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Institutional Legitimacy and Sustainable Nuclear Energy Governance: A Comparative Sociotechnical Analysis

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Abstract

As nuclear energy re-emerges as a key component of global decarbonization, its long-term sustainability increasingly depends on institutional legitimacy alongside technical performance. Drawing on institutional theory, sociotechnical systems theory, and energy justice scholarship, this study conceptualizes regulatory compliance as a governance-mediated outcome shaped by trust, equity, transparency, and inclusion (TETI). Building on the Q-NPT (Qudrat-Ullah Nuclear Peace and Trust) framework, a sequential explanatory mixed-method design develops a composite TETI Governance Index using structured coding of regulatory documents, international peer-review findings, and participatory governance practices across ten advanced and emerging nuclear programs. The index enables comparative assessment of governance quality through standardized indicators and aggregation of the four governance dimensions. Comparative analysis across the ten programs reveals systematic governance differences between advanced and emerging nuclear systems, with more institutionally mature programs generally exhibiting higher TETI scores and stronger regulatory compliance. Results suggest that governance systems characterized by greater transparency, equity, stakeholder inclusion, and institutional trust are associated with stronger regulatory compliance and institutional resilience. Regression analysis indicates a positive relationship between the TETI Governance Index and compliance performance, although the small comparative sample and proxy measures preclude causal inference. By reframing regulatory compliance as a governance-mediated sociotechnical outcome, this study advances a theoretically grounded framework for strengthening safe, equitable, and sustainable civilian nuclear energy governance.

Keywords: nuclear energy governance; institutional legitimacy; sociotechnical systems; energy justice; governance resilience; sustainability; regulatory compliance



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1. Introduction

Nuclear energy supplies approximately 10% of global electricity and nearly one-quarter of low-carbon electricity generation, positioning existing nuclear power plants as important components of global decarbonization strategies (International Atomic Energy Agency (IAEA) [1]). As many reactors extend beyond their original design lifetimes through license renewals and modernization programs, nuclear governance has increasingly shifted from questions of deployment toward the long-term stewardship of operating systems. This transition highlights that nuclear sustainability depends not only on technical safety and safeguards but also on institutional legitimacy—the capacity of governance systems to sustain public confidence, regulatory credibility, and international cooperation over extended operational lifecycles. Recent research confirms that support for emerging

nuclear technologies is shaped not only by technological characteristics but also by governance conditions, institutional trust, transparency, communication, and decision-making processes [2–4].

Although engineering excellence and regulatory oversight remain essential, the long-term resilience of nuclear governance increasingly depends on institutions perceived as transparent, equitable, accountable, and inclusive. In complex sociotechnical systems, governance durability requires not only technical performance but also the ability of institutions to maintain trust, respond to societal expectations, and preserve confidence in regulatory decision-making. Recent studies of nuclear discourse and public engagement emphasize the importance of stakeholder representation, participatory processes, and institutional responsiveness in shaping nuclear legitimacy [5].

Existing nuclear governance scholarship has primarily focused on non-proliferation regimes, safeguards implementation, technological innovation, and nuclear development pathways [6–8]. Comparatively less attention has been given to the long-term governance of operating nuclear fleets, where institutions must continuously adapt to technological, environmental, and societal changes while maintaining legitimacy. This gap is significant because nuclear programs increasingly face challenges beyond engineering performance, including declining public trust, demands for greater transparency, and expectations for procedural fairness and accountability [2,9,10]. While existing frameworks provide valuable insights into safety regulation, safeguards verification, and public acceptance, they offer limited guidance for systematically assessing legitimacy-oriented governance characteristics across national nuclear systems.

Energy governance and energy justice scholarship further emphasize that infrastructure legitimacy depends not only on technical effectiveness but also on procedural fairness, the equitable distribution of benefits and risks, and meaningful stakeholder participation [2,11,12]. Recent research on nuclear acceptance highlights the importance of transparent and inclusive governance structures in shaping public legitimacy and support for nuclear development [2]. Because nuclear systems operate within environments characterized by strict safety expectations, safeguards obligations, and public scrutiny, compliance with regulatory requirements alone may not ensure durable governance. Institutional legitimacy, supported by transparent decision-making, equitable practices, and inclusive engagement, may strengthen compliance cultures and reinforce confidence in nuclear institutions [13,14]. However, these legitimacy dimensions remain insufficiently integrated into comparative nuclear governance frameworks.

This study applies the Q-NPT (Quadrat-Ullah Nuclear Peace and Trust) framework as an analytical and diagnostic framework for evaluating institutional legitimacy in nuclear governance. Recent nuclear governance research emphasizes the importance of integrating trust, equity, transparency, and inclusion as complementary dimensions of sustainable decision-making [15,16]. Q-NPT conceptualizes these four dimensions—Trust, Equity, Transparency, and Inclusion (TETI)—as an interconnected governance architecture through which institutional legitimacy can be examined and compared. Its contribution does not lie in introducing these concepts as new governance ideas but in integrating them into a nuclear-specific legitimacy framework and operationalizing them for comparative assessment.

Q-NPT is not intended to replace established governance theories or propose an entirely new theory of nuclear governance. Rather, it is conceptualized as an integrative governance framework that extends existing theoretical perspectives by introducing a nuclear-specific legitimacy architecture. The framework synthesizes insights from energy justice, institutional legitimacy theory, responsible innovation, and adaptive governance into four operational governance dimensions: Trust, Equity, Transparency, and Inclusion (TETI). Its contribution lies in translating these complementary theoretical perspectives

into measurable dimensions for evaluating the sustainability, legitimacy, and resilience of nuclear governance systems.

The study conducts a structured comparative assessment across five advanced nuclear states (United States, France, Canada, United Kingdom, and Finland) and five emerging nuclear programs (Türkiye, United Arab Emirates, Egypt, Brazil, and Pakistan). Cases were selected using a maximum-variation strategy to capture diversity in regulatory maturity, safeguards implementation, institutional capacity, and sociopolitical context rather than statistical representativeness. Using documentary analysis, regulatory reports, international peer-review findings, and governance indicators, the study develops a TETI Governance Index to examine how governance dimensions are institutionalized across national systems and how governance quality is associated with regulatory credibility, compliance performance, stakeholder confidence, and institutional durability.

The study addresses three research gaps. First, nuclear governance research has emphasized technical compliance and regulatory oversight, while the legitimacy conditions supporting durable compliance remain underexamined. Second, although energy justice and governance scholarship highlights fairness, transparency, and participation, these concepts have rarely been operationalized for comparative nuclear governance assessment. Third, existing approaches provide limited tools for examining how legitimacy-oriented governance dimensions interact with regulatory resilience and institutional durability across diverse national contexts. Therefore, the research questions addressed in study are as follows:

1. How does long-term nuclear governance sustain institutional legitimacy and regulatory compliance within operating nuclear programs?
2. How are Trust, Equity, Transparency, and Inclusion institutionalized across national nuclear governance systems?
3. How is governance quality associated with regulatory durability, safeguards credibility, and broader non-proliferation outcomes?

These three research questions are sequentially related. The first question establishes the conceptual foundation by examining how governance legitimacy dimensions contribute to nuclear sustainability. The second operationalizes this conceptual framework through the development of the TETI Governance Index. The third evaluates the empirical relationship between governance legitimacy and compliance outcomes through cross-national comparison.

This paper makes three principal contributions. First, it extends nuclear governance scholarship beyond episodic licensing and facility approval by focusing on the long-term governance of operational nuclear systems. Second, it develops an institutional legitimacy perspective that identifies theoretically plausible pathways through which Trust, Equity, Transparency, and Inclusion may contribute to durable governance, regulatory credibility, and compliance culture within complex sociotechnical systems. Third, it enables the operationalization of these governance dimensions through the TETI Governance Index, enabling structured cross-national comparison while recognizing the limitations associated with small-N analysis and proxy-based measurement. Through this comparative analysis, the study provides evidence regarding how governance quality is associated with institutional durability, regulatory stability, and sustained international cooperation. Given the study's small-N comparative design, these findings are presented as patterns of association rather than evidence of causal relationships.

By positioning institutional legitimacy as a central dimension of durable nuclear governance, this study integrates insights from institutional theory, sociotechnical systems theory, energy justice, and non-proliferation scholarship into a unified comparative framework for evaluating governance performance. In doing so, it advances understanding of how

governance institutions may support the long-term sustainability of civilian nuclear energy under conditions of technological complexity, public scrutiny, and accelerating global energy transition. The following section reviews the relevant literature and develops the theoretical foundations of the Q-NPT framework as an institutional legitimacy perspective for analyzing nuclear energy governance.

2. Literature Review

The Materials Nuclear governance scholarship has evolved from a predominant focus on technical compliance, safety assurance, and regulatory oversight toward broader sociotechnical perspectives emphasizing institutional legitimacy, trust, equity, transparency, and inclusion. Recent research increasingly recognizes that the long-term sustainability of nuclear energy systems depends not only on technological performance and regulatory effectiveness but also on the capacity of governance institutions to maintain public confidence, stakeholder engagement, and international credibility. The following review examines four interconnected themes: the evolution of nuclear governance; the role of institutional legitimacy, trust, and compliance culture; the contributions of energy justice and inclusive governance perspectives; and existing governance assessment frameworks. Collectively, these themes identify limitations in current approaches and establish the theoretical rationale for the Q-NPT framework and the TETI Governance Index developed in this study.

2.1. Evolution of Nuclear Governance: From Technical Compliance to Sociotechnical Legitimacy

Nuclear governance has historically evolved around the central objective of ensuring safety, security, and non-proliferation through technically rigorous regulatory systems, institutional oversight, and international safeguards mechanisms. Early governance approaches were primarily shaped by concerns regarding reactor safety, operational reliability, nuclear material control, and compliance with international obligations. Within this traditional paradigm, governance effectiveness was largely evaluated through technical indicators, regulatory performance, inspection regimes, and adherence to established safety standards [6,7]. The International Atomic Energy Agency [1] continues to emphasize the importance of regulatory independence, safety culture, and safeguards implementation as fundamental pillars of responsible nuclear governance.

However, the contemporary governance challenge of nuclear energy has expanded beyond technical compliance toward questions of institutional legitimacy, societal acceptance, and long-term governance durability. As nuclear reactors increasingly operate beyond their original design lifetimes through license extensions, modernization programs, and life-management strategies, governance systems must address not only engineering performance but also changing societal expectations, stakeholder concerns, and evolving political contexts. Recent scholarship suggests that the sustainability of nuclear systems depends increasingly on the ability of institutions to maintain credibility, transparency, and public confidence throughout extended operational lifecycles [8,15–18].

From a sociotechnical systems perspective, nuclear energy represents more than a technological infrastructure; it constitutes a complex configuration of technologies, institutions, regulatory arrangements, organizations, and social actors. Earlier studies of sociotechnical transitions emphasized the importance of regime formation, including the establishment of technological systems, institutional rules, and governance structures surrounding emerging energy technologies [19]. However, nuclear energy increasingly requires attention to regime reproduction—the continuous maintenance, adaptation, and renewal of existing systems over decades of operation. This distinction is particularly relevant because many contemporary nuclear governance challenges arise not from the initial deployment of reactors

but from sustaining institutional effectiveness during aging infrastructure management, cybersecurity adaptation, radioactive waste stewardship, and public engagement.

Figure 1 shows the evolution of nuclear governance from a predominantly technical compliance paradigm toward an integrated sociotechnical legitimacy paradigm. The timeline illustrates the historical expansion of governance priorities from safety assurance and safeguards implementation toward broader considerations of trust, transparency, stakeholder inclusion, and institutional resilience.

