuing energy sovereignty without adequate institutional efficiency can lead to a state of "precarious autarky." The underlying mathematical formulation demonstrates that institutional openness and transparency (SDG 16) function, in effect, as structural catalysts for macro-level resource and energy efficiency.

### 5.5. Comparative Synthesis of Results

While Malta possesses a higher absolute baseline capacity, Fiji demonstrates a superior institutional efficiency in translating sectoral synergies into systemic autonomy. This suggests that particularly in remote island contexts, the quality of governance acts as a more powerful

resilience multiplier than raw infrastructural scale. Figure 5 illustrates the systemic resilience index ($R$) *versus* the institutional maturity Index ($I_m$) for all selected study cases using both the SDG 16 and WGI proxy indexes.

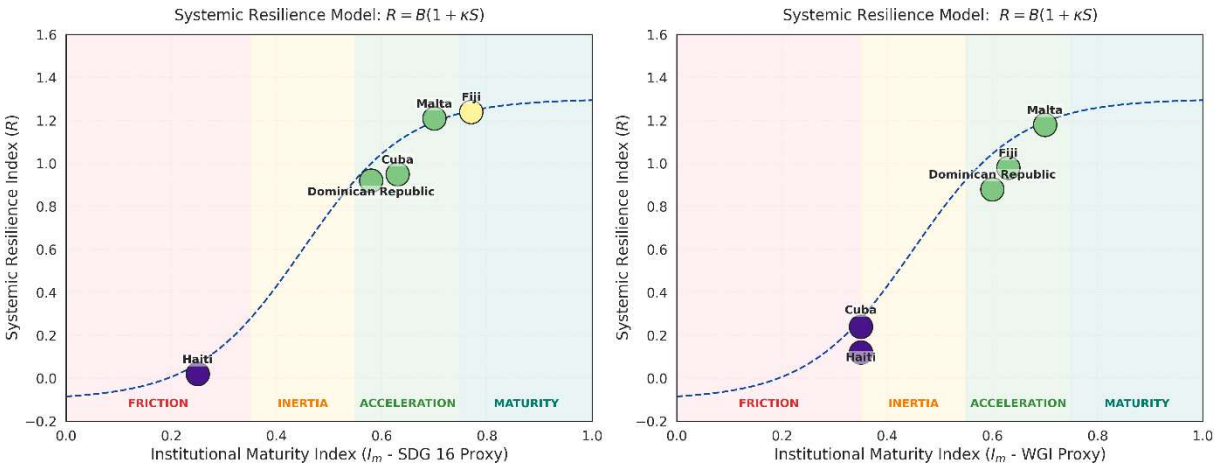


Figure 5. Systemic Resilience VS Institutional Maturity using SDG and WGI metrics.

As shown in Figure 5 and Table 2, Malta exhibits a higher baseline capacity (B), whereas Fiji displays a higher structural synergy component (1+ $\kappa$S). In a hypothetical scenario of total isolation —defined here as Functional Insularity — Fiji is better equipped to operate as a closed system than Malta. Functional insularity is defined here as the emergent property of a complex system—be it a geographic island, a remote territory, or a microgrid—to maintain operational stability and vital systemic functions through internal mechanisms, thereby minimizing reliance on exogenous flows of energy, capital, and resources.

A pivotal finding of this model is the performance of Fiji, which achieves a composite resilience score ($R$ = 1.24) that surpasses that of established European island states such as Malta ($R$ = 1.2). While the latter possesses a superior absolute baseline capacity ($B$), Fiji's higher institutional maturity ($I_m$= 0.77) yields a unitary sensitivity coefficient ($\kappa$= 1.0). This dynamic suggests a "Sovereignty Paradox": in highly integrated systems like the European Union, institutional frameworks are optimized for interdependence rather than functional isolation. In contrast, remote island states like Fiji have inherently evolved internal governance structures that prioritize self-sufficiency. Thus, the framework demonstrates that in a state of functional insularity, institutional efficiency acts as a more powerful resilience multiplier than raw infrastructural scale.

