
FROM NESI 1.0 TO NESI-X: A HYBRID LEAPFROGGING ARCHITECTURE FOR ADAPTIVE TRANSFORMATION OF NIGERIA'S ELECTRICITY SUPPLY INDUSTRY

Waliu Musa^{1,*}, Taiwo Emmanuel Okharedia², Muhammed Ibrahim³, Aneke Nnamere Ezekiel⁴, Isaac Adekanye⁵, Oluwaseun Adebisi¹, Umar Abubakar Saleh⁶

¹Federal University of Agriculture, Abeokuta

²Department of Electrical and Electronic Engineering, Atlantic International University, Hawaii, USA

³Department of Electrical/Electronic Engineering, Federal University of Petroleum Resources, Effurun, Delta State, Nigeria

⁴State University of Medical and Applied Sciences, Igbo-Eno Orba, Enugu State, Nigeria

⁵Operations Manager, Detrio Consult Limited, Lagos, Nigeria

⁶Department of Electrical and Electronic Engineering, Federal University Lokoja, Kogi State, Nigeria

Email: musa.waliu@pg.funaab.edu.ng*, tokharedia@gmail.com, abusumayya70@yahoo.com,
ezekiel.aneke@sumas.edu.ng, isaacadek@ieee.org, adebisioluwaseun@funaab.edu.ng,
abubakarumarsaleh1982@gmail.com

*Corresponding author: Waliu Musa

DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

More than a decade after the 2013 restructuring and privatization of Nigeria's electricity sector, the Nigerian Electricity Supply Industry (NESI) continues to face interacting technical, commercial, financial, and institutional constraints. Rather than treating recurrent failures as isolated generation, transmission, distribution, metering, or regulatory problems, this paper develops NESI-X as a systemic hybrid-leapfrogging architecture for coordinated transformation. It distinguishes what can be leapfrogged from what cannot: distributed generation, mini-grids, storage, advanced metering, and data-driven operations can bypass selected technological pathways in generation, distribution, metering, monitoring, and maintenance, whereas transmission infrastructure and the institutions that sustain it must be progressively reinforced. Hybrid electricity-sector leapfrogging (HESL) is formally defined as this selective-bypass-plus-reinforcement logic, and the functions it treats as indispensable are named non-bypassable system dependencies (NSDs). NESI-X organizes this distinction into two tiers, transformation capabilities and enabling conditions, coupled through a qualitative causal-loop model and a directed conceptual dependency matrix expressed as expert-informed propositions rather than statistically estimated dependencies. The architecture draws on Nigerian primary regulatory and institutional sources, including the Electricity Act 2023, the National Integrated Electricity Policy, the 2026 Mini-Grid Regulations, FoNER, NISO, and NEMSA's statutory technical-assurance mandate, alongside recent literature on smart metering, mini-grids, digital twins, and cyber-physical security. A gated roadmap and layer-level KPIs are proposed alongside financing, institutional capacity, skills, interoperability, cybersecurity, and political-economy risks as adoption conditions. The contribution is a testable architecture, not a claim of validation.

Keywords: Nigeria Electricity Supply Industry; hybrid leapfrogging; non-bypassable system dependencies; distributed energy resources; regulatory governance

1. INTRODUCTION

More than a decade after Nigeria's 2013 power-sector privatization, the sector has undergone substantial institutional restructuring, yet persistent weaknesses in electricity reliability, metering, revenue recovery, infrastructure condition, and system coordination continue to constrain sector performance (Adeku et al., 2026). Responsibilities are now divided among generation companies (GenCos), the Transmission Company of Nigeria (TCN), distribution companies (DisCos), the Nigerian Electricity Regulatory Commission (NERC), and a growing set of state-level institutions. Evidence from selected distribution companies indicates that institutional and ownership restructuring has not, by

itself, guaranteed sustained improvements in service quality, billing, metering, or customer response (Akunne et al., 2023). The Electricity Act 2023 and the subsequent transition of market regulation to participating states have expanded the reform agenda, creating opportunities for sub-national innovation while increasing the need for coordination across federal and state jurisdictions (Federal Republic of Nigeria, 2023).

Existing studies on Nigeria's electricity sector examine individual dimensions of this problem - privatization outcomes, technical and commercial losses, smart-metering strategies, mini-grid deployment, digitalization, and regulatory reform - largely in isolation. Three gaps motivate NESI-X. First, Nigerian electricity research treats reliability, losses, distributed generation, metering, regulatory reform, and digitalization as partially independent problems rather than a coupled system. Second, the leapfrogging literature offers limited guidance on how bypassable technological pathways should coexist, within a single architecture, with infrastructure and institutions that remain physically or legally indispensable. Third, few conceptual approaches translate these interacting dimensions into an institutionally grounded architecture with explicit inter-layer dependencies, implementation gates, and measurable transition conditions. NESI-X is accordingly defined here as a proposed adaptive architecture for coordinating decentralized energy resources, digital intelligence, technical assurance, regulatory governance, and market liquidity within a progressively reinforced national electricity system, addressing these three gaps together rather than in isolation.

The paper's contribution has three parts, developed in Section 2 and applied in Section 3: hybrid leapfrogging - selective technological bypass, formally defined, coupled with progressive reinforcement of non-bypassable dependencies; an assurance-integrated architecture, in which NEMSA is treated not as peripheral compliance but as a cross-cutting technical-assurance spine running through every operational layer; and testability, since the architecture generates an explicit causal-loop model, a directed dependency matrix, implementation gates, layer-level KPIs, and five empirical propositions (P1–P5) for future testing against Nigerian data.

These contributions support four linked claims. Conceptually, the paper formalizes hybrid electricity-sector leapfrogging and reframes NESI dysfunction as a coupled-system problem, distinguishing evidence-supported feedback mechanisms from hypotheses requiring empirical testing. Architecturally, it proposes the NESI-X architecture across two conceptual tiers with an explicit dependency matrix, so that "integration" is a specified dependency rather than a general aspiration. Institutionally, it integrates NERC, state regulators, FoNER, NISO, and NEMSA's technical assurance mandate into a single architecture. For implementation, it converts the architecture into a gated roadmap with measurable entry/exit conditions and layer-level KPIs, naming financing, skills, technical assurance, cybersecurity, and political economy as implementation constraints rather than afterthoughts.

Three research questions guide the paper. RQ1: Which components of Nigeria's electricity supply system can be leapfrogged, and which infrastructure and assurance functions remain non-bypassable? RQ2: How can distributed generation, digital intelligence, governance, technical assurance, and market liquidity be configured as an interdependent transformation architecture? RQ3: What institutional, technical, financial, and cybersecurity conditions should govern progression between transformation stages? Section 2 develops the conceptual apparatus for RQ1, Section 3 addresses RQ2, and Section 4's roadmap together with Section 5's discussion takes up RQ3.

Diagnosing NESI's dysfunction must precede any proposed architecture, since a system's coupling can only be modeled once its failure dimensions are known. The sector's problem is not merely insufficient installed generation capacity: a power system can possess substantial generation assets and still fail to deliver reliable electricity if transmission observability, distribution capacity, metering, revenue collection, gas availability, technical assurance, or regulatory coordination is inadequate. Table 1 identifies five interacting diagnostic dimensions. NESI-X responds through four operational layers - two transformation-capability layers and two enabling-condition layers - supported by a cross-cutting technical-assurance spine represented by NEMSA, as Section 3 develops.