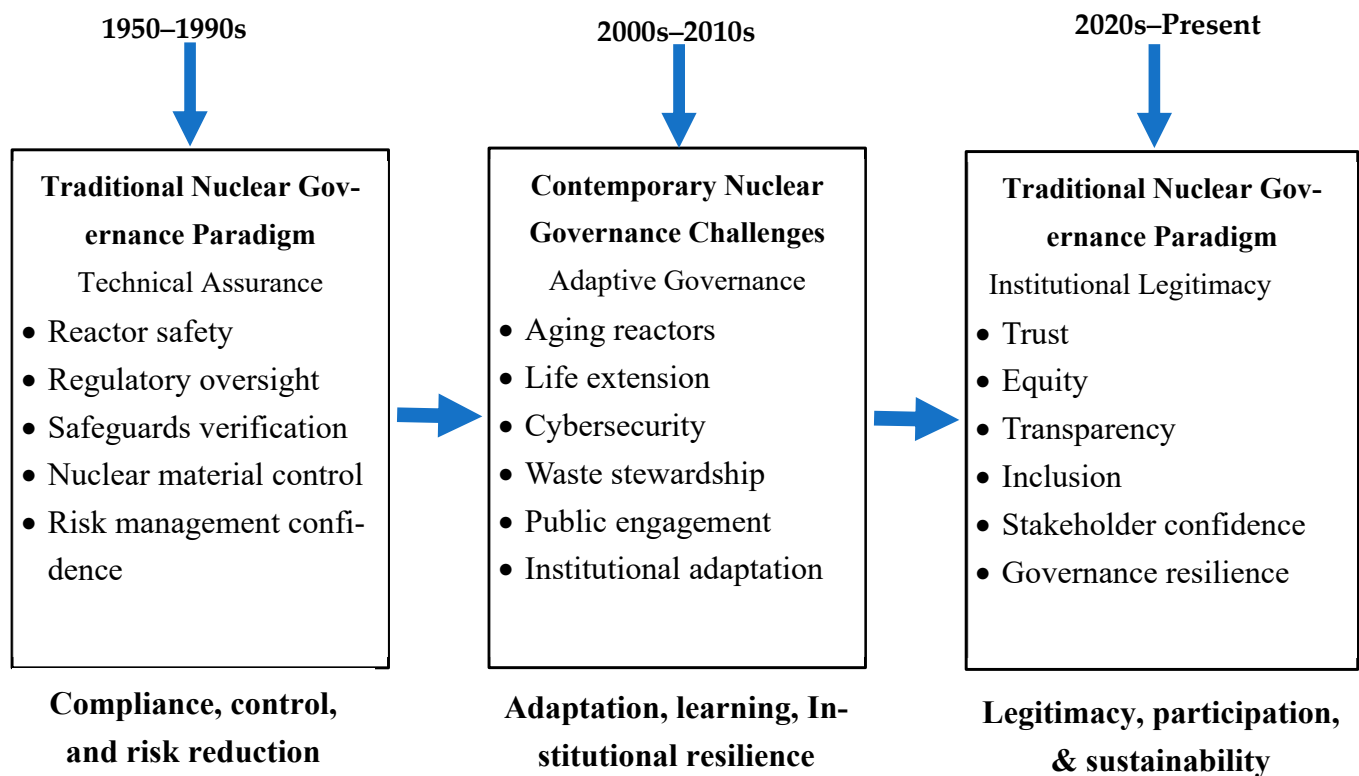


Figure 1. Evolution of nuclear governance: from technical assurance to sociotechnical legitimacy.

Milestone anchors:

- 1950s–1990s: Establishment of international nuclear institutions, safety regulation, safeguards systems, and emphasis on technical assurance (e.g., IAEA establishment in 1957; NPT opened for signature in 1968; Three Mile Island (1979) and Chernobyl (1986) strengthened global safety governance).
- 2000s–2010s: Expansion of risk governance, safety culture, stakeholder engagement, and attention to institutional learning (e.g., post-Fukushima (2011) emphasis on transparency, resilience, and public confidence).
- 2020s–Present: Increasing recognition that nuclear sustainability requires integrated governance approaches combining technical performance with legitimacy dimensions (e.g., [2,8,15,16]).

Nuclear governance involves complex interactions among technological innovation, institutional arrangements, and policy environments [20]. Earlier governance research often focused on specific decision points, such as reactor deployment, technology selection, licensing, and public opposition to new facilities. While these studies provide valuable project-level insights, they offer limited understanding of how institutional legitimacy is continuously produced and maintained throughout long-term nuclear operation. Recent governance research therefore calls for broader approaches integrating technical assurance with institutional and societal dimensions of nuclear sustainability [8,15,16].

This shift reflects a broader transition from compliance-centered toward legitimacy-oriented governance. Technical compliance remains essential for nuclear safety and non-proliferation, but durable institutional performance also depends on perceptions of fairness, transparency, trust, and accountability that shape stakeholder cooperation and public confidence. Institutional legitimacy therefore provides a complementary lens for examining nuclear governance resilience.

Cheng et al. [8] demonstrate that contemporary nuclear planning increasingly requires integrated assessment approaches incorporating multiple sustainability dimensions beyond technical and economic criteria. However, their review focuses primarily on planning, evaluation methods, and development pathways, leaving institutional legitimacy mechanisms relatively underexplored. Similarly, Qudrat-Ullah [15,16] emphasizes the importance of Trust, Equity, Transparency, and Inclusion as complementary governance dimensions supporting institutional credibility and stakeholder confidence.

Recent empirical studies further reinforce this perspective. Agyekum et al. [2] identify transparency, public participation, and inclusive governance as key determinants of nuclear acceptance, while Butorac et al. [3] show that support for emerging nuclear technologies depends not only on technological characteristics but also on governance conditions, institutional trust, and decision-making processes.

Collectively, the literature indicates a transition from a technical assurance paradigm toward a sociotechnical legitimacy paradigm. However, a systematic comparative framework for assessing how legitimacy-oriented governance dimensions are institutionalized across national nuclear programs remains limited. This gap motivates the development and examination of the Q-NPT framework and its Trust–Equity–Transparency–Inclusion (TETI) governance architecture.

2.2. Institutional Legitimacy, Trust, and Compliance Culture in Nuclear Governance

Institutional legitimacy provides a critical theoretical foundation for understanding why governance systems endure beyond the formal existence of rules, regulations, and enforcement mechanisms. Institutional theory suggests that organizations and regulatory systems achieve durability not only through coercive authority but also through normative acceptance, shared expectations, and perceptions of appropriateness among relevant stakeholders [9,10,13]. In nuclear governance, legitimacy refers to the extent to which regulatory institutions, decision-making processes, and governance arrangements are perceived as credible, fair, transparent, and deserving of continued support by governments, industry actors, communities, and international partners.

Nuclear governance has traditionally emphasized formal compliance mechanisms, including regulatory oversight, safety standards, inspection regimes, and safeguards verification. While these mechanisms remain essential, contemporary governance scholarship recognizes that formal compliance alone may not ensure durable institutional performance. Civilian nuclear systems operate within complex sociotechnical environments characterized by public scrutiny, political contestation, technological uncertainty, and intergenerational responsibilities. Therefore, regulatory institutions must maintain not only technical competence but also social credibility and institutional trust.

Within nuclear non-proliferation governance, compliance similarly depends on both technical verification and institutional relationships. The Nuclear Non-Proliferation Treaty (NPT) framework and International Atomic Energy Agency (IAEA) safeguards system rely on formal monitoring mechanisms, but their effectiveness also depends on cooperation, transparency, information exchange, and perceptions of procedural fairness among participating states [6,7,14]. Safeguards credibility is therefore not solely a technical outcome but

also a governance outcome shaped by interactions among verification institutions, national regulators, and political actors.

The concept of compliance culture further emphasizes that sustained adherence to regulatory expectations depends on organizational values, institutional norms, and internalized commitments rather than external enforcement alone. In nuclear systems, this distinction is particularly important because safety failures, safeguards violations, or governance breakdowns can affect confidence in nuclear institutions beyond individual facilities.

Recent scholarship highlights trust as a key mechanism linking governance practices with legitimacy outcomes. Agyekum et al. [2] identify trust, transparency, communication, and public participation as recurring determinants of societal support for nuclear technologies, while noting that fewer studies examine how institutional structures create or undermine trust over time. Similarly, Butorac et al. [3] demonstrate that support for advanced nuclear technologies depends not only on technological characteristics but also on governance quality, institutional credibility, and decision-making processes. These findings suggest that legitimacy is actively constructed through governance interactions rather than being a consequence of technical performance alone.

Stakeholder inclusion further strengthens the relationship between legitimacy and compliance culture. Nuclear governance involves communities, regulators, industry actors, policymakers, and international organizations with diverse interests and risk perceptions. Meaningful inclusion therefore requires more than information sharing; it requires mechanisms through which stakeholders perceive that their concerns influence decision outcomes.

Energy justice scholarship provides an additional connection between legitimacy and governance durability. Principles of procedural justice, distributive fairness, and recognition emphasize that infrastructure systems achieve long-term acceptance when benefits, risks, and decision-making authority are perceived as fairly distributed [11]. These principles are particularly relevant for nuclear systems because of concentrated expertise, long operational lifetimes, localized risks, and intergenerational responsibilities.

Despite these advances, the existing literature often examines trust, acceptance, or participation separately rather than as interconnected governance dimensions. Research also frequently focuses on specific technologies or projects rather than governance characteristics embedded within national regulatory systems. Limited attention has been given to how legitimacy-oriented mechanisms interact with regulatory resilience, compliance performance, and institutional durability across diverse nuclear contexts.

The Q-NPT framework addresses this gap by conceptualizing Trust, Equity, Transparency, and Inclusion (TETI) as interconnected institutional dimensions contributing to legitimacy-oriented nuclear governance [15,16]. Rather than replacing technical safeguards or regulatory compliance systems, Q-NPT complements them by examining the institutional conditions that may strengthen compliance cultures and sustain governance credibility.

Accordingly, this study conceptualizes institutional legitimacy as a governance capability linking technical compliance with sociotechnical durability. Trust supports cooperation; Equity addresses fairness in risks, benefits, and decision-making influence; Transparency strengthens accountability and credibility; and Inclusion enables meaningful stakeholder participation. Together, these dimensions provide the theoretical foundation for examining how governance quality may be associated with regulatory resilience, safeguards credibility, and the long-term sustainability of civilian nuclear energy systems.

2.3. Energy Justice, Public Acceptance, and Inclusive Governance in Nuclear Energy Systems

Energy justice scholarship provides an important theoretical foundation for understanding why technically successful energy infrastructures may still encounter social and

political challenges. Unlike traditional approaches focused primarily on efficiency, reliability, or economic performance, energy justice emphasizes the distribution of benefits and risks, fairness of decision-making processes, and recognition of affected communities and stakeholders [11]. These dimensions are particularly relevant for nuclear energy because of long operational lifecycles, geographically concentrated risks, intergenerational responsibilities associated with radioactive waste, and complex relationships among communities, governments, regulators, and international institutions.

Historically, nuclear governance has often emphasized technical expertise, regulatory compliance, and engineering performance as primary sources of legitimacy. However, contemporary energy justice perspectives suggest that technical competence alone may be insufficient to sustain public confidence when stakeholders perceive limited participation, unequal risk distribution, or inadequate transparency. Legitimacy is therefore understood not only as a regulatory achievement but also as an ongoing social process shaped by interactions between institutions and stakeholders.

Recent research demonstrates that acceptance of nuclear energy is increasingly influenced by governance conditions rather than technological characteristics alone. Agyekum et al. [2] identify transparency, communication, stakeholder engagement, and inclusive governance as recurring determinants of societal attitudes toward nuclear technologies. Similarly, Butorac et al. [3] show that support for emerging nuclear technologies is influenced by institutional trust, decision-making processes, and perceptions of fairness. These findings suggest that technological innovation alone may not ensure acceptance; governance arrangements must also be perceived as credible, transparent, and responsive.

Stakeholder inclusion has become an increasingly important element of nuclear governance. Özyirmidokuz et al. [5] demonstrate that public perceptions are shaped by whose perspectives are represented in governance processes and whether institutions provide meaningful opportunities for participation and dialogue. Inclusion therefore extends beyond information provision to encompass stakeholder influence in decisions affecting communities and future generations.

Energy justice also highlights the importance of equity in nuclear governance. Equity involves not only the distribution of benefits and risks but also recognition of diverse stakeholder perspectives, knowledge systems, and social priorities. Nuclear systems often provide national benefits, such as energy security and decarbonization, while concentrating perceived risks and responsibilities among particular communities. Consequently, governance systems that neglect distributive and procedural equity may experience legitimacy challenges even when technical safety standards are satisfied.

