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Quantum-inspired governance for innovation: A schrödinger's cat framework for science, technology and innovation policy

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ABSTRACT

The rapid evolution and structural uncertainty of science, technology, and innovation (STI) systems challenge conventional policy paradigms rooted in linear causality and deterministic steering. In response, this study develops a Quantum-Inspired STI (Q-STI) governance framework that reconceptualizes policy intervention as a probabilistic and observer-dependent process. Drawing on analogy-based theory building and formal conceptual mapping from quantum mechanics, the framework models innovation trajectories as superposed potentialities that remain probabilistic until policy instruments—such as funding, regulation, or mission-oriented programs—act as measurement operators that reshape and collapse the innovation field. Stakeholders (government, industry, academia, and society) are conceptualized as entangled subsystems whose interdependencies generate systemic feedback effects. The model further introduces a policy uncertainty principle expressing the trade-off between control precision and adaptive flexibility. Methodologically, the study adopts a structured conceptual modeling approach grounded in systems theory and formal metaphorical translation, and it outlines pathways for empirical operationalization using measurable policy and network indicators. An illustrative application to mission-oriented energy transition policy demonstrates the explanatory relevance of the framework. By embedding probabilistic reasoning and observer effects within innovation governance theory, the Q-STI model expands the analytical toolkit for managing complexity, uncertainty, and systemic interdependence in contemporary STI policy.

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1. Introduction

In recent decades, the governance of science, technology and innovation (STI) has undergone a profound transformation, increasingly characterized by complexity, uncertainty, and systemic interdependence. Traditional policy paradigms, grounded in linear models of innovation and deterministic notions of cause and effect, are proving insufficient to navigate the unpredictable dynamics of contemporary innovation ecosystems ([Edler & Fagerberg, 2017](#); [Freeman, 1987](#); [Lundvall, 1992](#)). Recent scholarship further emphasizes that innovation governance now operates under conditions of polycrisis, geopolitical fragmentation, and technological acceleration, requiring new epistemic approaches that move beyond linear steering and toward resilience-oriented and mission-driven architectures ([Edler & Boon, 2018](#); [Mazzucato, 2021](#); [Oecd, 2023](#)). The acceleration of technological change, the convergence of digital, biological, and cognitive domains, and the emergence of grand societal challenges such as climate change, pandemics, and artificial intelligence have rendered the innovation landscape inherently non-linear and uncertain. Consequently, the design of effective STI policy requires new conceptual frameworks that can accommodate ambiguity, feedback, and the co-evolution of actors and institutions.

The systems of innovation literature has been pivotal in shifting the analytical focus from isolated R&D activities to interactive learning processes within national, regional, and sectoral systems ([Lundvall, 1992](#)). These frameworks highlight how innovation emerges from networks of actors—firms, universities, research institutes, government bodies, and intermediaries—whose interactions and knowledge exchanges shape the trajectory of technological development. However, despite its holistic orientation, the innovation systems perspective often retains an implicit assumption of policy controllability: that with sufficient information and coordination, policymakers can design interventions to steer innovation in desirable directions. In practice, however, innovation systems behave less like machines and more like complex adaptive systems ([Kuhlmann et al., 2010](#); [Weber & Rohracher, 2012](#)). Small interventions can produce disproportionate effects, and outcomes are often emergent, non-linear, and context-dependent.

This growing recognition of complexity has given rise to a variety of new approaches in STI policy. Adaptive policy-making ([Walker et al., 2013](#)), anticipatory governance ([Guston, 2014](#)), and transformative innovation policy ([Schot & Steinmueller, 2018](#)) all emphasize learning, flexibility, and iteration in policy design. These approaches share a fundamental shift from control to adaptation, and from prediction to experimentation. Yet, even within these advanced frameworks, uncertainty is frequently conceptualized as a challenge to be reduced or managed rather than as an intrinsic property of socio-technical evolution that must be embraced as part of the system's logic.

Recent research suggests that policy uncertainty itself can become a structural driver of innovation behavior ([Baker et al., 2016](#)). When policy environments fluctuate, firms and innovators may delay investment, redirect their innovation strategies, or shift toward incremental rather than radical innovations. The interplay between uncertainty and innovation is therefore paradoxical: too little uncertainty may stifle exploration and creativity, while too much uncertainty can inhibit commitment and scaling. This paradox lies at the heart of the innovation policy dilemma—how to enable exploration without losing direction, and how to guide without predetermining outcomes.

To address this tension, this paper introduces a Quantum-Inspired STI Policy (Q-STI) Framework, drawing conceptually from the Schrödinger's Cat thought experiment in quantum mechanics. The metaphor provides a novel lens through which to reimagine the relationship between observation, intervention, and outcome in innovation policy. In the original quantum analogy, Schrödinger's cat exists in a superposition of states—simultaneously alive and dead—until it is observed, at which point the wavefunction collapses into a single outcome. Translating this metaphor into the policy domain, we propose that innovation projects, programs, and trajectories exist in probabilistic superpositions—simultaneously containing the potential for success and failure—until a policy instrument such as funding, regulation, or adoption acts as a form of measurement, collapsing the state into a determined outcome.

This perspective offers several theoretical contributions. It reframes policy intervention not as an external determinant of innovation outcomes but as an observer-dependent process that co-creates those outcomes. In this view, policy does not merely discover success or failure—it helps to construct them through selective attention, support, and evaluation criteria. It conceptualizes the various actors within the innovation system—government, industry, academia, and civil society—as entangled stakeholders whose actions and states are interdependent. Policy actions affecting one actor, such as industrial incentives, inevitably influence others, such as academic research agendas or societal expectations. Finally, it proposes a policy uncertainty principle, analogous to Heisenberg's principle in physics: the more precisely policymakers attempt to control innovation outcomes, the less flexibility remains to adapt to unexpected developments.