Table 1: NESI 1.0 as a Coupled System: Diagnosis Matrix

Dimension	Observed Problem	Systemic consequence	NESI-X response
Technical resilience	Limited real-time visibility, aging and strained assets, and weak predictive capability.	Faults propagate through the network; maintenance remains reactive rather than planned; reliability deteriorates over time.	Digital intelligence, Wide Area Measurement Systems (WAMS), Phasor Measurement Units (PMU), digital twins, and predictive analytics are all part of Layer 2.
Distributed energy architecture	Centralized topology remains vulnerable to system-wide disturbance and access gaps.	Local loads are exposed to national-grid failures or protracted transmission/distribution extension cycles.	This layer includes Distributed Energy Resources (DER), mini-grids, energy storage, and intentional islanding.
Technical assurance and safety	Continuous need for standards enforcement, inspection, testing, certification, and meter/equipment assurance as physical and digital infrastructure expands.	Unsafe or non-compliant installations, equipment failure, degraded interoperability, and reliability risk that outpaces oversight capacity.	The NEMSA technical-assurance spine: inspection, testing, certification, and compliance with standards, operating alongside the Standards Organization of Nigeria (SON).
Governance coordination	Federal and state regulatory roles are still evolving under the Electricity Act 2023.	Divergent state-level rules raise coordination risk and transaction costs.	Harmonized standards, regulatory sandboxing, and FoNER coordination (Layer 3).
Market liquidity	High Aggregate Technical, Commercial and Collection (ATC&C) losses, and weak collection efficiency.	Reduced capacity to finance metering, operations and maintenance, and network reinforcement.	The focus areas include AMI, revenue assurance, loss analytics, and targeted investment (Layer 4).

The financial dimension is the most thoroughly documented in current Nigerian regulatory evidence. NERC's 2025/Q4 Quarterly Report states that the weighted average ATC&C loss across all DisCos in 2025/Q4 was 34.90%, comprising 17.97 percentage points of technical/commercial loss and 20.64 points of collection loss (NERC, 2026a, §2.3.5). These components combine multiplicatively rather than additively, following the standard ATC&C convention:

$$ATC\&C = 1 - [(1 - \text{Technical/Commercial Loss}) \times (1 - \text{Collection Loss})] \quad Eq. 1$$

$$ATC\&C = 1 - [(1 - 0.1797) \times (1 - 0.2064)] = 1 - (0.8203)(0.7936) = 34.90\%$$

This reconciles exactly with NERC's reported aggregate figure, sits 14.36 percentage points above the 20.54% efficient-loss target used in MYTO 2025 tariffs, and translates to a cumulative revenue loss of ₦139.19 billion for DisCos in that quarter alone; only Eko outperformed its ATC&C target, by 2.68 percentage points (NERC, 2026a, §2.3.5). This situation is not a marginal inefficiency but nearly fifteen percentage points of avoidable revenue loss recurring quarterly, sustained by the same structural weaknesses documented across the post-privatization literature. Smart-metering strategies have been directly linked to ATC&C loss mitigation in Nigerian distribution systems (Odje et al., 2021), so metering functions as a liquidity and data-quality intervention with system-wide consequences, not merely a customer-service improvement.

Nigeria is simultaneously moving toward a more decentralized electricity architecture, formalized in the National Integrated Electricity Policy and Strategic Implementation Plan (NIEP-SIP) mandated under Section 3 of the Electricity Act 2023 (Federal Ministry of Power, 2025). NERC's 2026

Mini-Grid Regulations recognize both isolated and interconnected mini-grids, the latter permitted up to 10 MW (NERC, 2026b), and the World Bank's Nigeria Electrification Project has already supported 125 mini-grids and more than a million solar home systems, helping over 5.5 million Nigerians gain electricity access (World Bank, 2024). Nigeria, therefore, need not replicate every historical stage of conventional electricity system development, particularly where distributed energy and digital technologies offer alternative pathways to access and modernization. The concept of energy leapfrogging is directly relevant here but must be applied carefully rather than treated as a slogan: its developmental effect depends on economic, institutional, and behavioral conditions being in place to sustain it, not merely on acquiring newer technology (van Benthem, 2015). Section 2 formalizes this idea as hybrid electricity-sector leapfrogging.

NESI 1.0 is used throughout this paper as analytical shorthand for the current fragmented configuration; the designation does not imply Nigeria has ever formally operated a versioned electricity-industry architecture, nor is it an official government classification.

2. CONCEPTUAL AND METHODOLOGICAL FOUNDATION

This section formalizes the paper's central construct - hybrid electricity-sector leapfrogging - names the dependencies it treats as non-bypassable, sets out the evidence-synthesis method, and develops the causal-loop model coupling Table 1's five dimensions into a single system.

2.1 Hybrid Electricity-Sector Leapfrogging (HESL)

HESL is defined here as a transformation pathway in which selected technological development stages are bypassed where alternative technologies provide functionally equivalent or superior outcomes, while physically indispensable infrastructure and institutionally non-bypassable functions are progressively reinforced rather than circumvented. What can be leapfrogged includes conventional generation-expansion sequencing; distribution-extension pathways; manual meter reading; and reactive maintenance - selected pathways in generation, distribution, metering, monitoring, and maintenance, not a wholesale bypass of any single sector-wide stage. Digital intelligence is best understood as the enabling capability that makes this leapfrogging possible, rather than a leapfroggable stage itself: Nigeria can leapfrog the sequence in which metering, monitoring, and generation technologies are adopted, but it deploys digital intelligence as the observability layer that lets the rest of the leapfrogging happen safely, rather than "leapfrogging" it.

The construct can be expressed compactly as:

Hybrid Leapfrogging = Selective Bypass + Progressive Reinforcement + Institutional Assurance

Nigeria can leapfrog selected stages of electricity-sector development; it cannot leapfrog the physical and institutional dependencies that make an electricity system work. That proposition, developed architecturally in Section 3 and tested through explicit propositions in Section 5, is the paper's core contribution.

2.2 Non-Bypassable System Dependencies (NSDs)

The functions HESL does not permit to be bypassed are named here as non-bypassable system dependencies (NSDs): the transmission backbone; protection coordination; equipment and interconnection technical standards; NEMSA inspection, testing, and certification; cybersecurity; competent technical personnel; regulatory coordination across federal and state jurisdictions; and financial liquidity. These are precisely the functions NEMSA's statutory mandate covers, which is why Section 3 treats technical assurance as a distinct, cross-cutting element rather than folding it into "governance." NESI-X can, therefore, be summarized as:

NESI-X = Leapfroggable Pathways + Non-Bypassable System Dependencies

NESI-X does not treat technical assurance as another sectoral silo; it treats assurance as the cross-cutting condition that makes leapfrogging safe, interoperable, measurable, and scalable.

2.3 Evidence Synthesis and Conceptual Modeling

This is a conceptual, policy-architecture paper rather than a calibrated econometric or simulation study, and its methodology is a transparent conceptual-synthesis protocol rather than a

formal systematic review. The synthesis combines four elements: primary Nigerian regulatory documents, including NERC quarterly reports; the Electricity Act 2023; the NIEP-SIP; the 2026 Mini-Grid Regulations, NERC's orders establishing FoNER and NISO, and NEMSA's establishing instrument and current mandate (NEMSA, 2023); peer-reviewed literature on smart metering, mini-grids, digital twins, AI in power systems, and cyber-physical security, focused predominantly on 2020–2026 studies and supplemented by one classical leapfrogging reference (van Benthem, 2015); qualitative causal-loop modeling formalizing Table 1's coupling; and architecture and roadmap design informed by the preceding elements. Table 2 maps each evidence stream to its primary sources and purpose within the architecture.