Despite these advances, important gaps remain. Existing energy justice and public acceptance studies often focus on individual projects, stakeholder perceptions, or specific cases rather than comparative assessment across national nuclear governance systems. Furthermore, trust, transparency, equity, and participation are frequently examined as separate factors rather than as interconnected dimensions of institutional legitimacy. Limited methodological guidance also exists for translating these qualitative governance principles into measurable indicators suitable for comparative analysis.

The Q-NPT framework addresses this gap by integrating energy justice principles with institutional legitimacy theory through the dimensions of Equity and Inclusion, while linking them with Trust and Transparency as complementary governance mechanisms [15–17]. Within this framework, Equity captures fairness in the distribution of nuclear risks and benefits, while Inclusion reflects meaningful stakeholder participation in governance processes. Together with Trust and Transparency, these dimensions provide the foundation for the TETI Governance Index developed in this study.

Accordingly, energy justice scholarship supports a broader understanding of nuclear sustainability: not only whether nuclear technologies are technically safe but how institutions maintain legitimacy, trust, and social resilience throughout the nuclear lifecycle. This perspective provides the theoretical basis for examining Trust, Equity, Transparency, and Inclusion as integrated dimensions of nuclear governance quality.

2.4. Governance Assessment Frameworks and the Need for an Integrated Nuclear Legitimacy Model

Existing approaches to nuclear governance assessment have generated important insights into safety regulation, energy planning, technological development, public acceptance, and institutional performance. However, these approaches have largely examined governance dimensions separately rather than conceptualizing legitimacy as an integrated sociotechnical construct. Traditional nuclear assessment frameworks have emphasized technical indicators, regulatory compliance, safeguards effectiveness, operational reliability, and risk management [1]. While essential, these approaches provide limited understanding of how institutional characteristics—such as trust, transparency, equity, and inclusion—contribute to the long-term durability of nuclear governance systems.

Recent research increasingly recognizes that nuclear governance requires broader analytical perspectives incorporating social, institutional, and policy dimensions. Reviews of nuclear energy assessment models highlight a shift toward more integrated approaches addressing sustainability, policy coordination, and multidimensional decision-making [8]. However, existing models remain primarily focused on planning, technology pathways, and development strategies, with limited attention to the legitimacy mechanisms that sustain regulatory credibility and compliance over extended operational lifecycles. Similarly, studies on nuclear acceptance demonstrate the importance of transparency, communication, stakeholder participation, and procedural fairness [2,3], but they primarily examine public perceptions rather than the institutional structures through which governance legitimacy is created and maintained.

Broader energy governance studies further demonstrate the importance of institutional quality, political stability, and governance capacity for sustainable energy transitions [21,22]. However, these macro-level analyses generally examine national energy outcomes rather than the specific governance mechanisms shaping nuclear regulatory credibility, safeguards confidence, and compliance resilience.

Theoretical perspectives from institutional theory, energy justice, and sociotechnical systems theory provide important foundations for addressing this limitation. Institutional theory highlights the role of legitimacy, norms, and organizational credibility in sustaining institutions [9,10,13]. Energy justice emphasizes procedural fairness, equitable distribution of risks and benefits, and meaningful participation [11,12]. Sociotechnical systems theory highlights the interactions among technologies, institutions, social expectations, and political arrangements. However, these perspectives have rarely been integrated into a nuclear-specific operational framework that enables systematic cross-national comparison.

The Q-NPT (Qudrat-Ullah Nuclear Peace and Trust) framework addresses this gap by conceptualizing nuclear governance legitimacy through four interconnected dimensions: Trust, Equity, Transparency, and Inclusion (TETI) [15,16]. Q-NPT is not intended to replace existing nuclear safety, safeguards, or regulatory assessment systems. Rather, it integrates insights from institutional legitimacy, energy justice, responsible innovation, and adaptive governance into a nuclear-specific legitimacy architecture. Its contribution lies in operationalizing these perspectives into measurable governance dimensions for evaluating nuclear governance sustainability.

Within Q-NPT, Trust reflects confidence in regulatory authorities, operators, and governance processes; Equity concerns the fair distribution of benefits, risks, and responsibilities;

Transparency captures openness, accountability, and access to information; and Inclusion represents meaningful stakeholder participation in governance processes. Unlike conventional assessment models that primarily evaluate technical performance or regulatory compliance, Q-NPT examines the institutional conditions that may support compliance durability, stakeholder confidence, and regulatory resilience.

Accordingly, this study develops the TETI Governance Index as a comparative tool for assessing how legitimacy-related governance characteristics are institutionalized across advanced and emerging nuclear programs. By translating theoretical concepts into measurable indicators, the framework bridges the gap between conceptual discussions of nuclear legitimacy and empirical assessment of governance patterns.

Thus, the existing literature provides strong assessments of nuclear safety, safeguards, and technological performance while increasingly recognizing the importance of governance legitimacy. However, an integrated framework linking legitimacy dimensions with comparative nuclear governance assessment remains underdeveloped. The Q-NPT framework and TETI Governance Index contribute to addressing this gap by examining how trust, equity, transparency, and inclusion may be associated with durable, transparent, and resilient nuclear governance systems.

3. The Theoretical Framework: The Q-NPT Framework

The Q-NPT framework provides a governance-oriented conceptual architecture for examining how institutional legitimacy dimensions interact with traditional nuclear safety, safeguards, and compliance mechanisms. It extends existing nuclear governance perspectives by integrating Trust, Equity, Transparency, and Inclusion (TETI) as complementary dimensions for analyzing long-term governance resilience and compliance durability.

3.1. Conceptual Foundations and Purpose of Q-NPT

The Q-NPT (Qudrat-Ullah Nuclear Peace and Trust) framework was introduced as a governance-oriented conceptual framework for examining how institutional characteristics influence the sustainability, legitimacy, and resilience of civilian nuclear energy systems [15–18]. Unlike conventional nuclear governance approaches that primarily emphasize technical safeguards, verification procedures, regulatory compliance, and nuclear material control, Q-NPT extends the analytical focus toward the institutional conditions under which these mechanisms operate.

The central premise of Q-NPT is that nuclear governance is not sustained exclusively through technical assurance. Rather, durable nuclear systems require interaction among technological reliability, regulatory effectiveness, institutional legitimacy, and stakeholder confidence. Accordingly, Q-NPT conceptualizes nuclear governance as a sociotechnical system in which formal safeguards mechanisms are embedded within broader institutional and societal contexts.

The framework proposes four interconnected governance dimensions: Trust, Equity, Transparency, and Inclusion (TETI). These dimensions are not presented as novel concepts individually; rather, the contribution of Q-NPT lies in their integration into a nuclear-specific governance architecture that connects legitimacy-oriented institutional characteristics with long-term compliance durability and governance resilience.

3.2. The Novel Contribution of the Q-NPT Framework

Existing research has examined trust, equity, transparency, and inclusion independently across fields such as institutional theory, energy justice, public acceptance, and participatory governance. However, these dimensions have rarely been integrated into a unified framework specifically designed for nuclear governance.

The novelty of Q-NPT is therefore threefold. First, Q-NPT repositions legitimacy as an enabling governance infrastructure rather than merely an outcome of successful technical performance. Traditional nuclear governance models typically assess whether systems comply with safety and safeguards requirements; Q-NPT examines the institutional conditions that may support sustained compliance and public confidence over time. Second, Q-NPT integrates social legitimacy dimensions with formal safeguards architecture. Rather than treating technical compliance and societal acceptance as separate domains, the framework conceptualizes them as interacting components within a broader governance ecosystem. Third, Q-NPT provides the foundation for developing the TETI Governance Index, which translates abstract legitimacy dimensions into comparative governance indicators. This enables empirical exploration of governance variation across national nuclear programs.

Thus, the contribution of Q-NPT is not the identification of Trust, Equity, Transparency, and Inclusion as isolated concepts but their systematic integration into a nuclear governance assessment framework.

3.3. *The Four Governance Dimensions of Q-NPT*

The four governance dimensions of Q-NPT are as follows:

1. **Trust:** Trust represents confidence in the credibility, competence, and integrity of nuclear governance institutions. It includes perceptions of regulatory independence, institutional reliability, and confidence in oversight mechanisms. Within Q-NPT, trust is conceptualized as a relational condition that may influence cooperation among regulators, operators, communities, and international organizations.

The framework does not assume that higher trust automatically produces improved compliance outcomes; rather, it proposes that trust is an analytically important governance condition whose relationship with institutional performance requires empirical examination.

2. **Equity:** Equity refers to the fairness with which nuclear-related risks, benefits, responsibilities, and decision-making authority are distributed across stakeholders and generations. Nuclear energy involves long-term consequences associated with waste management, environmental risks, and resource allocation. Therefore, Q-NPT incorporates equity as a governance dimension concerned with distributive and procedural fairness.
3. **Transparency:** Transparency represents openness, accessibility, and accountability in nuclear governance processes. It includes disclosure practices, independent assessment, information availability, and communication regarding safety, safeguards, and regulatory decisions.

Within Q-NPT, transparency is viewed as a mechanism for reducing information asymmetry and strengthening institutional accountability rather than as a guarantee of public acceptance.

4. **Inclusion:** Inclusion refers to meaningful stakeholder participation in nuclear governance processes. Unlike communication-based approaches that emphasize information dissemination, Q-NPT defines inclusion as the extent to which affected stakeholders have opportunities for meaningful participation and influence. The framework recognizes that the effectiveness of inclusion mechanisms may vary depending on institutional, cultural, and political contexts.

3.4. *Q-NPT as an Integrated Governance Architecture*

The four dimensions of Q-NPT are conceptualized as interconnected governance capabilities rather than independent variables. Trust influences perceptions of institutional

credibility, transparency supports accountability, equity addresses fairness concerns, and inclusion provides mechanisms for stakeholder participation. Together, these dimensions form a governance architecture that surrounds and complements existing nuclear safety, security, and safeguards mechanisms.

Figure 2 presents Q-NPT as a conceptual governance architecture rather than a causal model. The framework does not suggest that TETI dimensions directly determine compliance outcomes. Instead, it proposes that these dimensions represent institutional conditions that may shape governance legitimacy, stakeholder confidence, and long-term institutional resilience.