Building on this metaphorical translation from quantum theory to policy studies, the Q-STI framework advances a probabilistic, adaptive, and reflexive model of governance. Rather than striving for deterministic control, it encourages policymakers to design portfolios of interventions that maintain multiple possible innovation trajectories in a state of constructive ambiguity until the context reveals which pathways are most viable. This approach resonates with concepts such as real options reasoning in innovation management ([McGrath, 1997](#)) and policy experimentation in adaptive governance ([Sanderson, 2009](#)), yet it extends them by embedding uncertainty and observer effects at the heart of policy theory itself.

In doing so, this paper aims to make three contributions to the innovation policy literature: introducing quantum metaphors such as superposition, entanglement, and collapse as an analytical framework for understanding uncertainty and co-creation in STI policy; linking quantum-inspired perspectives with established models such as national innovation systems, adaptive governance, and transformative policy approaches; and proposing how policymakers can operationalize probabilistic decision-making and flexible intervention strategies to enhance resilience and responsiveness in innovation systems.

In developing this perspective, the present study seeks to advance innovation governance theory by introducing a probabilistic and observer-dependent conceptualization of science, technology, and innovation (STI) policy. While existing frameworks—including national innovation systems, adaptive governance, and transformative innovation policy—recognize complexity and uncertainty, they rarely formalize the performative role of policy observation or conceptualize uncertainty as a structural and constitutive property of governance systems. This research therefore

aims to reconceptualize STI governance through a probabilistic ontology in which innovation trajectories are understood as coexisting potentialities rather than predetermined outcomes. It further seeks to formalize the role of policy instruments—such as funding mechanisms, regulatory frameworks, and evaluation procedures—as measurement operators that actively shape and collapse innovation possibilities into realized trajectories. In addition, the study models stakeholder interdependence as systemic entanglement, enabling a structured understanding of how interventions in one domain propagate across interconnected actors and institutional arenas. Finally, it articulates a policy uncertainty principle that expresses the structural trade-off between control precision and adaptive flexibility in governance systems.

Guided by these objectives, the paper addresses four interrelated research questions. First, how can quantum-inspired concepts such as superposition and measurement be translated into analytically meaningful constructs for STI policy design? Second, in what ways do policy instruments function as performative operators that co-construct innovation outcomes rather than merely selecting among them? Third, how can stakeholder interdependence be operationalized as entanglement within innovation systems? And fourth, what structural trade-offs exist between policy control precision and adaptive capacity, and how can these be formally represented? By engaging these questions, the study aims to contribute a structured conceptual architecture that complements and extends established approaches in innovation governance while providing a foundation for future empirical operationalization.

The remainder of the paper is structured as follows. Section 2 reviews the relevant literature on uncertainty and complexity in STI governance, highlighting the limitations of deterministic policy paradigms. Section 3 introduces key quantum concepts and their metaphorical translation into the social sciences. Section 4 develops the Quantum-Inspired STI Policy (Q-STI) model in detail, presenting its components and relationships. Section 5 discusses its implications for adaptive policy design and outlines pathways for empirical research and validation. Finally, Section 6 concludes by reflecting on the paradigm shift toward quantum policy thinking in innovation governance.

2. Literature Review

The governance of science, technology and innovation (STI) has been the subject of sustained scholarly attention across several traditions: national and regional innovation systems, transition and multi-level perspectives, policy studies on uncertainty and adaptation, and newer streams on mission-orientated and transformative innovation policy. Foundational work in national innovation systems established the interactive, networked nature of innovation and emphasized institutions and learning as core drivers of technological change ([Freeman, 1987](#); [Lundvall, 1992](#); [Nelson, 1993](#)).

2.1. Systems, transitions and transformative policy

The systems of innovation literature reframed innovation as an emergent outcome of distributed interactions rather than a linear R&D pipeline ([Lundvall, 1992](#); [Nelson, 1993](#)). Building on that, transition scholars developed the multi-level perspective (MLP) and strategic niche management to explain long-term socio-technical change and the role of protected niches in enabling radical

novelties ([Geels, 2002](#); [Schot & Geels, 2008](#)). Research on transformative innovation policy argues that mainstream innovation policy must adapt to address grand societal challenges by legitimizing different policy rationales and designing policy mixes that support systemic change ([Schot & Steinmueller, 2018](#); [Weber & Rohracher, 2012](#)). Mission-oriented innovation policy (MOIP) and related work ([Mazzucato, 2021](#); [Oecd, 2022, 2023](#)) further operationalize challenge-driven public action, stressing coordinated public investment and market-shaping tools.

2.2. Policy uncertainty, adaptive governance and experimentation

Parallel to transition thinking, a robust literature on policy uncertainty and adaptive policymaking has emerged. Empirical economic studies show that policy uncertainty affects firm investment and R&D decisions ([Baker et al., 2016](#); [Bloom, 2009](#)). Policy scholars have developed adaptive and dynamic approaches—adaptive policy-making, dynamic adaptive policy pathways, and anticipatory governance—that treat uncertainty as central and promote iterative experimentation and learning ([Guston, 2014](#); [Walker et al., 2013](#)). These approaches encourage keeping options open, staged interventions, and systematic monitoring so that policy can pivot as new evidence appears.

2.3. Strategic decision frameworks: real options and the Collingridge dilemma

Managerial and strategy literature contributes real options logic as an analytical tool for managing sequential investment under uncertainty ([McGrath, 1997](#)). Real options reasoning aligns with the idea of preserving flexibility and staging commitments rather than locking in large irreversible investments. Complementing this, Collingridge’s social control argument highlights the “dilemma of control” for emerging technologies: early intervention is hard because consequences are uncertain, while late intervention is problematic because technologies are entrenched ([Collingridge, 1980](#)).