Table 2: Methodological Source Mapping

Evidence stream	Primary sources	Purpose in architecture
Sector performance	NERC quarterly reports	ATC&C, reliability, and collection-efficiency evidence (Table 1, Section 1)
Legal/institutional structure	Electricity Act 2023; NERC orders establishing FoNER and NISO	Institutional allocation of governance and system-operation roles (Sections 3.3, 3.6)
Technical assurance	NEMSA establishing Act, her installation guidelines and current mandate under the Electricity Act 2023 (NEMSA, 2023)	Standards enforcement, inspection, and certification spine (Section 3.5)
Decentralization	2026 Mini-Grid Regulations; World Bank project data	DER/mini-grid pathway feasibility (Section 3.1)
Digitalization	Peer-reviewed literature on digital twins, AI, and cyber-physical security	Layer 2 design and cybersecurity risk framing (Section 3.2)
Leapfrogging theory	Energy-leapfrogging literature	Conceptual foundation for HESL (Section 2.1)

Evidence was organized into Table 1's five analytical domains, with Nigerian institutional claims restricted to primary regulatory and government sources rather than secondary commentary and Table 3's ratings assigned analytically from system-function logic rather than statistical estimation. The objective is a logically coherent, evidence-grounded architecture testable against multi-year Nigerian data - a testable architecture, not one whose validity is merely asserted. Validating Table 3's ratings through structured elicitation methods such as Delphi, DEMATEL, Interpretive Structural Modeling, or AHP/ANP is a natural next step this paper does not itself undertake.

2.4 Causal-Loop Logic

Only once NESI's dysfunction is established as multi-dimensional does it make sense to ask how the dimensions interact; the causal-loop analysis below uses reinforcing-loop logic to formalize Table 1's dimensions as a coupled system, rather than leaving them as parallel, independently addressable lists.

R1, the technical-financial feedback loop, is assembled from observable sector relationships: technical losses and poor service reduce effective revenue; weak revenue constrains maintenance and investment; inadequate investment further deteriorates performance, reinforcing the losses that began the cycle. Each link is independently plausible and consistent with Section 1's evidence, but the complete closed loop and each link's magnitude have not been empirically estimated for Nigeria - direction and strength require future empirical estimation. As a reinforcing loop, R1 is directionally symmetric: the same chain that produces decline would, under sustained investment, run in reverse as a virtuous cycle, so R1 is a lever available in both directions, not solely a description of failure.

R2, the regulatory-fragmentation loop, is treated more cautiously: fragmentation across a growing number of state jurisdictions plausibly raises transaction costs, creates inconsistent rules, and

increases investor uncertainty, but its strength and direction in the Nigerian context should be empirically estimated as the state-transition process matures, not presented as fact.

R3, the technical-assurance-data-revenue loop, formalizes the NEMSA function developed in Section 3 as a third reinforcing mechanism: NEMSA assurance activity improves measurement and equipment-condition integrity; more trustworthy data improves digital-intelligence outputs and billing accuracy; more accurate billing improves collectible revenue and investment capacity; and greater investment capacity, including in assurance itself, reinforces measurement integrity again. NEMSA's inspection and testing activities already generate equipment-condition, compliance, and certification records as a normal byproduct of its statutory function; NESI-X proposes that these verified records could, subject to appropriate data-governance arrangements, become a technical-data stream feeding the same asset-information systems that support digital-twin and predictive-maintenance applications. That integration is NESI-X's proposed architecture, not established Nigerian practice, and is labeled accordingly below.

A further loop describing regulatory fragmentation as self-correcting through harmonization pressure was considered but is not represented separately: it is a variant of R2 rather than functionally distinct, and a fourth loop would add diagram complexity without a materially new claim beyond R2 and Section 3.3's FoNER discussion. Figure 1 represents R1, R2, and R3 together, distinguishing R1's evidence-supported status from R2's and R3's hypothesized status through explicit labeling.

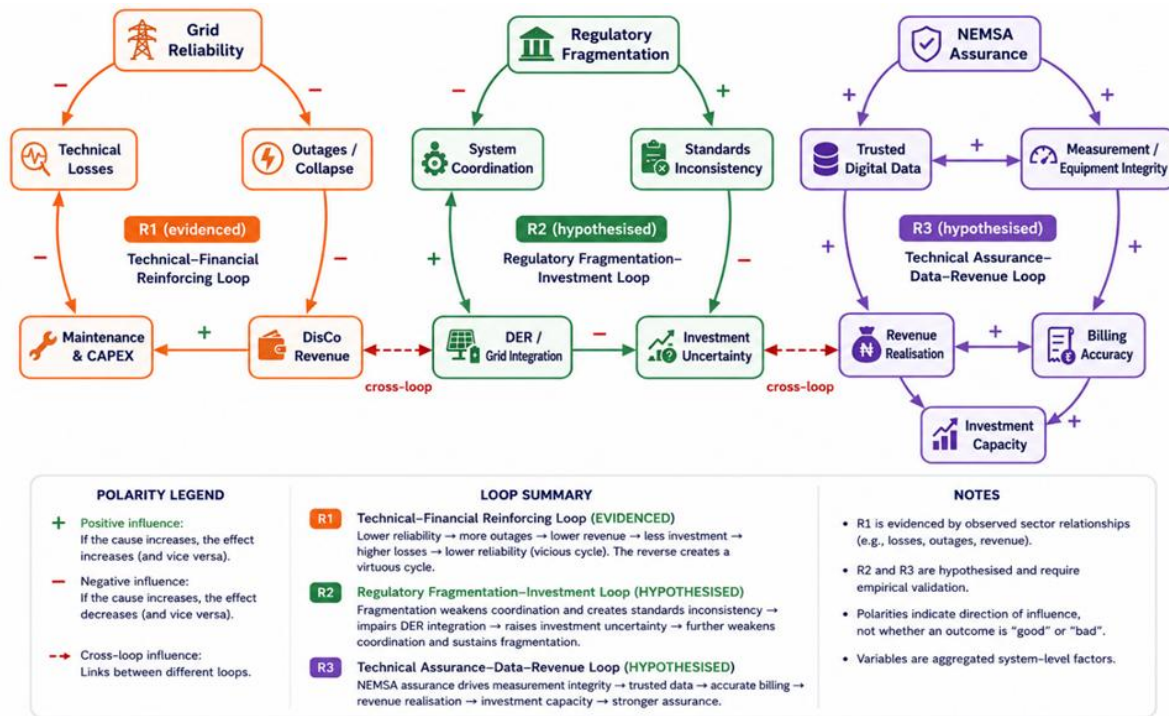


Figure 1: Qualitative causal-loop representation of NESI systemic coupling.

Distinguishing evidence-supported relationships from hypothesized ones strengthens the architecture, since a framework asserting every relationship with equal confidence is less useful to a reader - and less credible to a technical reviewer - than one that offers a path to test the difference. Concretely, R2's hypothesized strength and direction are the object of P3, which compares investment cycle times and DER interconnection approval times across states before and after FoNER-coordinated standard adoption; a null or reversed effect there would falsify R2 as specified. R3's hypothesized data-integrity channel is the object of P5, which compares an operational-data-only asset-condition model against an operational-plus-NEMSA-data model on the same asset population; no measurable improvement from the added NEMSA data stream would falsify R3's proposed mechanism. This gives each hypothesized loop a specific empirical test rather than leaving falsifiability implicit, and Section 5 converts this distinction into five explicit, individually testable research propositions.

3. NESI-X ARCHITECTURE

The causal coupling in Figure 1 motivates a structural response, but the response should treat the five diagnostic dimensions asymmetrically. Transformation capabilities are technological and infrastructural capabilities that directly alter NESI's physical or informational operating configuration: Layers 1 and 2. Enabling conditions are institutional and financial capabilities determining whether those technologies can be deployed, coordinated, financed, certified, and scaled sustainably: Layers 3 and 4, which, like the transmission backbone itself, cannot be bypassed and must be progressively built alongside the transformation-capability technologies. NESI-X is the overarching architecture: Figure 1 provides its causal logic; Figure 2 illustrates its structural configuration; Table 3 outlines its interdependencies; Table 4 details its implementation gates; Table 5 presents its performance indicators; and P1–P5 (Section 5) specify its empirical propositions. This tiering, shown in Figure 2, makes the paper's core proposition structurally explicit: Nigeria can leapfrog selected stages of electricity-sector development, but not the non-bypassable dependencies that make an electricity system work.