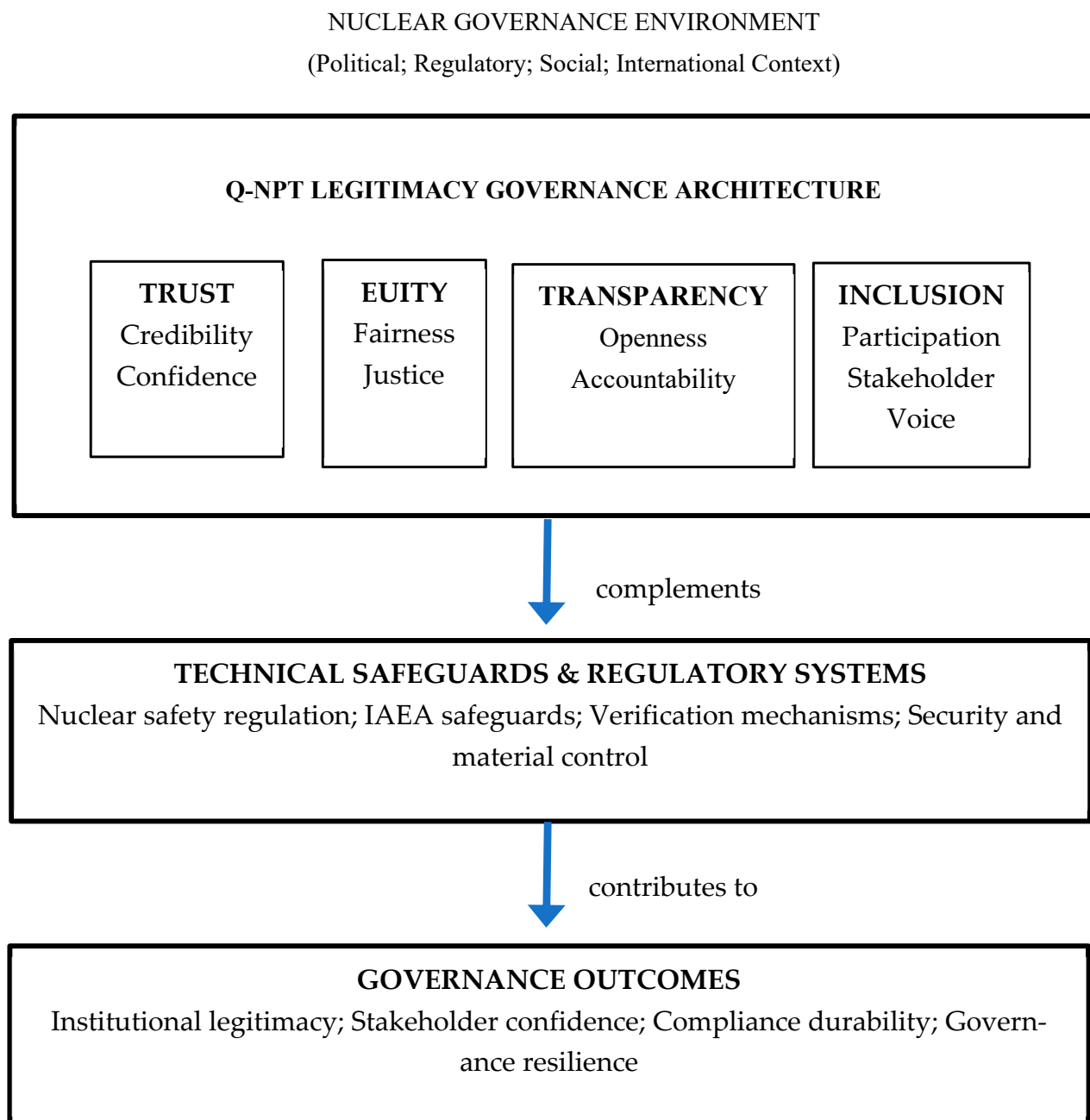


Figure 2. Q-NPT Governance Architecture: Institutional Legitimacy, Compliance, and Governance Durability.

3.5. Boundary Conditions and Applicability of the Q-NPT Framework

Although Q-NPT provides a broad governance perspective, its applicability is subject to important boundary conditions.

First, Q-NPT is primarily designed for civilian nuclear governance contexts involving operational or planned nuclear programs where institutional arrangements, regulatory structures, and stakeholder relationships exist. It is less applicable to purely technical engineering evaluations or reactor design optimization studies.

Second, Q-NPT is not intended to replace specialized frameworks for nuclear accident response, emergency management, safeguards verification procedures, or detailed proliferation-risk assessment. These domains require technical models and regulatory tools beyond the scope of governance legitimacy analysis.

Third, Q-NPT assumes the presence of minimally functioning governance institutions. In contexts characterized by severe institutional collapse, absence of regulatory authority, or extreme political instability, the framework may have limited explanatory value.

Finally, Q-NPT should be interpreted as an exploratory analytical framework rather than a universal causal theory. Its purpose is to identify and compare governance characteristics that may contribute to institutional resilience, legitimacy, and compliance durability.

4. Materials and Methods

This section outlines the research design, case selection strategy, data sources, governance operationalization procedures, coding protocol, and empirical modeling approach used to evaluate the Q-NPT governance framework across ten nuclear energy programs. A sequential explanatory mixed-method strategy integrates qualitative institutional coding with quantitative cross-national analysis. Governance constructs are operationalized into standardized indices and examined in relation to operational compliance indicators. The objective is not hypothesis testing or causal inference but the identification of cross-national patterns that may inform future research.

4.1. Research Design

This study employs integrating qualitative institutional analysis with quantitative cross-national modeling [23]. Structured coding of regulatory documentation, peer-review findings, and stakeholder records informs the construction of standardized governance indices. These indices are subsequently analyzed using statistical models. Integration occurs at the interpretation stage, where quantitative associations are evaluated in light of the qualitative institutional context. Given the limited cross-sectional sample ($N = 10$), statistical results are interpreted as exploratory diagnostic associations rather than confirmatory causal estimates.

This design follows a sequential mixed-method logic in which qualitative institutional evidence is first transformed into structured governance indicators and subsequently examined using quantitative descriptive analyses. The qualitative phase informs the quantitative operationalization, while the quantitative phase enables systematic cross-case comparison rather than hypothesis confirmation. This sequencing enhances methodological transparency by making explicit how documentary evidence is translated into measurable governance constructs suitable for comparative analysis.

The study proceeds in four stages: First, documentary and regulatory evidence was collected from national and international sources. Second, governance dimensions were coded using a standardized coding protocol. Third, coded indicators were aggregated into governance indices representing Trust, Equity, Transparency, and Inclusion. Fourth, these indices were analyzed descriptively and through regression models to examine their

association with compliance outcomes. This design prioritizes analytical transparency and cross-case comparability rather than statistical generalizability.

4.2. Comparative Case Selection

Ten countries were selected using purposive maximum-variation sampling [24] to capture substantial heterogeneity in nuclear governance systems while ensuring sufficient comparability for cross-case analysis. Unlike probability sampling, maximum-variation sampling is designed to examine whether theoretically relevant patterns emerge across cases that differ markedly in institutional characteristics. The objective was therefore not statistical representativeness but analytical comparison across contrasting governance environments.

Case selection was guided by four predefined criteria: (1) operational nuclear experience, (2) institutional maturity, (3) availability of regulatory and governance documentation, and (4) diversity of nuclear governance contexts. The selected cases include both established and emerging nuclear programs to enable comparative analysis across different stages of nuclear development and institutional evolution. Table 1 has been revised to explicitly demonstrate how each selected country satisfies these criteria and to clarify the rationale for its inclusion in the comparative analysis.

Table 1. Rationale and criteria justification for comparative case selection.

Country	Nuclear Status	Case-Selection Criterion Justification
United States	Established nuclear country	Extensive operational nuclear history; highly developed regulatory institutions; comprehensive availability of regulatory and safety documentation; represents a mature governance context
Canada	Established nuclear country	Long operational experience; independent regulatory authority; extensive public regulatory records; represents a mature but distinct governance model
France	Established nuclear country	Significant nuclear operational experience; advanced institutional capacity; extensive regulatory transparency; represents a highly nuclear-dependent governance system
United Kingdom	Established nuclear country	Long nuclear history; mature regulatory and stakeholder engagement frameworks; extensive governance documentation; represents an evolving advanced governance model
Finland	Established nuclear country	Strong institutional maturity; internationally visible regulatory practices; extensive peer-review evidence; represents high-trust nuclear governance
United Arab Emirates	Emerging nuclear country	Represents a new nuclear entrant; demonstrates rapid institutional development; strong availability of international regulatory assessments; provides an emerging governance context
Türkiye	Emerging nuclear country	Represents nuclear expansion and regulatory transition; emerging institutional capacity; increasing international regulatory engagement; provides a developing governance context
Egypt	Emerging nuclear country	Represents early-stage nuclear development; provides insight into institutional formation processes; increasing availability of regulatory information; reflects emerging governance challenges
Brazil	Intermediate nuclear country	Combines operational experience with ongoing institutional evolution; provides a transitional governance context; regulatory information is available through national and international sources
Pakistan	Emerging nuclear country	Represents an expanding nuclear system outside traditional OECD contexts; demonstrates evolving regulatory institutions; provides governance diversity and international safeguards relevance

Based on these criteria, the study included five established nuclear programs—the United States, Canada, France, the United Kingdom, and Finland—and five expanding or emerging programs—Türkiye, the United Arab Emirates (UAE), Egypt, Brazil, and Pakistan. The selected countries represent diverse regulatory traditions, institutional capacities, operational experience, and approaches to stakeholder engagement. The rationale for including each country is summarized in Table 1.

The selected cases do not represent the full population of civilian nuclear energy programs. Countries such as Japan, South Korea, China, India, Russia, Sweden, Argentina, and Ukraine were excluded primarily because of the study's scope, the need to maintain analytical balance across stages of nuclear development, and limitations in ensuring comparable documentary evidence across all governance indicators. Future studies using larger samples may evaluate whether the patterns identified here remain robust across a broader range of institutional contexts.

To facilitate interpretation, the sample is also classified according to program maturity. Five countries (United States, Canada, France, United Kingdom, and Finland) represent established nuclear programs characterized by mature regulatory institutions and extensive operational experience. Four countries (Türkiye, UAE, Brazil, and Pakistan) represent expanding or intermediate-stage programs, while Egypt represents an emerging nuclear program. These classifications are intended solely to aid comparative interpretation and are not used as explanatory variables in the empirical analysis.

4.3. Data Sources

We employed a multi-source dataset integrating regulatory, operational, and governance indicators across established and emerging nuclear energy programs. Regulatory data were obtained from national authorities, including the U.S. Nuclear Regulatory Commission (NRC), the Canadian Nuclear Safety Commission (CNSC), Autorité de sûreté nucléaire (ASN), the Office for Nuclear Regulation (ONR), the Radiation and Nuclear Safety Authority (STUK), and corresponding authorities in emerging programs: the Nuclear Regulatory Authority (NDK), the Federal Authority for Nuclear Regulation (FANR), the Egyptian Nuclear and Radiological Regulatory Authority (ENRRA), Comissão Nacional de Energia Nuclear (CNEN), and the Pakistan Nuclear Regulatory Authority (PNRA).

To operationalize the Q-NPT framework, the four TETI dimensions were translated into measurable governance indicators based on institutional legitimacy, energy justice, responsible innovation, and the adaptive governance literature. Table 2 summarizes the indicators used for documentary coding and construction of the TETI Governance Index.

Table 2. TETI Governance Dimensions and Indicators.

Dimension	Indicators
Trust	Public confidence, institutional credibility, stakeholder acceptance
Equity	Fair distribution of benefits and risks, access, burden sharing
Transparency	Information disclosure, reporting, accountability mechanisms
Inclusion	Stakeholder participation, consultation, community engagement

Indicators were coded using structured documentary evidence and aggregated to construct the composite TETI Governance Index. To evaluate regulatory effectiveness and institutional maturity, safeguards documentation and Integrated Regulatory Review Service (IRRS) mission findings from the International Atomic Energy Agency (IAEA) were

incorporated. Operational compliance variables included inspection outcomes, enforcement actions, peer-review findings, licensing performance, and reported events classified under the International Nuclear and Radiological Event Scale (INES).

Governance indicators were derived from multiple complementary evidence sources, including the following:

- Regulatory reports;
- Public consultation records;
- Stakeholder engagement documentation;
- IAEA IRRS mission reports;
- National nuclear governance publications; and
- Regulatory performance assessments.

To improve coding consistency and reproducibility, documentary evidence was evaluated according to a predefined source hierarchy (see Table 3). Higher-priority sources were used whenever available, while lower-priority sources served to supplement or corroborate information when primary documentation was incomplete.

Table 3. Source hierarchy used for governance coding.

Priority	Source Type	Purpose
Level 1	IAEA documentation (IRRS mission reports, safeguards reports, safety standards, peer-review findings)	Primary international reference for regulatory performance and institutional assessment
Level 2	Official national regulatory authorities (e.g., NRC, CNSC, ASN, ONR, STUK, FANR, PNRA)	Primary evidence for country-specific governance, regulatory practices, inspections, and compliance
Level 3	Peer-reviewed journal articles and independent institutional assessments	Corroboration and contextual interpretation of governance practices
Level 4	Public consultation records, stakeholder documentation, and national governance publications	Supplementary evidence for transparency, inclusion, and public engagement indicators

When multiple sources provided conflicting information, evidence from Level 1 and Level 2 sources was given precedence because these documents represent official regulatory assessments and internationally recognized oversight mechanisms. Information from Levels 3 and 4 was used primarily to corroborate findings, provide contextual interpretation, or fill gaps where primary documentation was unavailable. This structured hierarchy enhances the transparency, consistency, and reproducibility of the governance coding process.

4.4. Governance Operationalization and Coding Protocol

The governance dimensions of Trust, Equity, Transparency, and Inclusion are well-established constructs within governance theory, public administration, institutional theory, and participatory governance research [25–27]. The present study does not introduce these concepts as new theoretical constructs. Rather, it develops a novel operationalization of these established governance dimensions within the Q-NPT framework by converting them into standardized country-level indices suitable for comparative analysis of nuclear governance systems.