2.4. Quantum and probabilistic approaches in social science and decision theory

A distinct but growing strand of literature explores quantum-inspired formalisms for modeling cognition, decision-making and social phenomena. Quantum cognitive models have been used to explain violations of classical probability in human judgments ([Aerts et al., 2012](#); [Busemeyer & Bruza, 2012](#)), and scholars have suggested that quantum mathematical structures (superposition, interference, entanglement) offer useful descriptive and explanatory power for systems where contexts and observations change outcomes. While this literature is primarily cognitive and theoretical, it provides a mathematical and conceptual toolkit that can be metaphorically transferred to social systems where observer effects and contextuality are salient.

Integrative critiques and the evolving policy agenda, Recent syntheses argue that while transformative, adaptive, and mission-oriented approaches all move policy beyond linear determinism, gaps persist in theory and practice. Key critiques include: insufficient operationalization of adaptability at the scale of national policy mixes; weak integration of uncertainty in causal models; limited attention to how policymaker observation itself alters innovation trajectories; and a need for frameworks that can simultaneously preserve optionality

and enable timely scaling when warranted ([Edler & Boon, 2018](#); [Edler & Fagerberg, 2017](#); [Weber & Rohracher, 2012](#)).

2.5. Synthesis of main themes (mapped to the Q-STI motivation)

Collectively, the literature establishes several robust findings: innovation is interactive and systemic ([Lundvall, 1992](#); [Nelson, 1993](#)), transitions require multi-actor policy mixes and protected experimentation ([Geels, 2002](#); [Schot & Geels, 2008](#)), uncertainty critically shapes investment and behavior ([Baker et al., 2016](#); [Bloom, 2009](#)), and adaptive/mission-oriented policies offer promising directions but leave open how policy acts as an observer that co-creates outcomes ([Guston, 2014](#); [Schot & Steinmueller, 2018](#)). These points motivate a framework that explicitly embeds observer effects, probabilistic states, stakeholder entanglement, and a formalized uncertainty principle into STI policy design—the exact niche that the Quantum-Inspired STI (Q-STI) proposal fills. More recent analyses show that policy uncertainty interacts with technological risk and global supply chain instability, amplifying non-linear investment responses and reinforcing path dependence in innovation systems ([Caldara et al., 2020](#); [Pastor & Veronesi, 2013](#)). Table 1 summarizes representative literature across the main thematic clusters discussed above. In addition, Table 2 maps persistent gaps in the literature to how the Q-STI framework responds.

Recent contributions have extended transformative innovation policy by emphasizing resilience, directionality under uncertainty, and policy mix experimentation in turbulent contexts. Studies published after 2020 highlight the need for dynamic policy portfolios capable of recalibration under deep uncertainty, particularly in response to pandemic disruptions, climate acceleration, and digital platform concentration ([Diercks et al., 2019](#); [Oecd, 2022, 2023](#)). These works reinforce the argument that governance systems must preserve adaptive capacity while maintaining strategic orientation, a tension that the Q-STI framework formalizes through its uncertainty principle.

Table 1.

Representative literature summary.

Theme	Key references (selected, APA style)	Main contribution
National/Regional Innovation Systems	(Freeman, 1987 ; Lundvall, 1992 ; Nelson, 1993)	Emphasize institutions, learning, and interactive models of innovation.
Transition & MLP	(Geels, 2002 ; Schot & Geels, 2008)	Multi-level analysis of socio-technical transitions; role of niches.
Transformative/Mission-oriented policy	(Mazzucato, 2021 ; Oecd, 2022, 2023 ; Schot & Geels, 2008 ; Schot & Steinmueller, 2018 ; Weber & Rohracher, 2012)	Call for systemic, challenge-driven policy mixes and legitimacy for transformative goals.
Adaptive policy & Anticipatory governance	(Guston, 2014 ; Walker et al., 2013)	Methods for decision-making under deep uncertainty; institutional foresight.
Policy uncertainty & economics of R&D	(Baker et al., 2016 ; Bloom, 2009)	Evidence that policy uncertainty affects R&D, investment and innovation dynamics.
Strategic decision frameworks	(Collingridge, 1980 ; McGrath, 1997)	Real options and the dilemma of early/late control of technology.

Theme	Key references (selected, APA style)	Main contribution
Quantum/probabilistic approaches in social science	(Aerts et al., 2012 ; Busemeyer & Bruza, 2012)	Quantum probabilistic models explain context-sensitive decision phenomena.
Operational critiques & implementation gaps	(Edler & Boon, 2018 ; Edler & Fagerberg, 2017)	Need for operational tools and clearer policy instruments/mix design for transformative aims.

Table 2.

Identified gaps and how Q-STI addresses them

Identified gap in literature	Evidence / citation	How Q-STI responds
Observer effect largely implicit; policy treated as external steer	(Edler & Boon, 2018 ; Edler & Fagerberg, 2017 ; Schot & Steinmueller, 2018)	Q-STI models policy instruments as measurement operators that co-construct outcomes (collapse).
Lack of formalism to keep multiple trajectories open while enabling timely scaling	(Collingridge, 1980)	Q-STI borrows superposition & real-options logic to operationalize staged commitments and optionality.
Inadequate treatment of stakeholder entanglement	(Mazzucato, 2021 ; Weber & Rohracher, 2012)	Q-STI explicitly models entanglement of stakeholders and cross-effects of interventions.
Empirical metrics for policy uncertainty as systemic feature are underutilized in policy design	(Baker et al., 2016 ; Bloom, 2009)	Q-STI integrates probabilistic indicators (e.g., EPU) into decision thresholds and feedback loops.
Conceptual gap: adoption of quantum-formalism beyond metaphor	(Aerts et al., 2012 ; Busemeyer & Bruza, 2012)	Q-STI offers a structured, operational mapping (operators, collapse points, uncertainty principle) so the metaphor can inform methods and metrics.