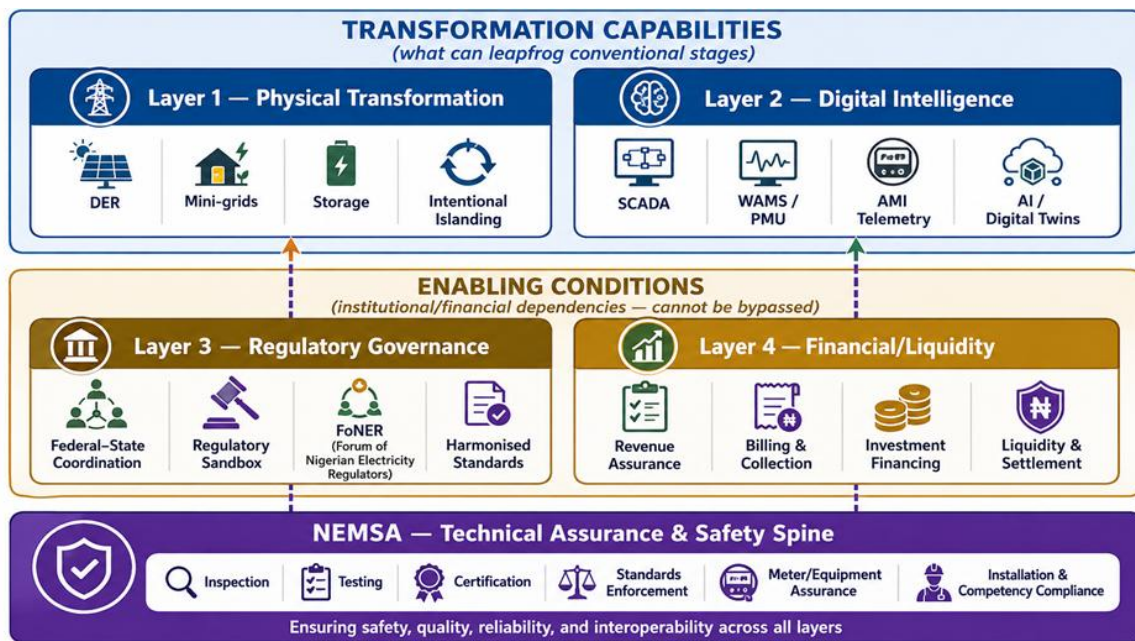


Figure 2: NESI-X architecture: transformation capabilities and enabling conditions.

NESI-X does not interpret decentralization as a substitute for transmission reinforcement. DER and mini-grids provide complementary resilience and access pathways while transmission capacity, protection, observability, and stability are progressively strengthened - decentralization is additive to the transmission backbone, not a replacement for it.

3.1 Layer 1 - Physical Transformation

This layer treats distributed energy resources, mini-grids, battery storage, and controllable local generation as strategic components of national resilience, not merely a rural-electrification substitute deployed where the conventional grid has not yet reached. NERC's 2026 Mini-Grid Regulations recognize both isolated and interconnected mini-grids (NERC, 2026b), and World Bank experience shows decentralized electricity is no longer a purely experimental pathway at scale (World Bank, 2024). The leapfrogging logic is architectural: an underserved community need not wait for a conventional transmission or distribution extension before receiving reliable electricity. But decentralization without interoperability and technical assurance can produce new fragmentation and a new category of safety risk rather than resolve the old one. Intentional islanding is not simply disconnection followed by continued local supply: it requires protection coordination, anti-islanding arrangements, synchronization on reconnection, frequency/voltage control, and, where relevant, black-start capability and DER inverter controls - none self-certifying. NESI-X therefore requires DER assets to comply with common protection, metering, telemetry, earthing, equipment, and interconnection requirements,

incorporated into the pre-commissioning and interconnection assurance pathway administered through the technical-assurance spine (Section 3.5). This gives Layer 1 a concrete engineering safeguard rather than an aspirational interoperability requirement: physical assets enter the system only once compliance has been independently verified, not merely declared by the deploying party.

3.2 Layer 2 - Digital Intelligence

This layer combines SCADA modernization, WAMS/PMU deployment, AMI telemetry, asset-condition monitoring, artificial intelligence, and digital-twin models to provide the observability that a more distributed system requires. A digital twin and an AI capability are not synonymous: the twin is the system-representation layer - a dynamic digital model of physical assets, topology, and state - while AI is an analytical capability operating on that representation and the validated data feeding it for forecasting, anomaly detection, or predictive maintenance. Digital-twin research shows a grid twin can support real-time analysis by linking physical-system measurements to a dynamic digital representation (Zhou et al., 2019). Recent work applies AI and reinforcement learning directly to cloud-based grid digital twins (Pei et al., 2024), while broader reviews identify combined digital-twin/AI use as an emerging pathway toward resilient grid management internationally (Ranawaka et al., 2024). The guiding principle for NESI-X in Nigeria should be "data before sophistication": a digital twin built on incomplete topology or unreliable measurements may appear visually impressive but will be operationally weak regardless of AI sophistication. NESI-X therefore prioritizes data governance, telemetry quality, and cybersecurity before deploying high-complexity AI.

Layer 2's data foundation need not come only from SCADA and AMI. NESI-X proposes that NEMSA-generated inspection, testing, and certification records could become a verified technical-data stream feeding the same asset-information systems supporting digital-twin and predictive-maintenance applications, illustrated in Figure 3 as a pathway from physical inspection through verified data, digital representation, and AI-based analytics to predictive maintenance and improved reliability and safety. This inspection-to-intelligence pipeline is one of the paper's more original operational contributions: it repositions a conventional statutory inspection function as a proposed active data source for a digitally intelligent grid, rather than a parallel, disconnected compliance process.

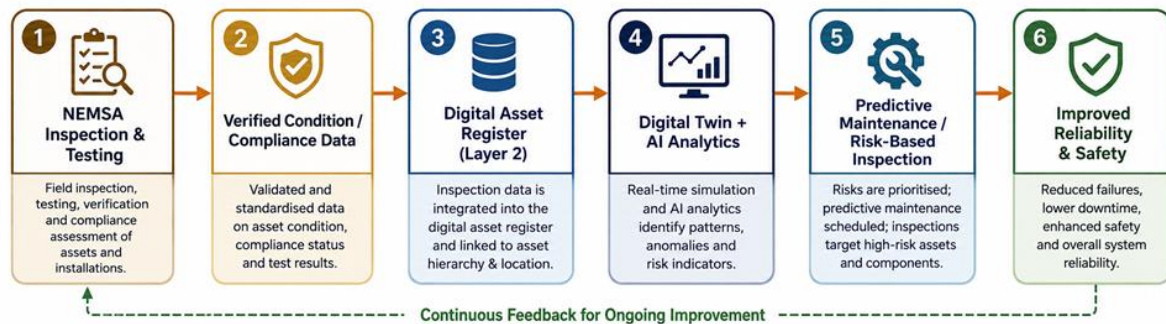


Figure 3: NEMSA inspection-to-intelligence pipeline within the NESI-X.

3.3 Layer 3 - Regulatory Governance

This layer does not transform the system directly; it determines whether Layers 1 and 2 can scale coherently across Nigeria's thirty-six states and the FCT. The Electricity Act 2023's decentralization can encourage valuable state-specific innovation but also creates a coordination challenge absent under the previous, purely federal structure. FoNER's 2026 inauguration - whose objectives include harmonized tariff-setting, market operations, consumer protection, and capacity-building among NERC and state regulators (NERC, 2026c) - provides an institutional basis for an adaptive regulatory layer. NESI-X proposes that FoNER could serve as a coordination platform for a regulatory sandbox operated against a national interoperability floor: states retain room to innovate in tariffs and DER business models - through data-informed, adaptive tariff-setting subject to regulatory approval - while core technical requirements (protection coordination, data exchange, cybersecurity

baselines, and metering interfaces) are harmonized, preventing state-level experimentation from producing incompatible electricity islands. This governance function is deliberately distinguished from technical assurance (Section 3.5), since economic/market regulation and technical standards enforcement are different institutional activities frequently, and inaccurately, conflated in general discussions of Nigeria's regulatory landscape.