Each Q-NPT pillar—Trust, Equity, Transparency, and Inclusion—was operationalized through structured coding of documentary evidence. The unit of analysis was the na-

tional nuclear governance system. Coding was conducted at the country level using a standardized coding manual developed prior to analysis.

Each index was constructed using multiple observable indicators designed to approximate its corresponding latent governance construct. This approach follows established practices in governance measurement, where complex institutional characteristics are represented through theoretically grounded multi-indicator measures.

4.4.1. Trust Index

The Trust Index operationalizes institutional trust through observable governance characteristics associated with credible, reliable, and accountable regulatory systems. Prior governance research identifies regulatory independence, accountability mechanisms, and demonstrated institutional performance as important foundations of public trust [25]. Underlying indicators included the following:

- Regulatory independence;
- Frequency of external review;
- Evidence of safeguards compliance;
- Public confidence indicators where available.

4.4.2. Equity Index

The Equity Index operationalizes fairness considerations in nuclear governance by examining how institutions address the distribution of benefits, risks, responsibilities, and decision-making opportunities among affected stakeholders and future generations. Energy justice research emphasizes distributive, procedural, and recognition dimensions of equity in energy transitions [28]. Underlying indicators included the following:

- Compensation mechanisms;
- Risk-sharing provisions;
- Intergenerational waste management responsibilities;
- Procedural fairness measures.

4.4.3. Transparency Index

The Transparency Index measures the extent to which nuclear governance institutions provide accessible information, disclose regulatory decisions, and maintain open communication regarding safety performance. Transparency is widely recognized as a central component of accountable and legitimate governance systems [25,26]. Underlying indicators included the following:

- Public availability of inspection reports;
- Regulatory disclosure practices;
- Accessibility of safety information;
- Publication of review findings.

4.4.4. Inclusion Index

The Inclusion Index operationalizes participatory governance by assessing whether affected stakeholders have formal opportunities to participate in nuclear governance processes. Collaborative governance research highlights meaningful participation as an important mechanism for improving legitimacy, trust, and policy acceptance [27]. Underlying indicators included the following:

- Formal consultation mechanisms;
- Stakeholder participation requirements;
- Evidence of public engagement;

- Participatory decision-making structures.

4.4.5. Compliance Score

The Compliance Score serves as the study's outcome indicator. Underlying indicators included the following:

- Inspection performance;
- Enforcement outcomes;
- Peer-review findings;
- Regulatory compliance records.

Each indicator was independently evaluated using an ordinal five-point scale ranging from 0 to 4 (Table 4). Ordinal scales of this type are widely used in qualitative content analysis and governance assessment because they provide structured differentiation among institutional characteristics while maintaining coding consistency [29,30].

Table 4. Coding Scale.

Score	Interpretation
0	No evidence
1	Limited evidence
2	Moderate evidence
3	Strong evidence
4	Extensive evidence

The coding manual defined explicit decision rules for each score to minimize subjective interpretation. The midpoint score (2) represented partial, inconsistent, or developing institutional implementation, whereas the highest score (4) required extensive and consistent documentary evidence supported by multiple sources.

Country-level scores were calculated as the arithmetic mean of indicator values within each pillar.

4.4.6. Normalization Procedure

All pillar scores were normalized to a 0–1 range using theoretical rather than sample-dependent bounds:

$$\text{Normalized Score} = \frac{\text{Observed Score} - \text{Minimum}}{\text{Maximum} - \text{Minimum}} \quad (1)$$

Because all indicators were coded on a 0–4 scale, normalization employed fixed theoretical bounds rather than sample minima and maxima. This approach improves comparability and reduces sensitivity to sample composition.

4.4.7. Measurement of Proxy Indicators and Treatment of Measurement Uncertainty

Because Trust, Equity, Transparency, and Inclusion are latent governance constructs, they were operationalized using multiple theoretically grounded proxy indicators. As with all proxy-based measures, these indicators may involve measurement uncertainty due to differences in data quality, reporting practices, and the imperfect representation of underlying constructs. Missing information was handled conservatively: indicators were coded only when supported by corroborating evidence from multiple sources, no statistical imputation was applied, and uncertain cases were documented and reviewed.

Three safeguards were used to minimize measurement uncertainty: (1) multiple indicators were employed for each governance dimension; (2) documentary triangulation was conducted across independent sources, including IAEA assessments, national regula-

tory documents, and institutional reports; and (3) predefined coding rules were applied to improve consistency and reduce subjective interpretation. Accordingly, the resulting indices should be viewed as structured approximations of latent governance constructs for comparative assessment and theory-informed pattern identification rather than precise measurements of institutional characteristics.

4.4.8. Reliability Procedures and TETI Composite Construction

To enhance coding reliability, a detailed coding protocol specifying definitions, decision rules, and coding examples was developed prior to data collection. A second independent reviewer examined a subset of coded observations. Discrepancies were resolved through discussion and documentary re-examination. Because of the limited sample size, reliability assessment is reported qualitatively rather than through formal inter-rater statistics.

For illustration, Transparency was coded as “4” when regulatory authorities routinely published inspection findings, peer-review reports, enforcement actions, and safety information in publicly accessible formats. A score of “1” reflected minimal public disclosure and limited access to regulatory information. A Composite Governance Index (TETI Composite) was constructed as

$$TETI = \frac{Trust + Equity + Transparency + Inclusion}{4} \quad (2)$$

The equal-weighting approach reflects the theoretical structure of the Q-NPT framework, which treats the four governance dimensions as conceptually important and analytically complementary.

Equal weighting was adopted because the Q-NPT framework conceptualizes Trust, Equity, Transparency, and Inclusion as theoretically complementary pillars of governance legitimacy rather than hierarchical determinants. Since no established theoretical basis exists for assigning differential importance to individual dimensions, equal weighting minimizes researcher-imposed assumptions and provides a parsimonious representation of governance quality. Accordingly, TETI scores reflect variations in governance legitimacy structures and institutional practices rather than direct measures of overall governance effectiveness. Empirical weighting approaches, such as factor analysis, principal component analysis, or structural equation modeling, were not applied because the small cross-national sample ($N = 10$) is insufficient for stable and reliable statistical estimation of weights. Future research using larger datasets may explore alternative weighting approaches.

4.4.9. Empirical Strategy

The primary model is

$$Compliance_i = \beta_0 + \beta_1(TETI_i) + \epsilon_i \quad (3)$$

The regression analysis is used as a descriptive tool to examine whether countries with stronger governance characteristics tend to exhibit higher compliance outcomes. It does not estimate causal effects, establish temporal ordering, or identify causal mechanisms. Governance and compliance measures were derived from distinct coding domains, with governance indicators capturing institutional processes and compliance indicators reflecting inspection and safeguards performance. Therefore, regression coefficients should be interpreted as cross-sectional associations that generate hypotheses for future longitudinal or quasi-experimental research rather than evidence of causality. Sensitivity analyses further examine individual governance dimensions and assess their consistency with composite-index results.

4.5. Data Integration and Validation

Advanced-program metrics were derived from published inspection records, stakeholder surveys, and peer-reviewed regulatory assessments, while emerging-program indicators were coded from IRRS mission outcomes, regulatory development stages, and national authority documentation. Methodological triangulation was applied by comparing evidence across regulatory reports, international assessments, stakeholder documentation, and peer-reviewed studies.

Validation of the TETI Composite followed a theory-driven approach appropriate for exploratory cross-national governance research. The framework's validity was established through three complementary approaches: (1) theoretical validity, by deriving Trust, Equity, Transparency, and Inclusion from the established governance and institutional literature; (2) content validity, by using multiple indicators to represent each dimension; and (3) documentary triangulation, through comparison of independent evidence sources, including IAEA assessments, national regulatory documents, and peer-reviewed studies.

Formal statistical validation methods, including exploratory factor analysis, confirmatory factor analysis, or structural equation modeling, were not applied because the small sample size ($N = 10$) does not support reliable estimation of latent construct structures. Therefore, the TETI Composite is interpreted as a theoretically informed and empirically grounded index for comparative pattern identification rather than a definitive measurement model. Future research using larger cross-national datasets may further examine alternative construct validation approaches.

4.6. Conceptual–Empirical Workflow

Figure 3 illustrates the conceptual–empirical workflow of the study. The Q-NPT governance pillars—Trust, Equity, Transparency, and Inclusion—are first operationalized through structured documentary coding. Indicator scores are then normalized and aggregated into governance indices. These indices are subsequently integrated into a composite governance measure and compared with compliance indicators through descriptive and statistical analysis.

The workflow reflects the sequential mixed-method logic of the study, in which qualitative institutional evidence is transformed into standardized governance indicators and subsequently examined through quantitative comparative analysis. The process begins with theory-informed construct identification, followed by documentary evidence collection, coding, normalization, aggregation, validation, and empirical assessment.

The workflow also highlights that the Q-NPT indices represent structured approximations of latent governance constructs. Their purpose is not to provide definitive measurements of institutional trust, equity, transparency, or inclusion but to enable systematic cross-country comparison and identify patterns worthy of further investigation. The workflow emphasizes transparency of operationalization, coding reproducibility, triangulation of evidence sources, and cautious interpretation of statistical associations.

The workflow is intended to generate theoretically informed insights and research propositions rather than causal claims regarding governance effectiveness [31]. Observed relationships between governance characteristics and compliance outcomes should therefore be interpreted as exploratory associations requiring further validation using larger samples, longitudinal designs, and more rigorous causal methods [32].

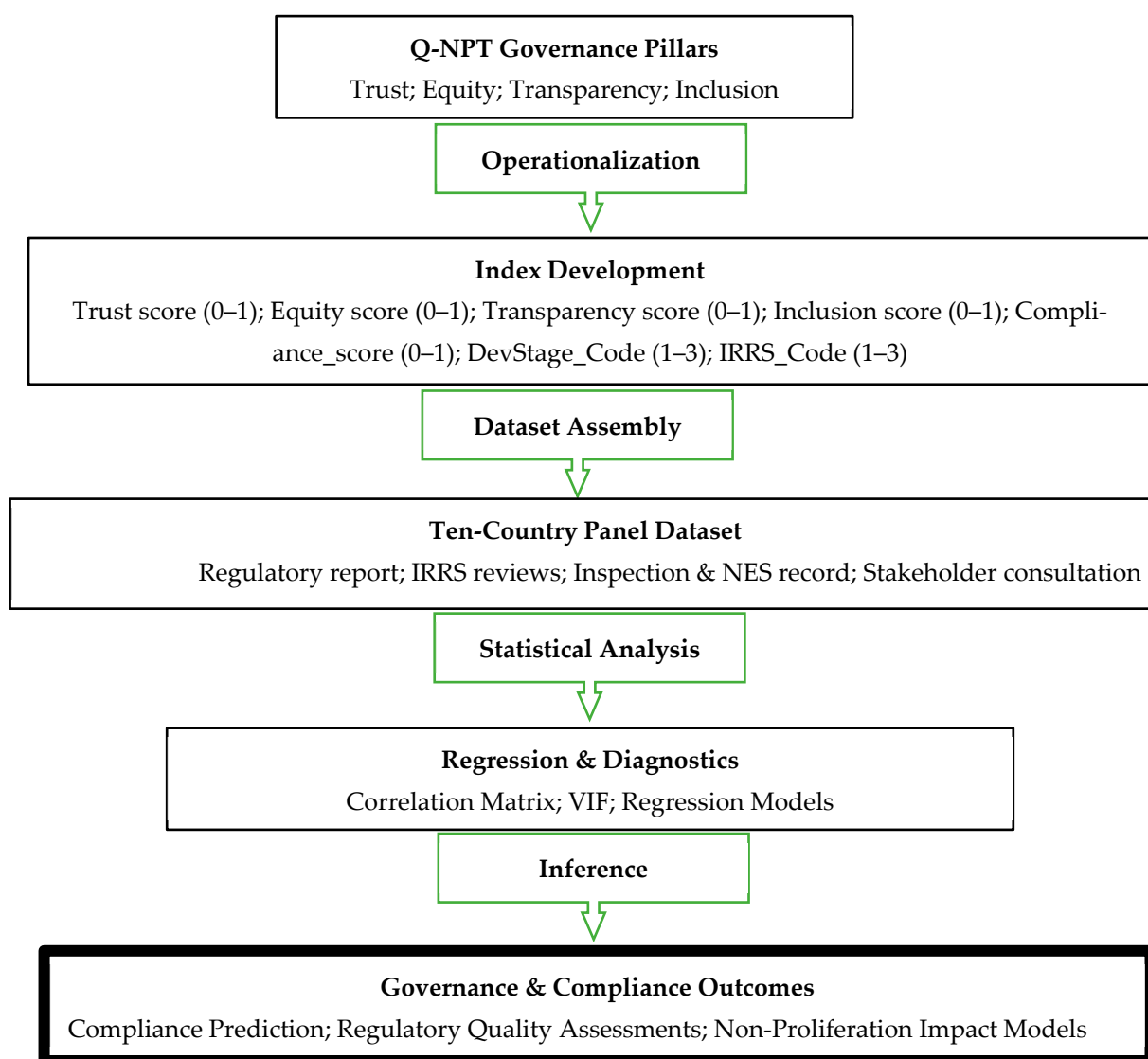


Figure 3. Conceptual–Empirical Workflow of the Q-NPT Framework.