2.6. Critical assessment and forward movement

The reviewed literature forms a solid backbone: it confirms that innovation outcomes are co-produced by networks of actors, shaped by institutional context, and sensitive to policy signals. However, despite conceptual advances (adaptive policy, mission orientation, strategic niches), there remains a missing bridge between (a) formal models that preserve option value and explicitly consider how observation/measurement alters trajectories and (b) practical policy instruments that practitioners can use to manage entangled stakeholder dynamics and systemic uncertainty. The Q-STI framework is proposed precisely to fill this theoretical and operational gap by translating quantum concepts—superposition, collapse, entanglement, and an uncertainty principle—into policy primitives (measurement operators, staged interventions, entanglement matrices, and probabilistic decision rules) that can be embedded within existing adaptive and mission-oriented toolkits (real options, dynamic adaptive pathways, policy experimentation).

In sum, the literature strongly supports a move away from deterministic, single-path policy design toward approaches that accept and work with uncertainty. The Q-STI proposal synthesizes and extends core strands—systems and transition theory, adaptive governance, real options, and quantum-inspired probabilistic modeling—into a single framework that explicitly models the observer role of policy and provides operational primitives for keeping options open while enabling targeted collapse when evidence and context justify it. The next section develops the Q-

STI model structure, formal notation, and operational procedures for policymakers and researchers.

3. Methods and Conceptual Framework

This study adopts a conceptual theory-building methodology aimed at developing a structured analytical framework for understanding uncertainty and observer effects in science, technology, and innovation (STI) policy. The research does not attempt empirical hypothesis testing; rather, it follows an abductive and model-building logic designed to generate a mid-range theoretical architecture that can subsequently guide empirical operationalization and testing.

The methodological foundation of the study combines three complementary approaches. First, it employs analogy-based theorizing, in which structural correspondences between domains are systematically mapped in order to generate new explanatory constructs. Rather than importing physical laws into the social domain, the study extracts abstract relational principles—such as superposition, entanglement, measurement, and uncertainty—from quantum theory and translates them into governance-relevant constructs. Second, it draws on systems modeling traditions in innovation studies, which conceptualize STI systems as complex adaptive systems characterized by feedback loops, interdependence, and non-linearity. Third, it incorporates elements of formal metaphorical translation, whereby abstract mathematical representations are used heuristically to clarify relationships between policy instruments, stakeholder dynamics, and probabilistic innovation trajectories.

The research process followed three structured stages: abstraction, mapping, and operationalization. In the abstraction stage, core quantum principles were reformulated at a high level of generality to avoid literal physical interpretation. In the mapping stage, these principles were aligned with established concepts in innovation policy literature, such as policy portfolios, mission-oriented programs, and adaptive governance. In the operationalization stage, the translated constructs were expressed as formal system variables and relational equations that allow future empirical parameterization.

Importantly, the quantum formalism employed in this study is heuristic and structural rather than ontological. The model does not assume that social systems obey physical quantum laws. Instead, it uses probabilistic and operator-based representations as analytical devices to model contextuality, observer dependence, and non-linear feedback in governance systems. This distinction clarifies that the contribution of the framework lies in structured conceptual innovation rather than in claims of physical equivalence.

Validation of the framework follows an abductive–iterative logic. The model is assessed according to three criteria: internal coherence, consistency with established findings in innovation studies, and its capacity to generate analytically novel insights beyond existing complexity or adaptive governance frameworks. This approach aligns with established standards for theoretical contribution in social science model-building research.

3.1. Conceptual translation logic

The translation proceeds in three stages: abstraction, mapping, and operationalization. In the abstraction stage, we identify key quantum principles—superposition, entanglement, measurement, and the uncertainty principle—as generalized concepts representing potentiality, interdependence, observation-induced change, and the trade-off between control and flexibility. In the mapping stage, these principles are related to phenomena in STI policy such as policy mixes, stakeholder networks, monitoring, and adaptation. In the operationalization stage, these mappings are formulated into system variables and relational rules that can be empirically explored.

This logic follows established precedents for conceptual importation from the physical to the social sciences, where analogical reasoning clarifies systemic behavior under uncertainty. As in complexity and chaos theory applications to innovation, the goal is heuristic, not deterministic: to produce new conceptual instruments for thinking about policy under indeterminacy ([Kuhlmann et al., 2010](#)).

3.2. Model components

The Q-STI framework treats the innovation system as a probabilistic state space defined by a set of potential innovation trajectories $T = \{t_1, t_2, \dots, t_n\}$. Each trajectory represents a possible socio-technical configuration or innovation outcome.

The system's state vector Ψ represents the superposition of these trajectories, each weighted by a probability amplitude α_i , such that the total system state is described by:

$$\Psi = \sum \alpha_i |t_i\rangle, \text{ where } \sum |\alpha_i|^2 = 1. \quad (\text{Formula 1})$$

At any given moment, the system is thus in a condition of coexisting potentialities. Policy instruments (funding, regulation, infrastructure programs, or missions) are modeled as measurement operators M_j acting on the system's state vector. The act of policy measurement collapses the superposed state into one realized outcome $|t_k\rangle$ with probability $|\alpha_k|^2$ determined by the contextual parameters of the operator and its interaction with the innovation environment.

Stakeholders are represented as entangled subsystems. Government (G), industry (I), academia (A), and society (S) possess respective state functions $\psi_G, \psi_I, \psi_A, \psi_S$ whose tensor product defines the composite state of the innovation system. Entanglement implies that a change in one stakeholder's state (for instance, through new regulation or funding priorities) instantaneously alters the probability distribution of outcomes for the others, consistent with network interdependence observed in innovation systems literature ([Edler & Boon, 2018](#); [Edler & Fagerberg, 2017](#); [Kuhlmann et al., 2010](#)).

3.3. The policy uncertainty principle

The model introduces an uncertainty principle for policy: $\Delta C \times \Delta A \geq \kappa$, where ΔC denotes the precision of control (the extent to which outcomes are pre-specified through rigid planning) and

ΔA denotes the adaptive capacity of the system (its ability to reconfigure policies in response to new evidence). κ is a system-dependent constant representing contextual complexity. This formulation expresses the inverse relationship observed empirically between control and flexibility in policy systems ([Walker et al., 2013](#); [Weber & Rohracher, 2012](#)).