3.4 Layer 4 - Financial/Liquidity

This layer likewise enables rather than transforms directly: reliable electricity must produce collectible revenue if the sector is to finance the maintenance Layers 1 and 2 depend on. Feeder-level energy accounting, automated billing, and transparent settlement form a data-to-cash chain in which AMI telemetry from Layer 2 feeds billing and revenue assurance directly (Odje et al., 2021). This chain is only as trustworthy as its measurements: meter testing, calibration, and certification are part of the technical-assurance spine below, so Layer 4's revenue-assurance function depends on Section 3.5 as much as on Layer 2's telemetry - an uncertified meter produces inaccurate billing regardless of digital sophistication. NESI-X treats this as a single, shared data infrastructure serving technical and commercial functions simultaneously, reducing the risk that separately commissioned digitalization projects create duplicated costs and incompatible databases - a failure mode that has characterized parts of Nigeria's metering rollout.

3.5 NEMSA: A Cross-Cutting Technical-Assurance Spine

Independent technical assurance of electrical infrastructure, before and during system integration, is a distinct institutional function from both the tariff/market regulation performed by Layer 3 and the technology deployed in Layers 1 and 2. It is deliberately represented as something other than a fifth layer because it is fundamentally different from the other four: it verifies safety and conformity to standards rather than transforming the system or regulating its economics. NESI-X therefore represents technical assurance as a cross-cutting spine beneath all four operational layers (Figure 2).

The Nigerian Electricity Management Services Agency (NEMSA) provides this spine's institutional interface. Under the Electricity Act 2023, NEMSA carries out electrical inspectorate services for NESI and enforces statutory technical standards and regulations, including inspection, testing, and certification of electrical installations, equipment, meters, and instruments (Nigerian Electricity Management Services Agency, 2023). NEMSA was established under the NEMSA Act 2015 (Act No. 6) and now operates under the Electricity Act 2023 framework, with the stated purpose of ensuring safe, reliable, sustainable electricity while guaranteeing the safety of lives and property (NEMSA, 2015). Its technical-assurance role operates within a wider standards ecosystem involving NERC, the Standards Organization of Nigeria (SON), utilities, manufacturers, and other technical institutions (Nigerian Electricity Management Services Agency, n.d.-b), rather than existing in isolation. This is materially different from NERC's function: NERC regulates market structure, tariffs, licensing, and economic conduct, while NEMSA enforces technical standards, safety, and equipment conformity - complementary rather than overlapping institutions.

Within NESI-X, NEMSA's spine connects to all four operational layers: to Layer 1 by verifying DER, mini-grid, and storage installations against protection, earthing, and interconnection requirements before integration (Section 3.1); to Layer 2 through the inspection-to-intelligence pipeline (Figure 3), where certification records become a data source for digital-twin applications rather than a parallel compliance archive; to Layer 4 through meter testing and certification, determining whether billing measurements can be trusted; and to Layer 3 by providing technical-assurance evidence and compliance requirements that inform the interoperability floor and technical conditions applied within regulatory experimentation, rather than by setting regulatory policy itself. This role is particularly important under a hybrid leapfrogging strategy, since accelerated deployment must not translate into accelerated technical risk; Section 2.4's causal-loop model formalizes this as R3, linking NEMSA assurance to measurement integrity, billing accuracy, and investment capacity.

3.6 NISO and TCN: Operational Coordination

The Electricity Act 2023 also provided for unbundling system and market operations from the Transmission Company of Nigeria (TCN). Under NERC Order No. NERC/2024/45, TCN's market- and system-operation functions transferred to a newly incorporated entity, the Nigerian Independent System Operator (NISO), while TCN retains responsibility for transmission infrastructure as a Transmission Service Provider (NERC, 2024). NISO functions as a critical operational coordination actor within Layer 2, particularly for system observability, balancing, dispatch coordination, and integration of distributed resources: as decentralization and digitalization proceed under Layers 1 and 2, NISO's system- and market-operation role and TCN's transmission-infrastructure role become the operational counterpart to the interconnection and technical-assurance requirements set out in Sections 3.1 and 3.5.

3.7 Conceptual Dependency Matrix

Table 3 makes the layers' dependence on one another explicit, rather than leaving cross-layer "integration" as a general aspiration. Rows represent the dependent/target component; columns represent the enabling/source component. Each cell reports the degree to which the row component's function is constrained without the column component functioning adequately:

Score	Meaning
0	No material dependency
1	Low / indirect dependency
2	Moderate dependency
3	Critical dependency

These scores are conceptual, expert-informed judgments assigned from system-function logic rather than statistical estimation - architectural hypotheses for future empirical testing (Delphi elicitation, DEMATEL, or Interpretive Structural Modelling), not statistical findings. Unlike a symmetrical matrix, the structure below is deliberately directional: governance and the NEMSA spine constrain the transformation-capability layers and Layer 4 at high strength, while dependencies among the transformation-capability layers themselves, and Layer 3's dependence on the layers it constrains, are lower.

Table 3: NESI-X Conceptual Dependency Matrix

Target (row) \ Enabling source (column)	L1 Physical	L2 Intelligence	L3 Governance	NEMSA Spine	L4 Financial
L1 Physical transformation	-	2	3	3	2
L2 Digital intelligence	2	-	2	3	1
L3 Regulatory governance	0	1	-	1	1
NEMSA spine	1	1	1	-	2
L4 Financial/liquidity	1	2	2	3	-

A few illustrations clarify these scores. Layer 1 depends critically (3) on Layer 3 and the NEMSA spine because DER cannot scale safely without interconnection standards and NEMSA-verified compliance. Layer 2 depends critically on the NEMSA spine (3), since digital intelligence cannot support dependable decisions without reliable field or inspection data and moderately on Layer 1 and Layer 3. Layer 4 depends critically on the NEMSA spine (3), since meter certification determines whether billing data can be trusted, and moderately on Layers 2 and 3. By contrast, Layer 3 is scored as having low dependency on the layers it constrains (0–1): governance shapes what Layers 1, 2, and 4 can do, but its own function is not materially constrained by their technological maturity - correcting a symmetrical-dependency reading that would otherwise overstate governance's reliance on the layers it regulates. Conversely, better revenue data finances reinforcement, and better reliability improves willingness to pay: the architecture is designed to create reinforcing improvement across layers, not a sequence of isolated projects.