The model specifies a governance threshold (approximately $I_m$ = 0.5) around which the marginal contribution of synergy changes. Below this point, as evidenced by the case of Haiti ($R$ =0.02, $\kappa$=-0.97), the system resides in a state of systemic friction. In this regime, the introduction of advanced technological vectors like green hydrogen does not merely yield diminishing returns; instead, it functions as an operational liability. The high complexity of the technology, coupled with institutional fragility (SDG 16), generates a negative interaction where the costs of maintenance and coordination exceed the synergistic gains. This provides a clear

policy directive: institutional stabilization must precede technological leaps to prevent systemic collapse.

The case of “Static Capacity” in Cuba presents a unique archetype characterized by blocked synergy. Despite possessing a significant theoretical synergy potential ($S$ = 0,93) and a stable baseline ($B = 0{,}60$), its resilience ($R$ = 0.95) remains below its theoretical potential. This results from a rigid sensitivity coefficient ($\kappa$=0.64), which suggests that while the physical components for a nexus (energy-food-transport) are present, the institutional transmission is inefficient. The benefits of hydrogen-based sectoral coupling are absorbed by bureaucratic inertia, preventing the system from entering the “Acceleration” zone. For such states, the model demonstrates that resilience cannot be engineered through technical inputs alone; it requires a structural opening of institutional flows.

The Dominican Republic is identified as a Strategic Accelerator ($B$ = 0,63, $\kappa$= 0.55). Positioned at the beginning of the sigmoidal curve's steep ascent, the country exhibits the highest potential for resilience return on investment (R-ROI). Because the Dominican Republic has already surpassed the $I_m = 0.5$ friction threshold, marginal improvements in governance (SDG 16) will result in disproportionately large gains in systemic resilience. This validates the hypothesis that an alternative energy economy is not merely a fuel transition but an institutional catalyst that enables a region to accelerate its development path from vulnerability to sovereign stability.

The policy implications of this research emphasize that achieving operational resilience requires context-specific strategies rather than universal interventions. For the Dominican Republic, the priority lies in establishing regulatory frameworks that incentivize the use of green ammonia in fertilizer production, thereby simultaneously advancing SDG 7 and safeguarding food security against external volatility. In contrast, Cuba serves as a critical case study for structural transformation; its 2026 administrative reorganization—reducing central state bodies from 27 to 21 to mitigate systemic bureaucracy (*Cubadebate*, n.d.) —validates the necessity of shifting focus from isolated technical research toward reforms designed to enhance the institutional sensitivity coefficient ($\kappa$). This restructuring acknowledges that institutional inertia, rather than mere technological scarcity, remains the primary barrier to scaling sectoral synergy, underscoring that without such foundational reform, even well-intentioned investments will fail to generate tangible operational resilience. Finally, for international organizations engaging with fragile states like Haiti, the findings underscore that climate financing must prioritize the stabilization of the institutional base and foundational infrastructure as a prerequisite for technological advancement, ensuring that systemic capacity is sufficiently developed to absorb and integrate complex investments efficiently.

### 5.6. Model Scope, Boundary Conditions, and Limitations

While the CRI framework provides a scalable, non-linear architecture for pathfinding analysis, its application must be contextualized within specific boundary conditions and inherent data

limitations. First, utilizing historical United Nations SDG indicator databases introduces a structural temporal asymmetry. These indicators function as slow structural variables that map long-term evolutionary trajectories, meaning they possess a multi-year data latency. Consequently, the CRI framework does not attempt to simulate high-frequency, tactical logistics during the immediate, chaotic hours of a sudden-onset crisis —such as the immediate aftermath of extreme meteorological phenomena or acute geopolitical shocks. Instead, the model is strictly bounded to quantify the pre-shock structural readiness and macro-elasticity of the territory, establishing the baseline constraints under which long-term foresight planning must operate.