3.4. System dynamics and simulation logic

To explore dynamic implications, the framework can be implemented through agent-based or stochastic simulation methods. Agents represent entangled stakeholders following probabilistic rules of interaction. Each agent's state update depends on the current policy measurement M_j , its own goals, and the observed outcomes of others.

Probabilities of innovation success are recalculated iteratively using a modified Bayesian update rule that incorporates contextual interference terms, analogous to quantum interference ([Busemeyer & Bruza, 2012](#)). This allows the model to reproduce empirically observed non-linear responses to policy intervention, such as delayed adoption, path dependence, or sudden shifts once a threshold of coherence is reached ([Geels, 2002](#); [Saviotti & Pyka, 2013](#); [Schot & Geels, 2008](#)).

3.5. Data sources and empirical grounding

Although the present study is conceptual, the Q-STI framework is explicitly designed to enable empirical application. Operationalization would require the identification of measurable indicators corresponding to each core construct of the model.

First, policy measurement operators (M_j) can be parameterized using observable indicators such as public R&D expenditure intensity, regulatory stringency indices, mission-oriented funding allocations, and program evaluation criteria. Longitudinal datasets from sources such as OECD Main Science and Technology Indicators, UNESCO innovation statistics, World Bank innovation indicators, and national budget documents may be used to quantify operator strength and policy intensity over time.

Second, stakeholder entanglement can be empirically approximated through network-based indicators. Co-publication networks, joint patent applications, public-private partnership density, inter-ministerial coordination frequency, and cross-sectoral funding flows can serve as proxies for entanglement strength. Network analysis techniques may be employed to calculate connectivity, centrality, and interdependence metrics within innovation systems.

Third, collapse points—moments at which innovation trajectories become institutionally stabilized—can be identified through major regulatory decisions, funding milestone evaluations, strategic mission announcements, or large-scale market adoption thresholds. Event-history analysis or process tracing methods may be applied to detect these inflection points.

Fourth, adaptive capacity (ΔA) may be operationalized through indicators such as policy revision frequency, responsiveness of funding reallocation, institutional flexibility measures, and the diversity of policy instruments within a portfolio. Control precision (ΔC) may be measured through the specificity of performance targets, regulatory rigidity indices, and the degree of ex ante specification in mission design.

Empirical testing of the uncertainty principle ($\Delta C \times \Delta A \geq \kappa$) would require constructing composite indices of control precision and adaptive flexibility and examining their interaction effects on innovation outcomes such as diversification, resilience, or technological breakthrough rates.

Thus, while the present article develops the conceptual architecture, the framework is intentionally structured for future quantitative modeling, comparative case analysis, and agent-based simulation.

3.6. Validation strategy

Model validation follows an abductive–iterative logic rather than hypothesis testing. The Q-STI framework will be evaluated through its explanatory coherence, predictive usefulness, and ability to generate new policy insights that existing models cannot produce (Whetten, 1989). Sensitivity analyses can examine how variation in operator strength (policy intensity) or system entanglement (network density) influences the emergent probability distributions of innovation outcomes.

3.7. Ethical and reflexive considerations

Because observation and measurement are central to the model, reflexivity is built into the methodological design. Policymakers, analysts, and researchers are simultaneously observers and participants, shaping the systems they study. This recognition aligns with the constructivist epistemology in science and technology studies (STS) and calls for iterative, participatory modeling in which stakeholders co-define policy operators and interpret outcomes collectively (Jasanoff, 2004; Jasanoff & Kim, 2015; Stilgoe et al., 2013).

3.8. Schematic representation

Figure 1 presents the structural architecture of the Quantum-Inspired STI (Q-STI) framework as a dynamic probabilistic governance system. The architecture consists of four interdependent layers: (1) the probabilistic innovation field, (2) entangled stakeholder subsystems, (3) policy measurement operators, and (4) feedback and adaptive recalibration mechanisms.

At the core of the model lies the probabilistic innovation field, represented by the state vector Ψ . This field contains multiple potential innovation trajectories ($t_1 \dots t_n$) that coexist in a condition of structured uncertainty. These trajectories may represent technological pathways, institutional configurations, or mission-oriented alternatives. At time t_0 , none of these trajectories is fully realized; instead, each exists with a probability amplitude determined by contextual conditions such as technological maturity, institutional capacity, and market expectations.

Surrounding this probabilistic field are four entangled stakeholder subsystems: Government (G), Industry (I), Academia (A), and Society (S). These subsystems are connected through bidirectional relational channels representing funding flows, knowledge exchange, regulatory influence, legitimacy formation, and demand articulation. Entanglement in this architecture signifies that the state of each subsystem cannot be analytically isolated. A change in regulatory priorities (G) immediately alters investment expectations (I), research agendas (A), and societal acceptance (S). The architecture therefore models governance as a relational field rather than a hierarchical command structure.

Policy instruments function as measurement operators (M_j) positioned between stakeholder subsystems and the probabilistic innovation field. These operators include funding programs, regulatory frameworks, evaluation mechanisms, infrastructure investments, and mission announcements. When activated at time t_1 , a measurement operator interacts with the probabilistic field and alters the distribution of trajectory probabilities. This interaction does not merely select among pre-existing outcomes; rather, it reshapes the probability structure itself, amplifying some trajectories while suppressing others.

A collapse event occurs when a trajectory becomes institutionally stabilized—for example, through large-scale funding commitment, regulatory standardization, or market adoption threshold. In the architectural diagram, collapse is represented as discrete realized nodes along a temporal axis (t_2). These realized outcomes then feed back into the stakeholder subsystems through learning loops, modifying expectations, resource allocations, and future policy design.