Nigeria already offers partial evidence supporting each transformation-capability layer's feasibility, though this should not be overstated as proof that NESI-X as a whole is validated. The World Bank's Nigeria Electrification Project supported 125 mini-grids and over a million solar home systems, giving over 5.5 million Nigerians electricity access (World Bank, 2024), now backed by NERC's 2026 Mini-Grid Regulations (NERC, 2026b) - meaningful support for Layer 1's feasibility, though not itself demonstrating the interoperability and technical-assurance requirements NESI-X adds. FoNER provides a concrete institutional development aligned with Layer 3, with objectives including harmonized regulatory approaches and joint capacity-building between NERC and state regulators (NERC, 2026c); NESI-X does not claim FoNER has already resolved regulatory fragmentation. Digital twins are technically mature enough internationally to be a plausible Layer 2 pathway, but Nigerian evidence should not be overstated: cybersecurity research highlights that increasing digital connectivity widens the cyber-physical attack surface (Pei et al., 2024; Nemade et al., 2024), so NESI-X treats digital twins as requiring Nigerian validation through pilot substations and feeders rather than as an already proven national solution. Nigerian-specific evidence at this intersection remains limited: no digital-twin grid study using Nigerian utility data was identified in the sources reviewed. The closest available Nigerian evidence is an IoT-and-neural-network fault-detection system for smart-grid components tested on a modified IEEE 30-bus network, reporting roughly 95% detection accuracy across several fault types (Omowaye et al., 2025) - a predictive-monitoring result adjacent to, but not itself, a digital-twin implementation. This gap is consistent with the caution above: NESI-X's digital-twin proposition should be read as requiring Nigerian pilot validation, not as resting on existing Nigerian digital-twin evidence. NEMSA's inspection, monitoring, investigation, and certification function, by contrast, is not a pathway requiring validation in the same sense - it is an existing, operating capability whose integration with digital asset management and revenue assurance, rather than its existence, is the genuinely novel element NESI-X proposes.

4. IMPLEMENTATION ARCHITECTURE: PHASED ROADMAP, KPIS, AND RISK CONTROLS

NESI-X deliberately uses gates rather than calendar milestones to sequence its implementation. A state, utility, plant, or network should not advance merely because a calendar date has arrived; advancement should require evidence that the necessary data, skills, cybersecurity controls, regulatory rules, technical-assurance capacity, and financing are genuinely in place. This is the architecture's primary safeguard against reproducing the historical pattern of installing technology faster than the institutions required to operate, finance, and certify it safely. Table 4 sets out the four phases in indicative terms, and Figure 4 presents the same roadmap as a gated timeline.

Table 4: NESI-X Phased Transformation Roadmap (Gated)

Phase	Indicative period	Primary actions	Gate / success condition
0 - Stabilize	2026-2027	Establish a common asset/data taxonomy, including NEMSA inspection and certification data; prioritize critical grid observability; baseline ATC&C, reliability, and outage metrics; and map regulatory responsibilities across federal and state levels.	Baseline dataset and governance ownership have been approved.
1 - Foundation	2027-2029	Pilot DER interoperability; expand AMI/feeder energy accounting; deploy PMU/WAMS at strategically important nodes; establish regulatory sandbox procedures; pilot integration of NEMSA inspection/testing records with utility asset-management systems.	Pilots demonstrate data integrity, safety, and measurable operational value.
2 - Integration	2029-2032	Scale digital twins, predictive analytics, and DER coordination; harmonize technical standards across participating states; incorporate verified NEMSA inspection data into digital twin and predictive maintenance systems.	Cross-layer KPIs improve simultaneously; no major interoperability or cybersecurity failure.
3 - Adaptive maturity	2032 onward	Continuous optimization, automated decision support, data-informed adaptive tariff-setting subject to regulatory approval, coordinated DER participation, risk-informed technical assurance, and resilience planning.	The system demonstrates sustained reliability, liquidity, interoperability, and learning capacity.

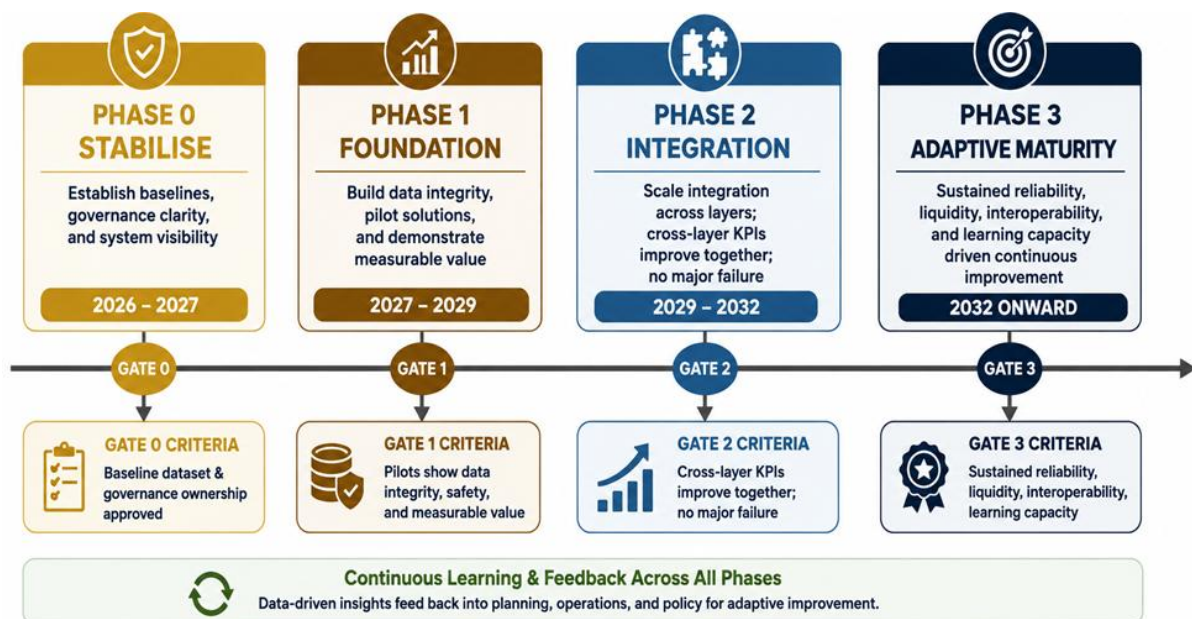


Figure 4: NESI-X gated transformation roadmap.

Table 5 converts each layer and the system as a whole into measurable indicators so that "progress" under NESI-X is something a regulator, utility, or independent researcher can actually check against data rather than assess only qualitatively. Baseline values are deliberately left unspecified here rather than invented: Phase 0 of the roadmap exists precisely to establish them from primary Nigerian data before Phase 1 targets are set. KPIs are divided into a core set likely measurable from currently available Nigerian data and an advanced set dependent on data infrastructure the roadmap itself is designed to build.

Table 5: Key Performance Indicators by Layer

Layer	KPI	Operational definition	Data source	Tier	Roadmap Phase
L1 Physical	Islanding readiness	Share of critical loads capable of intentional islanding within a defined response time.	DisCo/NERC outage records; utility asset registers	Core	Phase 1
L1 Physical	DER hosting capacity	Additional DER capacity a feeder can accommodate before violating protection or voltage limits.	DisCo/NISO network studies	Advanced	Phase 2
L2 Intelligence	Telemetry completeness	Valid data points received / expected data points x 100.	TCN, DisCo SCADA/telemetry logs	Core	Phase 1
L2 Intelligence	Digital-twin model fidelity	Agreement between predicted and observed system states under predefined validation scenarios.	Pilot digital-twin validation records	Advanced	Phase 2
L3 Governance	Regulatory sandbox cycle time	Elapsed time from sandbox application to regulatory decision.	NERC, state regulator, FoNER records	Core	Phase 1
NEMSA spine	Inspection closure rate	The formula for calculating the inspection closure rate is: (Corrective actions closed / Corrective actions issued) x 100.	NEMSA inspection and certification records	Core	Phase 0
NEMSA spine	AMI/meter certification coverage	Active, NEMSA-certified meters / total customer meters x 100.	NEMSA, DisCo meter registers	Core	Phase 1
L4 Financial	ATC&C loss	As defined in Section 1: $1 - [(1 - \text{Technical/Commercial Loss}) \times (1 - \text{Collection Loss})]$.	NERC quarterly reports	Core	Phase 0
System-level	SAIDI / SAIFI	Standard reliability indices, where applicable.	NERC, TCN, DisCo aggregated reporting	Core	Phase 1–2
System-level	LOLE / EENS	Loss of load expectation / expected energy not served, where data permit.	TCN, NISO system-operation data	Advanced	Phase 2–3

Four risks condition whether the roadmap's gates are actually cleared rather than remaining aspirational. Financing is the first and most immediate constraint: digitalization, DER deployment,

storage, metering, and network reinforcement all require capital while the sector works through historical liquidity weaknesses documented in Section 1. NESI-X responds by prioritizing projects that create measurable technical and commercial value simultaneously - for example, feeder digitalization that improves both outage visibility and revenue assurance from the same investment. Skills are the second constraint: digital-grid transformation requires engineers, technicians, data scientists, protection specialists, cybersecurity professionals, and regulators capable of working across disciplinary boundaries historically kept separate in Nigerian institutional training, built through joint university-NAPTIN-utility-regulator competency pathways around digital substations, DER control, AMI analytics, and cyber-physical security.