Second, a geographical constraint arises from the phenomenon of transboundary spillovers, or telecoupling. Because the global SDG framework evaluates territories while they are actively integrated into international trade, domestic performance metrics—such as circular production (SDG 12, which informs the latent synergy component $S$ —can occasionally mask severe dependencies on external supply chains. When a geopolitical or climate disruption triggers a transition into a state of functional insularity, these foreign dependencies are abruptly severed.

To prevent analytical distortion, the framework does not treat current indicators as an absolute operational guarantee, but rather as a measure of latent autonomous capacity under a conservative, worst-case decoupling scenario. The framework is explicitly designed to model a temporary state of strategic stress; its primary objective is not to simulate a permanent autarkic equilibrium, but to identify the critical structural thresholds and time-horizons a territory can endure before the depletion of its physical asset stock ($S$) triggers systemic collapse.

## 6. Conclusions

This study introduces the Composite Resilience Index (CRI) as a conceptual and mathematical framework for examining how institutional conditions may modulate the contribution of cross-sectoral synergy to systemic resilience. Its central proposition is that structural integration should not be assumed to produce uniform resilience gains: the effects of synergy depend on baseline capacity, the specification of the interaction mechanism, and the institutional conditions through which sectoral connections are coordinated.

The exploratory application to Malta, the Dominican Republic, Cuba, Fiji, and Haiti illustrates how contrasting structural and institutional configurations generate different modelled resilience profiles. The sensitivity analysis further shows the importance of examining how these profiles respond to changes in model parameters. The comparison between SDG 16 and the World Bank's Worldwide Governance Indicators, however, reveals heterogeneous agreement across cases. In particular, the divergence observed for Cuba and the change in the estimated coefficient for Fiji indicate that institutional measurement choices materially affect some model outputs. These findings support the need for further specification testing rather than a claim of universal empirical validation.

The concept of Functional Insularity extends the analysis beyond geographical isolation by focusing on a territory's capacity to maintain essential functions when external support becomes constrained. This perspective may be relevant to urban and regional systems whose energy, food, transport, and other essential services depend on interconnected infrastructure and institutional coordination. Nevertheless, the present application is conducted at the national level and does not directly establish the CRI's validity for cities or demonstrate resilience under observed disruption.

The framework may provide a basis for exploring alternative policy sequences, including whether improvements in institutional coordination should precede or accompany investments in technically complex infrastructure. Such implications should be interpreted as model-dependent hypotheses until tested against independent observations of service continuity, disruption response, and recovery. Future research should strengthen the mathematical reproducibility of the CRI, assess alternative parameterizations and governance measures, and test the framework with temporally resolved and territorially appropriate data.

Overall, the contribution of the CRI lies in formalizing a governance-modulated perspective on structural synergy and in identifying testable propositions about the relationship between interdependence and resilience. Its wider applicability will depend on independent empirical validation and careful adaptation to the functional boundaries, infrastructures, and institutional arrangements of the systems under study.

## 7.Future Work

The reliance on United Nations SDG indicators establishes a globally standardized baseline, yet subsequent empirical refinement should focus on enhancing model validation through localized, multi-source triangulation. Integrating verifiable performance data from independent administrative registries and remote sensing will systematically filter out subjective policy noise, grounding the Institutional Maturity Index ($I_m$) in tangible territorial outcomes. Beyond data validation, the techno-economic scaling of the alternative energy vector ($S$) presents fertile ground for stochastic optimization. Future iterations should integrate Monte Carlo simulations to assess how the price volatility of scarce Proton Exchange Membrane (PEM) electrolysis catalysts, such as platinum and iridium, impacts the long-term viability of national decarbonization strategies under global supply-chain shocks.

Concurrently, the intrinsic mathematical modularity of the CRI architecture allows for seamless scalability to incorporate alternative socio-technical catalysts. The framework can easily expand to parameterize additional synergistic drivers—such as pervasive digitalization, closed-loop blue economy strategies, and climate adaptation policies—into the non-linear transfer function. This will provide a more granular, multi-dimensional diagnostic matrix to map highly optimized, sovereign transition pathways for functionally isolated territories worldwide.

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Ethics

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