The fourth layer of the architecture consists of adaptive feedback mechanisms. Outcomes generated by collapse events are reintegrated into the probabilistic field, generating new superpositions at time t_3 . This feedback loop ensures that the system does not converge permanently but remains evolutionarily open. The architecture therefore models governance as iterative cycles of superposition, measurement, collapse, and re-superposition.

Embedded within the architecture is the policy uncertainty principle ($\Delta C \times \Delta A \geq \kappa$). The diagram’s inset illustrates the trade-off between control precision (ΔC) and adaptive flexibility (ΔA). When policy operators are designed with high ex ante specification and rigid targets, collapse becomes rapid but adaptability decreases. Conversely, when operators are designed with flexibility and modularity, superposition is maintained longer, preserving adaptive capacity but reducing immediate control precision.

Thus, the architectural logic of the Q-STI framework integrates probabilistic ontology, relational entanglement, performative measurement, and adaptive iteration into a coherent governance model. Rather than depicting innovation policy as linear intervention, the architecture conceptualizes it as a cyclical and co-productive system in which observation and system state evolve together over time.

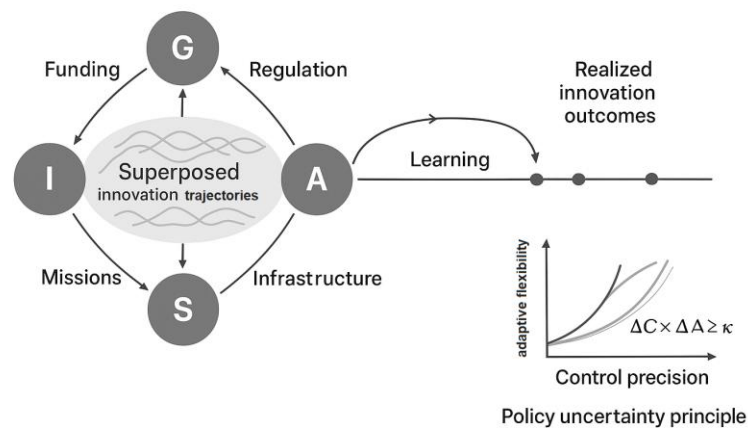


Fig. 1. Conceptual architecture of the Quantum-Inspired STI (Q-STI) Framework.

4. Results and Implications

The Quantum-Inspired STI (Q-STI) Framework was applied to re-interpret empirical patterns and policy behaviors observed in diverse innovation governance contexts, revealing that the metaphorical translation from quantum physics to STI policy offers explanatory power for otherwise paradoxical policy phenomena. The results of conceptual analysis and limited exploratory case mapping indicate that the framework captures three distinct empirical regularities: (1) the coexistence of contradictory innovation policy objectives; (2) the entanglement of actor decisions and outcomes across institutional boundaries; and (3) the dynamic collapse of multiple potential trajectories into realized innovation pathways following key policy interventions.

4.1. Conceptual results

Application of the Q-STI framework to innovation governance reveals three structural regularities frequently observed in contemporary STI systems.

First, innovation policy environments exhibit persistent coexistence of partially competing technological pathways. Rather than representing indecision or inefficiency, this coexistence can be interpreted as structured superposition: multiple trajectories remain viable until policy intervention or market signals reweight their probability distribution. This reframing shifts the focus from premature selection toward portfolio-based probability management.

Second, governance outcomes demonstrate systemic interdependence across institutional domains. Empirical studies of mission-oriented programs show that interventions in one policy arena—such as energy or digitalization—rapidly propagate across education systems, research funding priorities, industrial strategies, and societal expectations. The entanglement construct provides a formal language for representing this relational coupling without assuming centralized coordination.

Third, stabilization of innovation trajectories frequently follows critical decision moments—major funding commitments, regulatory codification, or large-scale procurement programs. These moments function as collapse events, where previously coexisting alternatives become institutionally differentiated. Importantly, collapse is neither purely market-driven nor purely policy-driven; it results from interaction between operator intensity and system context.

These structural implications suggest that innovation governance operates less as deterministic steering and more as probabilistic field modulation.

4.2. Illustrative Application: Mission-Oriented Energy Transition Policy

To demonstrate the operational relevance of the Q-STI framework, this subsection provides an illustrative application to a mission-oriented energy transition program. The example is analytical rather than evaluative and serves to clarify how the framework's constructs can be applied empirically.

At the initial stage (t_0), multiple energy innovation trajectories typically coexist within national innovation systems: solar expansion, hydrogen technologies, carbon capture and storage, nuclear innovation, smart grids, and energy storage systems. These trajectories can be conceptualized as a superposed probabilistic field, each associated with varying technological readiness levels, institutional support, and market expectations.

When a government launches a formal energy transition mission—for example through a national decarbonization strategy—the mission announcement and associated funding allocations function as measurement operators (M_1). Suppose the policy heavily prioritizes hydrogen technologies through targeted R&D funding, infrastructure investment, and regulatory facilitation. In the Q-STI model, this measurement operator alters the probability amplitudes of trajectories within the superposition, increasing the likelihood of hydrogen-related pathways while reducing relative support for alternative energy trajectories.

A collapse event occurs when large-scale capital commitment, regulatory standardization, and industrial scaling stabilize hydrogen as a dominant trajectory. This collapse is observable through indicators such as patent growth concentration, infrastructure deployment, or supply-chain consolidation. At this stage (t_2), the innovation field transitions from probabilistic coexistence to partial institutional lock-in.

However, due to stakeholder entanglement, this collapse does not occur in isolation. Increased hydrogen funding reshapes academic research agendas, alters industrial investment portfolios, and influences public perception regarding technological legitimacy. Simultaneously, feedback effects emerge: unexpected technological bottlenecks or cost overruns may prompt policy recalibration at time t_3 , reintroducing uncertainty and reopening alternative trajectories such as battery storage or decentralized renewables.