5. Results

This section examines the association between nuclear governance quality—captured by the TETI composite index, which operationalizes the Q-NPT dimensions of Trust, Equity, Transparency, and Inclusion—and operational compliance performance across ten countries. The analysis is comparative and exploratory, aiming to identify cross-national governance patterns rather than establish causal relationships. Tables 5 and 6 report the underlying governance pillar scores, the composite TETI index, Compliance scores, and institutional indicators for advanced and emerging nuclear programs, respectively. These tables provide full transparency of the constructed dataset and enable replication and independent assessment of cross-national variation.

Because national nuclear governance indicators are reported across different years, the study applies a temporal harmonization procedure. Given that institutional governance characteristics evolve gradually rather than changing instantaneously, the analysis treats the selected indicators as representations of governance conditions within the study period rather than as year-specific performance measures. Rather than directly comparing raw values from different reporting years, indicators were normalized relative to their respective reporting scales and institutional benchmarks. The harmonization approach preserves cross-country comparability by focusing on relative governance characteristics and institutional

patterns rather than absolute annual values. The most recent publicly available data within the defined study period were used for each country. Although this approach improves cross-country comparability, temporal differences remain a limitation.

Table 5. Advanced Nuclear Programs.

Variable/Country	United States	Canada	United Kingdom	France	Finland
Data Year	2024	2023–2024	2024	2016	2016
Trust score	0.80 [33,34]	0.85 [35,36]	0.82 [33,37]	0.78 [38]	0.75 [38]
Equity score	0.60 [34]	0.65 [36]	0.60 [37]	0.55 [38]	0.50 [38]
Transparency score	0.90 [34]	0.92 [36]	0.88 [37]	0.75 [38]	0.80 [38]
Inclusion score	0.70 [33]	0.85 [36]	0.75 [37]	0.60 [38]	0.65 [38]
Compliance score	0.88 [34]	0.90 [36]	0.87 [37]	0.85 [38]	0.84 [38]
DevStage_Code	3	3	3	3	3
IRRS_Code	2 [33]	2 [35]	3 [33]	2 [38]	2 [38]
IRRS_Intensity	0.82 [33]	0.80 [35]	0.92 [33]	0.70 [38]	0.75 [38]

Note: Trust, Equity, Transparency, and Inclusion scores represent normalized expert-informed composite assessments (0–1) derived from structured qualitative synthesis of documentary evidence, including IAEA reports, national regulatory documents, the peer-reviewed literature, and authoritative institutional sources. The scores do not represent direct measurements of latent governance constructs but rather structured approximations based on triangulated evidence. DevStage_Code, IRRS_Code, and IRRS_Intensity are ordinal institutional indicators used for contextual comparison and are not included in the primary TETI calculation.

Table 6. Emerging Nuclear Programs.

Variable/Country	Türkiye	UAE	Egypt	Brazil	Pakistan
Data Year	2024	2023	2026	2016	2023–2024
Trust score	0.60 [39]	0.65 [40]	0.40 [41]	0.55 [38]	0.58 [42,43]
Equity score	0.40 [39]	0.45 [40]	0.30 [41]	0.35 [38]	0.38 [42]
Transparency score	0.50 [39]	0.70 [40]	0.35 [41]	0.60 [38]	0.55 [42]
Inclusion score	0.45 [39]	0.50 [40]	0.25 [41]	0.40 [38]	0.42 [42]
Compliance score	0.70 [39]	0.72 [40]	0.60 [41]	0.75 [38]	0.73 [42]
DevStage_Code	2	2	1	2	2
IRRS_Code	2 [39]	2 [40]	1 [41]	2 [38]	2 [43]
IRRS_Intensity	0.60 [39]	0.65 [40]	0.10 [41]	0.55 [38]	0.65 [43]

5.1. Descriptive Patterns

Table 7 presents descriptive statistics for the governance scores, the TETI Composite Index, compliance outcomes, and institutional indicators across the ten-country sample. The mean TETI Composite score was 0.602 (SD = 0.153), indicating moderate variation in governance characteristics among the selected nuclear programs. Among the four governance dimensions, Transparency exhibited the highest average score (M = 0.650), whereas Equity showed the lowest average score (M = 0.478).

Table 7. Descriptive Statistics of Governance Scores and Compliance Variables.

Variable	Mean	SD	Minimum	Maximum
Trust score	0.623	0.148	0.400	0.850
Equity score	0.478	0.112	0.300	0.650
Transparency score	0.650	0.194	0.350	0.920
Inclusion score	0.557	0.192	0.250	0.850
TETI Composite	0.602	0.153	0.325	0.818
Compliance score	0.784	0.099	0.600	0.900

This pattern suggests that while regulatory transparency mechanisms are relatively well established across the sampled nuclear programs, participatory and distributive dimensions of nuclear governance remain comparatively less developed. Trust (M = 0.623)

and Inclusion ($M = 0.557$) occupied intermediate positions, reflecting variation in institutional legitimacy, stakeholder engagement practices, and public participation mechanisms across countries.

Compliance scores were relatively high ($M = 0.784$; $SD = 0.099$) and demonstrated less dispersion than the governance scores. This pattern is consistent with the stronger institutional standardization typically associated with nuclear regulatory and safeguards systems. However, the relatively narrower variation in compliance performance compared with governance scores suggests that formal compliance outcomes may not fully capture broader dimensions of institutional legitimacy, stakeholder inclusion, and governance quality. Please note that these statistics are interpreted as descriptive patterns within the selected cases rather than population estimates or evidence of causal relationships.

Across the advanced nuclear programs (United States, Canada, United Kingdom, France, and Finland), TETI Composite scores ranged from 0.670 to 0.818, while Compliance scores ranged from 0.840 to 0.900. Emerging nuclear programs (Türkiye, UAE, Egypt, Brazil, and Pakistan) displayed lower and more dispersed TETI Composite scores, ranging from 0.325 to 0.575, and Compliance scores ranging from 0.600 to 0.750.

As illustrated in Figure 4, advanced programs generally cluster in the upper-right region of the scatterplot, characterized by relatively higher governance scores and stronger compliance outcomes. Emerging programs display greater dispersion across both dimensions, suggesting more heterogeneous governance trajectories. This visual pattern indicates a positive association between governance quality, as represented by the TETI Composite Index, and compliance performance.

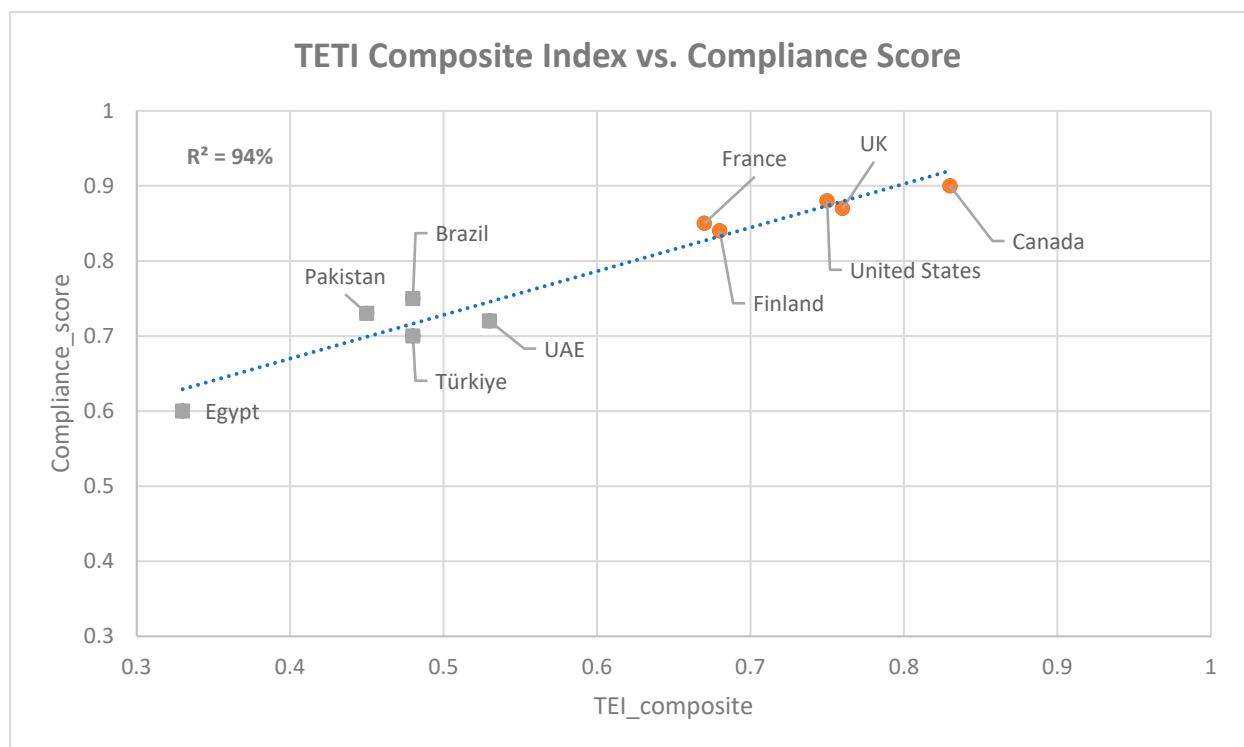


Figure 4. TETI Composite Index and Compliance Score: Advanced and Emerging Programs. Notes: Circles denote advanced programs (United States, Canada, United Kingdom, France, Finland). Squares denote emerging programs (Türkiye, UAE, Egypt, Brazil, Pakistan).

The observed clustering pattern may reflect multiple interacting institutional factors, including regulatory maturity, operational experience, safeguards implementation history, institutional capacity, and the availability of governance infrastructure. Therefore,

differences between advanced and emerging nuclear programs should not be attributed exclusively to governance characteristics captured by the TETI framework.

The qualitative examination of the cases reveals three broad descriptive clusters: Advanced Programs: United States, Canada, United Kingdom, France, and Finland. These countries exhibit relatively high TETI Composite scores and consistently strong compliance performance, reflecting mature regulatory institutions, established oversight mechanisms, extensive operational experience, and developed governance infrastructures.

Intermediate Programs: Brazil, Pakistan, Türkiye, and the UAE. These countries occupy an intermediate position, combining expanding nuclear ambitions with varying levels of institutional maturity. Although compliance performance is generally positive, governance scores demonstrate greater variation, reflecting different pathways of regulatory development, stakeholder engagement, and institutional consolidation.

Emerging Program: Egypt. Egypt represents the lowest-scoring case in both governance and compliance measures within the sample. As a relatively recent entrant into commercial nuclear power development, its position may reflect the institutional learning processes and governance capacity-building challenges commonly associated with early-stage nuclear programs.

These clusters are intended solely as descriptive groupings rather than formal classifications or causal categories. Nevertheless, they provide useful contextual insight into cross-national variation in governance characteristics and compliance performance.

5.2. Correlation Analysis

Table 8 presents Pearson correlation coefficients among the four Q-NPT governance scores (Trust, Equity, Transparency, and Inclusion), compliance performance, and regulatory review intensity. All four governance scores demonstrate strong positive associations with compliance performance ($r = 0.93\text{--}0.96$), indicating that nuclear programs with higher levels of assessed governance quality also tend to exhibit stronger compliance outcomes within the sampled cases.