Interoperability and cybersecurity are the third constraint, growing more serious precisely as the other layers succeed. Smart-grid expansion under Layers 1-2 creates substantially more communication interfaces, and therefore, more attack surface than NESI 1.0's largely analog configuration presents today. Recent research emphasizes holistic cyber defense for smart grid environments - proactive threat detection, secure integration, and continuous monitoring rather than perimeter security alone (Nemade et al., 2024). NESI-X treats cybersecurity as a design requirement embedded within every layer, including the NEMSA spine's data flows into Layer 2, rather than as a separate IT project bolted on afterward. Political economy is the fourth constraint and the one most likely underestimated by a purely technical reading: reform touches tariffs, subsidies, investment rights, and the distribution of authority between federal and state governments, and a technically coherent architecture can still fail if stakeholders perceive it as redistributing costs or authority without credible accountability. The architecture therefore requires transparent KPIs, public reporting, meaningful stakeholder participation, and independent evaluation, rather than self-reported progress.

5. EMPIRICAL PROPOSITIONS AND DISCUSSION

NESI-X is not a prediction that Nigeria will automatically achieve a resilient electricity system simply by adopting four technologies or institutional mechanisms; it is a systems architecture and a set of testable propositions. Its core claim, made structurally explicit by Section 3's tiering, is that Nigeria can leapfrog *selected stages* of electricity-sector development but cannot leapfrog the institutional, technical-assurance, and financial dependencies that make an electricity system work; those enabling conditions and the NEMSA spine that verifies them must be progressively built, not bypassed, regardless of how quickly transformation-capability technologies can be deployed.

Three distinctions follow directly from this claim. First, distributed generation can meaningfully reduce dependence on a single, centralized national grid pathway, but it cannot eliminate the underlying need for transmission and distribution coordination, protection coordination, and independent technical assurance of the assets being connected (Section 3.5). Second, digital twins and artificial intelligence can greatly enhance our ability to see and make decisions about systems, but they cannot resolve underlying issues such as missing sensors, poor data management, inadequate maintenance, or weak cybersecurity; if a complex digital system is built on a poorly maintained physical system, it will only create confident predictions about a system whose actual condition is not accurately known. Third, state-level regulatory autonomy under the Electricity Act 2023 can genuinely stimulate valuable local innovation, but without the interoperability floor proposed in Layer 3, it can just as easily fragment the national market further rather than resolving NESI 1.0's existing fragmentation. Each of these distinctions creates a clear expectation about what should be observable if the architecture's account of NESI's problems is accurate, which is what makes the architecture testable rather than merely plausible.

The architecture accordingly yields five propositions that future empirical work - ideally conducted with the primary Nigerian regulatory and utility data referenced throughout this paper - can test directly.

P1. ATC&C loss reduction correlates with feeder-level metering penetration, consistent with existing Nigerian evidence at the DisCo level (Odje et al., 2021), but the marginal effect of additional metering should diminish measurably where Layer 3 governance capacity or NEMSA spine meter-certification capacity is weak, since metering alone cannot correct misaligned tariffs, weak enforcement, or uncertified meters.

P2. DER and mini-grid deployments interconnected under common technical standards and NEMSA-verified compliance should show measurably lower post-disturbance restoration times and fewer safety-related incidents than isolated deployments lacking equivalent verification, holding local generation capacity constant.

P3. The strength and direction of R2, the hypothesized regulatory-fragmentation loop, are empirically testable by comparing investment cycle times and DER interconnection approval times across Nigerian states before and after FoNER-coordinated standard adoption, once a sufficient number of states have transitioned and a baseline period is available for comparison.

P4. Transformation-capability KPIs (Table 5, Layers 1-2) should stagnate wherever governance, technical assurance, or liquidity indicators fall below an identifiable threshold, largely independent of Layer 1/2 technological maturity - enabling-condition maturity should constrain observed outcomes in practice, not merely in Table 3's conceptual ratings.

P5. Integration of verified NEMSA inspection, testing, and certification data with utility asset-management datasets will improve asset-condition classification and predictive-maintenance performance relative to models using operational data alone - testable by comparing an operational-data-only model against an operational-plus-NEMSA-data model on the same asset population.

None of these five propositions is claimed to have already been demonstrated in Nigeria; each is offered as a testable proposition consistent with the methodological discipline established in Section 2.4, where R1 was distinguished from R2 and R3 precisely along these lines. This maintains the paper's evidence-first posture through to its final analytical section, rather than relaxing it once the architecture itself has been presented.

6. LIMITATIONS, INTERNATIONAL TRANSFERABILITY, AND CONCLUSION

6.1 Limitations

This paper lacks an econometric estimation of the causal relationships it proposes and a calibrated system dynamics simulation of NESI as a whole. R1, R2, and R3 are causal-loop propositions rather than fitted models, and none has been empirically validated against Nigerian time-series data. Table 3's dependency scores are conceptual, derived from system-function logic rather than statistical estimation. Because these scores were assigned by the author team rather than through structured elicitation, they carry a risk of single-team framing bias. For example, the NEMSA core structure's uniformly high dependency scores reflect the authors' institutional familiarity with NEMSA's mandate but could plausibly be contested by DisCo or NERC-side reviewers with different operational perspectives or prior expectations. Independent expert elicitation (Delphi, DEMATEL, or AHP/ANP, as already flagged in Section 2.3) remains necessary before Table 3's scores can be treated as more than a starting hypothesis for empirical and expert scrutiny.

The paper also performs no cost-benefit optimization of the Table 4 roadmap, and Table 5's KPI baselines are deliberately left unspecified pending the Phase 0 baselining that the roadmap proposes, rather than being populated with placeholder numbers that might misrepresent current evidence. The architecture has not yet been field-validated as an integrated system; Section 3.7's evidence supports the feasibility of individual layers, not NESI-X's validated performance as a whole. Nigeria's regulatory conditions, particularly the state transition process and FoNER's evolving mandate, remain in flux, and data availability for empirical validation may itself be constrained by the same institutional immaturity the architecture seeks to address.

6.2 International Relevance and Transferability

NESI-X is specifically developed for Nigeria, and its evidence base is entirely Nigerian. However, the underlying architecture - distinguishing bypassable technological pathways from indispensable physical and institutional infrastructure and coupling transformation capabilities to enabling conditions through an explicit dependency structure - is not specific to Nigerian institutional detail in its logic, even though it is specific to Nigerian institutions in its evidence. The architecture is plausibly transferable, as a conceptual template rather than a ready-made solution, to electricity systems sharing a similar combination of conditions: weak grid reliability alongside rapid DER growth,

regulatory authority fragmented across sub-national jurisdictions, high technical and commercial losses, limited digital grid infrastructure, and an active energy-access agenda. Nigeria serves as the primary application context for this paper, but it does not limit its theoretical relevance; testing the transferability of these findings to other national contexts with similar conditions - for example, elsewhere in Sub-Saharan Africa and South Asia - is a natural extension of the empirical agenda above, although this paper does not pursue that comparison directly.