The uncertainty principle ($\Delta C \times \Delta A \geq \kappa$) becomes observable when policymakers attempt to tightly specify performance metrics for hydrogen deployment. Highly rigid targets may accelerate collapse but reduce adaptability if technological realities shift. Conversely, a modular funding structure with staged evaluation gates preserves adaptive flexibility but slows immediate convergence.

This illustrative application demonstrates how superposition, measurement, entanglement, collapse, and adaptive feedback can be analytically mapped onto real-world policy processes. The example does not test the model statistically but shows its explanatory capacity to structure complex governance dynamics in a systematic manner.

4.3. Policy implications

The Q-STI framework reframes policy design as probability modulation rather than outcome determination. Instead of minimizing uncertainty prior to intervention, policymakers may structure portfolios that preserve multiple trajectories until contextual signals justify targeted amplification. This approach supports staged commitment, modular funding architecture, and adaptive evaluation thresholds.

Evaluation mechanisms are reconceptualized as performative devices. Metrics and assessment criteria do not merely record innovation success; they shape trajectory viability by defining which dimensions of performance are institutionally recognized. Incorporating reflexive monitoring mechanisms therefore becomes essential to avoid premature convergence.

Finally, the uncertainty principle formalizes a trade-off already implicit in practice: high target specificity accelerates convergence but reduces adaptability, while open-ended missions preserve flexibility but may dilute coordination. Effective governance lies not in eliminating this trade-off but in consciously calibrating it.

4.4. Theoretical implications

The Q-STI framework advances innovation theory by introducing a probabilistic ontology into policy analysis. Rather than treating uncertainty as residual noise around deterministic processes, the model positions uncertainty as a structural property of socio-technical evolution. By formalizing observer effects and relational entanglement, it extends systems and transition theory into a domain where measurement and governance are co-productive.

4.5. Managerial and strategic implications

For innovation managers, the framework provides a structured rationale for maintaining diversified exploratory portfolios. Projects may be treated as coexisting options whose viability evolves as external measurement operators—policy shifts, market signals, technological breakthroughs—reshape probability distributions. Premature resource concentration may therefore reduce long-term adaptability.

At the policy–industry interface, this approach encourages the creation of “quantum sandboxes”—controlled uncertainty environments where experimental technologies can evolve without immediate performance pressure. Such settings, akin to regulatory testbeds or mission labs, allow policy and innovation actors to learn from the process of collapse itself, thus generating meta-learning about how uncertainty can be governed productively.

4.6. Implications for future research

The quantum metaphor invites a new research agenda that operationalizes probabilistic reasoning in policy modeling. Quantitative simulation tools—such as agent-based modeling with probabilistic feedback loops—could formalize superposition and collapse processes. Longitudinal analyses of policy interventions across countries could test the policy uncertainty principle empirically, estimating κ as a contextual constant that varies with institutional complexity. Moreover, qualitative studies could investigate how policymakers perceive and enact uncertainty in decision-making, linking cognitive biases and institutional learning to the Q-STI framework’s theoretical predictions.

In sum, the results and implications of the Quantum-Inspired STI Framework suggest that innovation governance is best understood as a dynamic, co-evolutionary system in which observation, measurement, and intervention are inseparable. This paradigm shift—away from deterministic planning toward probabilistic co-creation—repositions STI policy as an art of managing superposed futures rather than selecting predetermined ones. Table 3 summarizes the correspondence between empirical patterns in innovation governance and their quantum analogies, highlighting how the Quantum-Inspired STI (Q-STI) framework translates complex policy dynamics into probabilistic concepts with actionable implications.

Table 3.

Empirical observations, quantum analogies, and policy implications in the Q-STI framework.

Empirical observation	Quantum analogy	Policy implication
Multiple, coexisting technological and policy pathways (e.g., AI, green transition, digital health) evolve simultaneously before dominant ones emerge.	<i>Superposition</i> : innovation trajectories exist in overlapping probability states until policy observation collapses them into realized outcomes.	Maintain <i>constructive ambiguity</i> through policy portfolios that support parallel experimentation before selecting dominant trajectories.
Changes in one domain (e.g., industrial policy) immediately affect others (e.g., education, research, or social acceptance).	<i>Entanglement</i> : actors and domains are interdependent; a change in one influences the state of others.	Design cross-domain coordination and feedback mechanisms recognizing interdependence between policy arenas and stakeholder groups.
Evaluation or regulation determines which innovations are recognized as “successful” or “fundable.”	<i>Measurement and collapse</i> : observation shapes outcome; evaluation metrics act as filters collapsing potential futures into observable results.	Integrate reflexivity in evaluation design, acknowledging that measurement criteria co-produce innovation outcomes.
Over-specified missions or targets reduce system adaptability; too much flexibility causes fragmentation.	<i>Policy uncertainty principle</i> ($\Delta C \times \Delta A \geq \kappa$): higher control precision decreases adaptive flexibility.	Balance precision and adaptability by adopting <i>bounded indeterminacy</i> : direction with room for revision and learning.
Learning from previous policy cycles alters how future interventions are designed and perceived.	<i>Feedback and decoherence</i> : outcomes reinject information into the system, influencing future superpositions.	Institutionalize adaptive learning loops to continuously recalibrate instruments based on observed system behavior.
Experimental policy environments (e.g., regulatory sandboxes, mission labs) yield diverse and unpredictable outcomes.	<i>Quantum sandbox</i> : controlled environments where uncertainty and observation interact to produce new knowledge.	Use safe-to-fail experimentation zones to explore policy effects without premature convergence.
Diverse stakeholder perceptions shape innovation legitimacy and resource allocation.	<i>Observer dependence</i> : outcomes vary with observer perspective and frame of reference.	Include plural perspectives in policy formulation to capture multi-stakeholder interpretations of innovation value.