Table 8. Pearson Correlation Matrix of Governance Scores and Compliance Variables.

Variable	Trust Score	Equity Score	Transparency Score	Inclusion Score	Compliance Score	IRRS Intensity
Trust score	1.00	0.97	0.96	0.97	0.96	0.91
Equity score	0.97	1.00	0.95	0.98	0.93	0.83
Transparency score	0.96	0.95	1.00	0.96	0.96	0.89
Inclusion score	0.97	0.98	0.96	1.00	0.95	0.86
Compliance score	0.96	0.93	0.96	0.95	1.00	0.88
IRRS Intensity	0.91	0.83	0.89	0.86	0.88	1

The strong correlations among the four Q-NPT governance scores ($r = 0.95\text{--}0.98$) indicate substantial alignment among the governance characteristics assessed through the documentary evidence-based evaluation. These high associations are theoretically plausible because the four dimensions reflect interconnected aspects of institutional governance, including legitimacy, openness, stakeholder engagement, and procedural fairness. At the same time, the high correlations indicate that estimating separate regression effects for individual governance scores may introduce multicollinearity concerns. Therefore, the subsequent regression analysis uses the aggregated TETI Composite Index rather than simultaneously entering the individual governance scores as independent predictors.

The correlation between the TETI governance scores and IRRS Intensity is also positive ($r = 0.83\text{--}0.91$), suggesting that stronger governance characteristics tend to coincide with

more intensive international regulatory review engagement. Again, these associations should be interpreted cautiously because the small sample size ($n = 10$) and exploratory design do not permit causal inference.

5.3. Bivariate Regression Analysis

To further explore the relationship between governance quality and compliance performance, a bivariate ordinary least squares (OLS) regression model was estimated:

$$\text{Compliance_score}_i = \beta_0 + \beta_1 \text{TETI_Composite}_i + \epsilon_i \quad (4)$$

This model is used as a descriptive analytical approach to examine whether countries with higher assessed governance quality, as represented by the TETI Composite Index, tend to display stronger observed compliance performance. The regression analysis is not intended to estimate causal effects or establish governance quality as a determinant of compliance outcomes. Results are presented in Table 9.

Table 9. OLS Regression Results: Compliance Score on TETI Composite Index.

Predictor	Coefficient (β)	Standard Error	t-Value	p-Value	95% Confidence Interval
Intercept (β_0)	0.424	0.036	11.79	<0.001	[0.341, 0.507]
TETI Composite (β_1)	0.598	0.058	10.32	<0.001	[0.465, 0.732]

Model statistics: $R^2 = 0.930$; Adjusted $R^2 = 0.921$; $F(1,8) = 106.5$; $p < 0.001$; $N = 10$ countries. The model accounts for 93% of the observed variance in compliance scores within sample.

The regression results indicate a strong positive association between the TETI Composite Index and observed compliance performance. Specifically, a one-unit increase in the TETI Composite Index is associated with an estimated 0.598-unit increase in compliance score within the observed sample ($\beta_1 = 0.598$, $p < 0.001$). The high explained variance suggests that governance characteristics captured by the Q-NPT framework are strongly associated with variation in compliance outcomes among the selected nuclear programs.

However, these results should be interpreted cautiously. The analysis is based on a small cross-national sample ($n = 10$) and relies on expert-informed governance scores derived from documentary evidence. The observed association should therefore be interpreted as an empirical pattern rather than evidence of a causal relationship.

Several alternative explanations may contribute to the observed relationship, including regulatory maturity, institutional capacity, economic resources, nuclear operating experience, safeguards implementation history, and broader governance conditions. Countries with mature nuclear programs may simultaneously possess stronger governance institutions and stronger compliance performance, making it difficult to isolate the independent contribution of governance quality.

Future research using larger cross-national datasets, longitudinal designs, and more rigorous identification strategies could examine whether the observed governance–compliance relationship remains robust after accounting for potential confounding factors and alternative explanations.

5.4. Governance Pillar Associations

To explore the relative contribution of individual governance dimensions, separate regressions were estimated for Trust, Equity, Transparency, and Inclusion. These analyses were conducted to examine whether individual governance dimensions display different patterns of association with Compliance_score. They are not intended to identify independent causal effects or determine the relative importance of each governance pillar. The

results suggest that Trust ($\beta = 0.38$) and Transparency ($\beta = 0.33$) exhibit stronger associations with Compliance_score than Equity and Inclusion.

This pattern may indicate that institutional credibility and information accessibility are particularly relevant dimensions within the observed sample. However, these findings should be interpreted cautiously because the four governance dimensions are theoretically interconnected and may reflect overlapping aspects of broader institutional capacity.

In particular, Trust, Equity, Transparency, and Inclusion are not independent explanatory factors. Improvements in one dimension may occur alongside improvements in others, making it difficult to isolate the unique contribution of any individual pillar using a small cross-sectional dataset. The findings are therefore best viewed as indicative rather than definitive, highlighting governance dimensions that may warrant closer examination in future research.

Future studies using larger samples and more advanced analytical approaches may evaluate whether specific governance dimensions provide distinct explanatory value after accounting for institutional maturity, regulatory capacity, and other contextual factors.

5.5. Interpretation

Overall, the empirical findings suggest a positive association between TETI-based governance indicators and observed compliance performance across the ten-country sample. The observed relationship is broadly consistent with the theoretical proposition underlying the Q-NPT framework that governance characteristics related to trust, equity, transparency, and inclusion may be relevant dimensions of effective nuclear governance. The consistency of the observed relationship across advanced and emerging programs is broadly consistent with the theoretical proposition that governance quality and compliance outcomes may be related.

However, the findings should be interpreted as evidence of an empirical pattern rather than confirmation of a causal mechanism. The analysis does not demonstrate that improvements in governance indicators necessarily produce improvements in compliance outcomes, nor does it establish the direction of the relationship between governance quality and regulatory performance. Rather, it identifies a governance–compliance relationship that merits further empirical examination.

Several factors may contribute to the observed association, including regulatory maturity, institutional resources, operational experience, international engagement, safeguards history, and broader national governance capacity. These factors may interact with governance quality and influence both the development of governance institutions and compliance performance.

The primary contribution of the analysis is therefore not causal estimation but the development and preliminary assessment of a structured governance measurement framework. By operationalizing Trust, Equity, Transparency, and Inclusion into comparable indicators, the study provides an exploratory basis for future research examining how governance arrangements interact with nuclear regulatory performance across diverse institutional contexts. Future studies using larger datasets, longitudinal designs, and stronger causal identification strategies can further evaluate whether the observed governance–compliance association remains robust after accounting for alternative explanations.

6. Illustrative Application of the Q-NPT Framework to Existing Nuclear Power Plants

The exploratory findings presented in Section 5 suggest a positive association between TETI-based governance indicators and compliance performance across the ten-country sample. While these results do not establish causal relationships, they provide an illus-

trative basis for considering how the governance dimensions emphasized by the Q-NPT framework—Trust, Equity, Transparency, and Inclusion—may be relevant to the governance of operational nuclear facilities. Accordingly, the discussion in this section should be interpreted as a conceptual application of the framework rather than as an empirical test of its effectiveness.

The discussion that follows does not represent a claim that adoption of Q-NPT principles will necessarily improve nuclear safety, safeguards performance, or compliance outcomes. Rather, it illustrates how governance dimensions may complement existing technical and regulatory approaches by providing an additional analytical perspective for examining institutional characteristics associated with nuclear governance.

Across the countries examined, advanced nuclear programs generally exhibited higher TETI_composite scores and stronger compliance performance, while emerging programs displayed greater variability on both measures. These patterns are broadly consistent with the proposition that governance quality and compliance outcomes may be related. They also suggest that governance considerations may merit greater attention alongside traditional technical and regulatory approaches to nuclear oversight.

The advanced and emerging classifications used in this discussion are descriptive categories based on nuclear program maturity, regulatory development, and institutional experience, as defined in Section 4.2. They are not intended as rankings of governance quality, regulatory effectiveness, or institutional performance.

Existing nuclear power plants face governance challenges that extend beyond technical safeguards alone. Globally, many operating reactors are approaching or exceeding their original design lifetimes, creating complex issues related to equipment aging, license renewal, long-term waste management, cybersecurity, and stakeholder confidence [1]. Experience from reactor life-extension projects and major retrofit programs indicates that public acceptance, regulatory legitimacy, transparency, and institutional trust can influence implementation processes and long-term operational stability. These challenges highlight the potential relevance of governance-oriented approaches that complement technical safety and safeguards systems.

Within this context, the Q-NPT framework should be understood as an exploratory governance assessment framework rather than a validated predictive model. Its purpose is not to forecast compliance outcomes but to organize and examine governance characteristics that may be relevant to nuclear institutional performance. The framework may contribute to governance assessments in several ways:

- Supporting lifecycle governance for aging reactors by emphasizing institutional legitimacy, stakeholder confidence, and transparent decision-making during license renewal and modernization processes.
- Encouraging compliance-oriented organizational cultures through the integration of governance considerations with technical and regulatory requirements.
- Promoting transparency in fuel-cycle management, regulatory communication, and public reporting practices.
- Strengthening institutional oversight arrangements relevant to safety, safeguards, and non-proliferation objectives.
- Facilitating dialogue, stakeholder engagement, and cooperation among actors involved in peaceful nuclear development.

These potential contributions should be viewed as conceptual implications derived from the governance dimensions represented by the Q-NPT framework rather than as empirically demonstrated outcomes of the present study.

In advanced nuclear states—including the United States, Canada, the United Kingdom, France, and Finland—the Q-NPT framework may provide an additional governance

lens through which existing technical and regulatory systems can be evaluated. These countries generally possess mature oversight institutions, established regulatory processes, and extensive operational experience. Within such contexts, the framework highlights governance dimensions related to stakeholder engagement, institutional legitimacy, transparency, and public trust that may complement existing safeguards architectures. Previous studies have suggested that public confidence and stakeholder participation can influence societal acceptance of nuclear facilities, particularly in relation to reactor life-extension programs, waste management initiatives, and major infrastructure upgrades [44,45].

For emerging nuclear programs—including Türkiye, the United Arab Emirates, Egypt, Brazil, and Pakistan—the framework offers a conceptual structure for considering governance challenges associated with institutional development, regulatory capacity-building, and stakeholder engagement. These programs often operate in environments where governance arrangements are evolving alongside technological and operational capabilities. In such settings, the TETI dimensions may provide useful reference points for assessing governance maturity and identifying areas where institutional strengthening could support long-term program development.

Because the TETI dimensions are operationalized through documentary indicators, their application should be interpreted as a structured assessment of observable governance characteristics rather than a direct measurement of underlying social trust, legitimacy, or institutional effectiveness. Whether governance approaches informed by these principles translate into improved compliance outcomes remains an empirical question that requires further investigation.

Table 10 presents an illustrative comparison of how the governance dimensions emphasized by Q-NPT may be relevant in advanced and emerging nuclear contexts. The table is intended to highlight potential governance considerations rather than prescribe specific policy interventions.

Table 10. Illustrative Governance Relevance of the Q-NPT Framework in Various Nuclear States.

Dimension	Advanced Nuclear States	Emerging Nuclear States (Including Pakistan)	Illustrative Governance Relevance
Trust	Reinforces institutional credibility and public confidence within established regulatory systems	Supports development of institutional reliability and confidence in evolving governance systems	May strengthen confidence in regulatory processes and compliance practices
Equity	Encourages consideration of risk-benefit distribution, sustainability, and social legitimacy	Highlights fair distribution of risks, benefits, and opportunities among stakeholders	May contribute to perceptions of legitimacy and fairness
Transparency	Complements existing reporting, monitoring, and communication systems	Encourages development of accessible reporting and oversight mechanisms	May reduce informational asymmetries and enhance accountability
Inclusion	Supports stakeholder participation and public engagement within mature governance structures	Promotes early incorporation of participatory processes and stakeholder consultation	May strengthen procedural legitimacy and social acceptance
Technical Safeguards Integration	Applied alongside established technical, regulatory, and operational systems	Applied alongside developing regulatory and operational capabilities	Highlights the interaction between technical safeguards and governance considerations

Notes: Advanced nuclear states (United States, France, Canada, United Kingdom, and Finland) were selected to represent mature nuclear programs with established regulatory institutions and extensive operational experience. Emerging states (Türkiye, UAE, Egypt, Brazil, and Pakistan) were selected to represent programs characterized by recent expansion or evolving governance arrangements. The table illustrates potential governance considerations associated with the Q-NPT framework and should not be interpreted as evidence of causal effects [15,17].