6.3 Conclusion

NESI's persistent electricity problems are better understood as a coupled system than as a collection of isolated technical defects to be addressed one at a time. Verified regulatory evidence shows substantial ATC&C losses and quarterly revenue leakage exceeding ₦139 billion across DisCos, while current Nigerian policy is simultaneously opening genuine pathways for decentralized generation, digital grid intelligence, and multi-level governance. NESI-X's central proposition is that Nigeria can leapfrog selected technological pathways in generation, distribution, metering, monitoring, and maintenance but cannot leapfrog the non-bypassable system dependencies - governance, technical assurance, and liquidity, alongside the transmission backbone itself - that make an electricity system work.

Technical assurance, positioned in Section 3.5 as a cross-cutting spine rather than a fifth layer, is a further institutional requirement in its own right: as NESI decentralizes and digitalizes, infrastructure expansion must be matched by effective inspection, testing, certification, and safety assurance, or deployment will simply outrun the system's ability to verify that what has been built is safe and fit for purpose. NESI-X positions NEMSA as a technical-assurance spine connecting physical infrastructure, digital asset intelligence, regulatory governance, and revenue assurance, with a proposed contribution extending beyond conventional compliance toward integrating verified technical-condition data into asset management and risk-informed planning. As Section 6.2 argues, this coupling of bypassable technology to non-bypassable assurance is plausibly relevant wherever rapid DER growth meets fragmented governance and weak technical oversight, with Nigeria as this paper's primary evidence base rather than its outer boundary.

The roadmap in Section 4 is gated rather than calendar-driven because institutional readiness, skills, technical-assurance capacity, cybersecurity, interoperability, and financing determine whether investment actually translates into reliable and safe electricity, not the simple passage of time. The immediate research agenda is the empirical validation of P1-P5: quantifying the causal loops introduced in Section 2.4 against multi-year NERC, TCN, NISO, DisCo, NEMSA, and market data as it becomes available; evaluating pilot DER and digital-twin deployments as they are commissioned; and testing directly whether enabling-condition maturity constrains transformation-capability outcomes in the way the architecture predicts. NESI-X should ultimately be judged not by the elegance of its architecture but by whether these measurable outcomes improve as it is applied and tested against Nigerian evidence.

REFERENCES

- Adeku, A. Y., Yusufu, F. O., Yakubu, A., Abubakar, U., & Ozomata, L. J. (2026). Electricity Sector Reforms and Power Supply Reliability in Nigeria: Post-Privatization Realities and Prospects. *International Journal of Public Administration and Development Studies (IJPADS)*, 3(2), 1-17. <https://ijpads.com/index.php/ijpads/article/view/96>
- Akunne, C. S., Nwoye, M. I., Adewale, B. A., & Abubakar, H. L. (2023). Strategy Formulation and Resource Availability Determinants in Performance of Electricity Distribution Companies in Nigeria. *Journal of Human Resource and Sustainability Studies*, 11(4).
- Babayomi, O. O., Olubayo, B., Denwigwe, I. H., Somefun, T. E., Adedaja, O. S., Somefun, C. T., Olukayode, K., & Attah, A. (2023). A review of renewable off-grid mini-grids in Sub-Saharan Africa. *Frontiers in Energy Research*, 10, 1089025. <https://doi.org/10.3389/fenrg.2022.1089025>

- Federal Ministry of Power. (2025). National Integrated Electricity Policy and Strategic Implementation Plan (NIEP-SIP). Federal Republic of Nigeria. <https://power.gov.ng/download/national-integrated-electricity-policy/>
- Federal Republic of Nigeria. (2023). Electricity Act, 2023. Federal Ministry of Power. <https://www.power.gov.ng/download/electricity-act-2023/>
- Idowu, S. S., Ibietan, J., & Olukotun, A. (2020). Privatization of power sector in Nigeria: An evaluation of Ibadan and Ikeja Electricity Distribution Companies performance (2005-2018). *International Journal of Public Administration*, 43(16), 1413-1420. <https://doi.org/10.1080/01900692.2019.1672183>
- Nemade, B., Maharana, K. K., Kulkarni, V., Srivardhankumar, C., & Shelar, M. (2024). Revolutionizing smart grid security: A holistic cyber defence strategy. *Frontiers in Artificial Intelligence*, 7, 1476422. <https://doi.org/10.3389/frai.2024.1476422>
- Nigerian Electricity Management Services Agency. (2015). NEMSA Act, 2015 (Act No. 6). https://nems.gov.ng/wp-content/uploads/2019/05/NEMSA_ACT_2015.pdf
- Nigerian Electricity Management Services Agency. (2023). Electricity Act, 2023. <https://nems.gov.ng/wp-content/uploads/2024/05/ELECTRICITY-ACT-2023.pdf>
- Nigerian Electricity Management Services Agency. (n.d.-b). Mandate. <https://nems.gov.ng>
- Nigerian Electricity Regulatory Commission. (2024). Order on the establishment of the Independent System Operator for the Nigerian Electricity Supply Industry (Order No. NERC/2024/45). <https://nerc.gov.ng/wp-content/uploads/2024/05/Order-on-the-Establishment-of-the-Independent-System-Operator-for-NESI-1.pdf>
- Nigerian Electricity Regulatory Commission. (2026a). 2025/Q4 quarterly report. https://nerc.gov.ng/wp-content/uploads/2026/04/2025_Q4-Report.pdf
- Nigerian Electricity Regulatory Commission. (2026b). Mini-grid regulations 2026. <https://nerc.gov.ng/wp-content/uploads/2026/04/Mini-Grid-Regulations-2026.pdf>
- Nigerian Electricity Regulatory Commission. (2026c, March 25). NERC, State Regulators inaugurate Forum of Nigerian Electricity Regulators (FoNER) to improve electricity regulation. <https://nerc.gov.ng/media/nerc-state-regulators-inaugurate-forum-of-nigerian-electricity-regulators-foner-to-improve-electricity-regulation/>
- Odje, M., Uhunmwangho, R., & Okedu, K. E. (2021). Aggregated technical commercial and collection loss mitigation through a smart metering application strategy. *Frontiers in Energy Research*, 9, 703265. <https://doi.org/10.3389/fenrg.2021.703265>
- Omowaye, O. J., Oladipo, O. E., Adejumbi, B. S., Ogunlade, M. A., Onibonoje, M. O., & Ibitoye, O. T. (2025). An AI-based predictive maintenance technique for smart grid components. *NIPES Journal of Science and Technology Research*, 7(2), Special Issue: SEB4SDG 2025, 3218–3222. <https://doi.org/10.37933/nipes/7.4.2025.SI385>
- Pei, L., Xu, C., Yin, X., & Zhang, J. (2024). Multi-agent deep reinforcement learning for cloud-based digital twins in power grid management. *Journal of Cloud Computing*, 13, 152. <https://doi.org/10.1186/s13677-024-00713-w>
- Ranawaka, A., Alahakoon, D., Sun, Y., & Hewapathirana, K. (2024). Leveraging the synergy of digital twins and artificial intelligence for sustainable power grids: A scoping review. *Energies*, 17(21), 5342. <https://doi.org/10.3390/en17215342>
- van Benthem, A. A. (2015). Energy leapfrogging. *Journal of the Association of Environmental and Resource Economists*, 2(1), 93-132. <https://doi.org/10.1086/680317>
- World Bank. (2024, June 30). Expanding Nigeria's mini grid market. Energy Sector Management Assistance Program. <https://www.worldbank.org/en/news/feature/2025/03/07/expanding-nigeria-s-mini-grid-market>
- Zhou, M., Yan, J., & Feng, D. (2019). Digital twin framework and its application to power grid online analysis. *CSEE Journal of Power and Energy Systems*, 5(3), 391-398. <https://doi.org/10.17775/CSEEJPES.2018.01460>