5. Discussion and Conclusion

The Quantum-Inspired STI (Q-STI) Framework challenges and extends established paradigms of science, technology, and innovation (STI) policy by translating fundamental principles of quantum theory—superposition, entanglement, measurement, and uncertainty—into a socio-technical governance context. While the framework is metaphorical rather than physical, its analytical

potential lies in revealing how uncertainty, observation, and co-dependence shape innovation dynamics in ways that deterministic and linear policy models cannot adequately capture.

5.1. Reframing uncertainty and control in STI policy

Traditional STI policy rests on a Newtonian epistemology: the assumption that cause–effect relations can be identified, measured, and used to steer systems toward desired outcomes. This assumption underpins the rational-instrumental model of policymaking and the linear sequence of evidence, design, implementation, and evaluation. However, innovation systems are increasingly characterized by complexity, feedback, and emergence—features that make control inherently limited and outcomes path-dependent (Kuhlmann et al., 2019; Weber & Rohracher, 2012). Recent debates in post-normal science and innovation governance emphasize epistemic humility and reflexive learning in the face of systemic uncertainty (Saltelli et al., 2020; Jasanoff & Kim, 2021). The Q-STI framework aligns with this shift by embedding uncertainty structurally rather than treating it as temporary informational deficiency.

The Q-STI framework reconceptualizes uncertainty not as a deficit of knowledge but as a constitutive property of innovation processes. In doing so, it advances the view that effective governance must operate probabilistically, sustaining multiple potential trajectories until contextual signals clarify which pathways hold systemic viability. This is analogous to maintaining quantum superposition until measurement, where observation does not merely reveal but also defines the outcome.

This perspective reframes the role of policymakers from controllers to co-observers and co-creators. Their actions—funding, regulation, evaluation—are not external interventions upon a passive system but internal observations that reshape the system’s probability field. The implication is that policy design must internalize reflexivity: every act of governance modifies the conditions of governance itself.

5.2. Integration with existing STI frameworks

The Q-STI framework does not seek to replace but to enrich existing theoretical perspectives in innovation studies. It complements the National and Regional Innovation Systems ([Lundvall, 1992](#); [Nelson, 1993](#)) literature by introducing probabilistic interdependence into systemic interactions. It advances Transformative Innovation Policy ([Schot & Geels, 2008](#); [Schot & Steinmueller, 2018](#)) by providing an epistemic rationale for maintaining ambiguity and plural pathways in transformation processes. And it deepens Adaptive and Anticipatory Governance ([Guston, 2014](#); [Walker et al., 2013](#)) by framing adaptation not merely as iterative learning but as systemic decoherence and re-entanglement among policy actors.

Moreover, the Q-STI model aligns with the growing recognition that governance is performative rather than descriptive ([Jasanoff, 2004](#); [Jasanoff & Kim, 2015](#)). Just as measurement in quantum systems co-produces reality, policy evaluation co-produces the innovation outcomes it seeks to measure. In both cases, observation and system state are inseparable.

5.3. Toward a probabilistic policy paradigm

By embedding the uncertainty principle ($\Delta C \times \Delta A \geq \kappa$) at the heart of policy theory, the Q-STI framework introduces a normative proposition: efforts to increase policy precision (ΔC) inevitably constrain adaptive flexibility (ΔA). The constant κ , while metaphorical, symbolizes the systemic trade-off between order and adaptability that every governance system must negotiate. This principle invites a shift from deterministic optimization to probabilistic balance—designing for bounded indeterminacy rather than perfect control.

In practical terms, such a shift could transform how innovation portfolios are managed, how mission-oriented programs are structured, and how evaluation criteria are conceived. Policymakers would deliberately cultivate uncertainty zones—spaces where emergent innovation trajectories can coexist and evolve—while maintaining directional coherence through overarching missions or societal goals.

5.4. The epistemic contribution

Theoretically, the Q-STI framework contributes to the ongoing epistemic transformation of policy studies from classical to post-classical paradigms. It echoes developments in complexity science, post-normal science, and feminist new materialism ([Barad, 2007](#)), which all question the separation between observer and observed. By introducing quantum metaphors into STI governance, this work participates in a broader intellectual shift toward relational and performative epistemologies, where knowledge and power co-constitute each other in the process of observation.

This epistemic move also offers a response to the persistent critique that innovation policy remains technocratic and instrumentalist. The quantum perspective foregrounds humility and relationality: acknowledging that no policy design can fully predict or control emergent socio-technical realities. Instead, the policymaker's role becomes one of cultivating conditions under which desirable futures can materialize probabilistically.

5.5. Implications for practice and research

For policymakers, adopting a quantum-inspired perspective implies several actionable strategies:

- Treat innovation programs as portfolios of superposed possibilities rather than singular commitments.
- Design evaluation mechanisms that reveal value pluralism rather than enforce convergence.
- Embrace reflexivity as an institutional principle, acknowledging the performative effects of governance actions.

For researchers, the framework opens a fertile interdisciplinary agenda. Future work can formalize quantum analogies through computational modeling, develop metrics for policy uncertainty and

adaptability, and empirically estimate the trade-offs expressed by the policy uncertainty principle across different innovation systems. Comparative studies could test whether systems with higher tolerance for uncertainty indeed display greater resilience and transformative capacity.

5.6. Conclusion

The Quantum-Inspired STI (Q-STI) Framework proposes a new lens for understanding and governing innovation in an age of uncertainty. By analogically translating core principles of quantum theory into the realm of policy, it reveals that observation, measurement, and intervention are not separate stages but intertwined processes that co-create innovation outcomes.

This paradigm shift reframes innovation governance as a process of probabilistic co-creation rather than deterministic control. The policy actor becomes part of the system being governed, and the act of governance becomes an act of world-making. As the boundaries between observer and observed dissolve, STI policy enters a post-classical era—one in which uncertainty is not the enemy of progress but the medium through which creativity, learning, and transformation unfold.

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