The illustrative application presented in this section highlights how the governance dimensions emphasized by Q-NPT may be relevant to both advanced and emerging nuclear programs. The exploratory findings reported in Section 5 are broadly consistent with the proposition that governance quality and compliance outcomes may be related.

However, the present analysis does not demonstrate that governance improvements produce higher compliance performance, nor does it establish that Q-NPT-informed interventions would generate specific operational outcomes. Rather, the framework provides a structured lens for examining governance dimensions that may warrant further consideration in future assessments of nuclear energy systems. The primary contribution of this illustrative application is therefore conceptual: it demonstrates how governance dimensions can be integrated into discussions of nuclear institutional performance while recognizing the need for further empirical validation. Future research employing larger datasets, longitudinal designs, and comparative framework analysis will be necessary to evaluate these relationships more rigorously.

7. Discussion

The findings suggest that governance quality, as operationalized through the TETI_composite index, is positively associated with safeguards compliance across the ten countries included in the sample. Countries exhibiting stronger performance in Trust, Equity, Transparency, and Inclusion generally demonstrate higher compliance scores, while countries with lower governance scores tend to exhibit weaker compliance outcomes. Because the TETI_composite index represents an exploratory operationalization of governance constructs based on documentary indicators, these findings should be interpreted as evidence of an observed empirical pattern rather than direct evidence that governance quality determines compliance performance.

Cross-national differences in TETI scores should be interpreted within broader institutional contexts, including governance traditions, regulatory capacity, democratic institutions, economic resources, and historical experiences with nuclear development. The analysis does not attribute governance outcomes exclusively to nuclear-sector factors; rather, it examines how legitimacy-related governance characteristics interact with broader institutional environments to shape nuclear governance sustainability.

Although the observed relationship is substantial, the results should therefore be viewed as preliminary evidence of association rather than proof of causation. The analysis identifies a relationship between governance characteristics and compliance outcomes that warrants further investigation using larger samples, longitudinal designs, and more rigorous causal methodologies.

The qualitative clustering of cases provides additional context for interpreting the quantitative findings. Advanced nuclear programs—including those of the United States, Canada, the United Kingdom, France, and Finland—display relatively high governance and compliance scores. Intermediate programs—including those of Brazil, Pakistan, Türkiye, and the United Arab Emirates—occupy a middle position characterized by greater variation in governance indicators and compliance performance. Egypt appears as an emerging case with comparatively lower scores on both dimensions.

These classifications should not be interpreted as rankings of governance effectiveness. Rather, they represent descriptive categories reflecting differences in nuclear program maturity, regulatory development, institutional capacity, and operational experience. While these groupings provide useful comparative context, they do not establish that institutional maturity alone explains observed differences in governance or compliance performance. Broader socioeconomic, political, technological, and historical factors may also influence the relationship between governance characteristics and safeguards outcomes.

The findings can be situated within broader governance scholarship. The observed importance of Trust and Transparency is broadly consistent with Cultural Cognition research, which emphasizes the role of institutional trust in shaping public acceptance of technological risk and regulatory authority. Similarly, the results resonate with Energy Justice scholarship, which highlights procedural fairness, transparency, and equitable participation as important dimensions of energy governance. Institutional Legitimacy scholarship likewise suggests that regulatory credibility, accountability, and stakeholder confidence contribute to policy effectiveness and long-term institutional resilience.

These theoretical perspectives provide interpretive context for the observed associations but should not be considered empirical validation of the Q-NPT framework. Rather, they demonstrate conceptual alignment between the governance dimensions proposed by Q-NPT and established research traditions examining institutional trust, fairness, transparency, and legitimacy. The present findings are therefore consistent with theoretical perspectives that view governance quality as an important contextual factor influencing institutional performance.

The results also complement governance-oriented approaches such as KONVERGENGE, which emphasize integrated governance, stakeholder engagement, adaptive institutional arrangements, and multi-level coordination in addressing complex socio-technical challenges [46–48]. Similarly, the findings resonate with Energy Justice scholarship, which highlights distributional, procedural, and recognition dimensions of fairness in energy systems [11]. Cultural Cognition research emphasizes the role of institutional trust and risk perception in shaping public responses to controversial technologies [49,50], while Institutional Legitimacy scholarship highlights the importance of credibility, accountability, and stakeholder confidence in sustaining institutional authority [51,52].

However, Q-NPT differs from these approaches in its primary focus. Whereas Energy Justice concentrates on fairness within energy systems, Cultural Cognition focuses on risk perception and social acceptance, Institutional Legitimacy examines the foundations of organizational credibility and authority, and KONVERGENGE emphasizes integrated governance processes. Q-NPT is specifically proposed as a nuclear governance framework that organizes Trust, Equity, Transparency, and Inclusion as complementary dimensions for examining governance environments surrounding nuclear energy systems. Its potential contribution lies in providing a structured framework for comparative governance assessment and future empirical investigation rather than replacing existing governance theories or established regulatory approaches.

Accordingly, the present findings should not be interpreted as demonstrating the superiority of Q-NPT over alternative governance frameworks. Rather, they suggest that governance dimensions emphasized by Q-NPT may warrant greater consideration in future assessments of nuclear governance and safeguards effectiveness. The framework should be viewed as complementary to existing approaches rather than as a substitute for established theories, regulatory systems, or technical safeguards mechanisms.

The findings also contribute to ongoing discussions regarding the relationship between technical safeguards and broader governance systems. International safeguards, inspections, material accountancy, and verification procedures remain indispensable components of the global non-proliferation regime. However, the observed patterns suggest that compliance outcomes may also be associated with institutional conditions extending beyond technical controls. Transparency practices, stakeholder engagement mechanisms, regulatory credibility, and institutional trust may create environments that support sustained compliance and reinforce the effectiveness of formal safeguards systems.

This interpretation does not imply that governance characteristics substitute for technical safeguards. Rather, governance factors may operate as complementary institutional conditions

that influence how technical systems are implemented, maintained, and sustained over time. Effective nuclear governance therefore requires attention to both technical performance and the institutional environments in which safeguards and regulatory processes operate.

Several implications emerge from these observations. First, governance quality may help strengthen confidence among domestic and international stakeholders. Transparent decision-making processes and credible oversight institutions can reduce uncertainty and reinforce perceptions of regulatory integrity, potentially supporting cooperation within international monitoring and verification arrangements.

Second, the prominence of Trust and Transparency within the analysis suggests that governance legitimacy may be associated with institutional conditions that support voluntary compliance cultures, although this relationship requires further empirical investigation. Third, Equity and Inclusion may strengthen the societal foundations of nuclear governance by promoting procedural fairness, stakeholder participation, and public confidence, thereby supporting the long-term legitimacy and resilience of nuclear programs.

These observations suggest potential value in complementing existing technical assessments with governance-oriented indicators. While safeguards evaluations appropriately prioritize technical performance and regulatory compliance, structured assessments of transparency practices, stakeholder engagement processes, regulatory independence, and public trust may provide additional insight into the institutional conditions surrounding compliance systems. Governance diagnostics could therefore serve as supplementary indicators of institutional resilience and adaptive capacity.

More broadly, the findings support the proposition that effective non-proliferation depends not only on technical safeguards but also on the institutional environments within which those safeguards operate. The results suggest that governance characteristics associated with Trust, Equity, Transparency, and Inclusion may be related to conditions supporting sustained compliance, regulatory legitimacy, and institutional effectiveness. Within this context, Q-NPT offers a governance-oriented framework for examining the interaction between societal legitimacy and nuclear governance performance.

Nevertheless, several limitations must be acknowledged. The analysis is based on a small cross-sectional sample of ten countries and relies on proxy measures for both governance quality and safeguards compliance. The TETI_composite index simplifies complex governance dynamics into aggregate indicators, while the compliance score cannot capture the full diversity of national regulatory practices and safeguards performance. Moreover, omitted variables—including economic development, political institutions, regulatory capacity, technological maturity, and historical experience with nuclear energy—may influence the observed relationships.

Furthermore, because the sample size is insufficient for formal statistical validation techniques such as exploratory factor analysis or confirmatory factor analysis, the internal structure of the composite index requires examination using larger comparative datasets. Future research should therefore evaluate the robustness of the TETI framework using expanded country samples, longitudinal data, alternative weighting methods, and complementary qualitative approaches.

Consequently, the findings should be interpreted as exploratory rather than definitive. The present study provides an initial empirical examination of the relationship between governance characteristics and nuclear compliance outcomes while establishing a foundation for future research into how institutional trust, transparency, equity, and inclusion interact with technical safeguards systems.

A further limitation concerns the use of proxy indicators to represent latent governance constructs. Although the selected indicators are theoretically grounded and widely employed in governance research, they inevitably contain measurement error and may not fully capture

the multidimensional nature of trust, equity, transparency, and inclusion. Consequently, the simulation results should be interpreted as illustrating the dynamic relationships among governance dimensions rather than providing precise empirical estimates. Future research should calibrate the model using richer longitudinal datasets, multiple indicators for each construct, and formal measurement models to further reduce uncertainty.

8. Conclusions

This study provides an initial empirical examination of the relationship between governance quality and safeguards compliance through the Q-NPT framework. Across the ten-country sample, higher scores on the TETI_composite index were associated with stronger safeguards compliance, suggesting that governance dimensions encompassing Trust, Equity, Transparency, and Inclusion may be relevant to understanding variation in nuclear governance performance.

Because the study employs an exploratory cross-sectional design based on proxy indicators and a limited sample size, these findings should not be interpreted as establishing causal relationships between governance quality and compliance outcomes. Rather, they identify an empirical pattern in which stronger governance indicators tend to coincide with stronger compliance performance and provide an initial basis for further investigation.

While the exploratory design does not permit causal inference, the findings contribute to ongoing discussions regarding the role of governance in supporting effective nuclear oversight and non-proliferation objectives. The results indicate that technical safeguards operate within broader institutional environments and that governance characteristics may influence the conditions under which compliance systems function effectively.

However, governance characteristics should be understood as complementary institutional conditions rather than substitutes for established technical safeguards, regulatory controls, and international verification mechanisms. In this respect, Q-NPT offers a governance-oriented perspective that complements existing approaches to nuclear governance assessment.

The contribution of Q-NPT in this study is therefore the development of a structured analytical framework for examining governance dimensions within nuclear energy systems. The present analysis represents an initial operationalization of Trust, Equity, Transparency, and Inclusion rather than a definitive validation of the framework or proof that these dimensions directly improve safeguards performance. Future research should expand the empirical scope of the analysis through larger samples, longitudinal datasets, and alternative measurement strategies. Comparative studies across additional nuclear and non-nuclear jurisdictions could help evaluate the robustness and generalizability of the observed associations. Future studies should also examine the construct validity and measurement performance of the TETI framework using larger datasets that permit more advanced statistical validation approaches, including factor-based weighting methods or structural modeling techniques.

Further investigation of individual TETI dimensions may clarify whether particular governance attributes exert stronger relationships with safeguards performance than others. Such research would contribute to a more rigorous understanding of how governance quality interacts with technical, institutional, and societal factors in shaping nuclear governance outcomes.

Overall, the study suggests that governance factors represented by Trust, Equity, Transparency, and Inclusion merit greater attention within discussions of nuclear governance and safeguards effectiveness. The findings should nevertheless be interpreted as exploratory and hypothesis-generating rather than definitive evidence of governance effectiveness. By providing a structured framework for assessing these dimensions, Q-NPT offers a

foundation for future empirical research and policy dialogue concerning the governance conditions that support safe, secure, and publicly legitimate nuclear energy systems.

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Abbreviations

The following abbreviations are used in this manuscript:

Q-NPT Quadrat-Ullah Nuclear Peace and Trust framework
TETI Trust, Equity, Transparency, and Inclusion

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