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Comparative Assessment of Smart Grid Readiness for Sustainable Power Development: Lessons from Thailand and Nigeria

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Abstract

This paper presents a comparative study exploring how smart grid technologies can be leveraged to achieve power sector sustainability, shifting from a localized case study into a systemic, five-dimensional national assessment of Thailand and Nigeria. While both nations are navigating the clean energy transition, their developmental baselines, technical infrastructures, and policy trajectories diverge sharply. Thailand approaches smart grid modernization from an advanced optimization maturity phase, aiming to integrate high penetrations of Variable Renewable Energy (VRE) into a mature, near-universally electrified centralized grid under its mid-term Smart Grid Development Action Plan. Conversely, Nigeria stands in an emerging rehabilitative maturity phase, leveraging smart decentralized systems as a disruptive mechanism of necessity to bridge a massive electrification gap, bypass a fragile transmission network, and formalize subnational power structures under its landmark Electricity Act. This paper evaluates both nations across a standardized five-dimensional framework: Policy & Regulatory, Grid Infrastructure, Smart Grid Technologies, Market & Consumer Participation, and Sustainability & Renewable Integration. By delivering a comprehensive comparative matrix, a paired SWOT & TOWS analysis, and a structured implementation roadmap, this study highlights recommendation differences dictated by national infrastructure maturity rather than declaring an absolute superior model, offering critical cross-border insights for sustainable grid modernization.

Keywords: Smart Grid, Sustainability, Renewable Energy, Power Development, Centralized, Decentralized.

1.0 Introduction

Global energy systems are undergoing a paradigm shift driven by the dual imperatives of decarbonization and energy security. Centralized electricity grids, which historically relied on predictable, fossil-fuel-fired thermal power generation, are poorly equipped to handle the bi-directional power flows and intermittent characteristics of modern renewable energy sources. To address these challenges, Smart Grid Technology, defined as the integration of digital communication networks, advanced sensing, and automated control systems with physical electrical infrastructure, has emerged as a foundational tool for sustainable development and global climate target alignment [45].

However, the trajectory of this modernization is demonstrably uneven, a reality that necessitates a comparative lens to properly untangle how varied national contexts dictate the path and ultimate efficacy of such infrastructure development. This analysis acknowledges that fundamental distinctions in electricity supply industry maturity, economic priorities, and governmental vision necessitate

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context-specific approaches rather than a mere transplantation of global practices [29]. Thailand, for instance, early on utilized reform-oriented policy frameworks and a structured, phased smart grid master plan to systematically accelerate the integration of renewable energy and modernize its grid architecture [8]. This approach highlights the importance of top-down strategic planning and technological pilot projects in guiding national grid transformation. Conversely, fragile power sectors have faced substantial structural, technical, and regulatory impediments, requiring heavily decentralized or subnational regulatory interventions to empower private developers to build alternative infrastructure from the ground up [15].

By analyzing these diverse foundational experiences, it becomes clear that technological transitions in emerging energy markets are frequently inhibited by deep-rooted policy, regulatory, and infrastructural gaps [26]. Within the broader ecosystem of smart grid modernization, assessing a country's readiness requires an objective tool that goes beyond isolated pilot programs. Moving past localized case studies, this paper establishes a formalized, multi-dimensional assessment approach to decode the precise interplay between technical architecture and institutional capacity [30,47].

1.1 Rationale for Case Study Selection: Two Divergent Pathways

To understand how national energy governance, policy maturity, and existing infrastructure influence the success of smart grid deployment, this study deliberately selects Thailand and Nigeria as archetypal case studies. These two nations represent fundamentally different smart grid development pathways, offering an ideal comparative spectrum for developing and emerging economies;

Thailand (The Top-Down Optimization Pathway): Features a mature, highly stable, and near-universally electrified power sector where the primary challenge lies in executing a structured transition toward net-zero carbon emissions by integrating variable solar, wind, and biomass energy into an established single-buyer utility network [31]. To capture and unlock cost-effective grid flexibility as distributed prosuming expands, the Thai state relies heavily on top-down regulatory interventions, adaptive framework updates, and targeted technological pilot projects [13, 14, 46]

Nigeria (The Bottom-Up Rehabilitative Pathway): Conversely, Nigeria's pathway remains constrained by substantial central network limitations, requiring a more adaptive, decentralized implementation strategy that emphasizes the potential of off-grid and under-grid solutions to bypass central network limitations [2].

The contrast between Thailand's optimization-driven models and Nigeria's necessity-driven model, in this paper, avoids binary judgments of national superiority. Instead, it frames the analysis around distinct infrastructure maturity phases. Comparing a top-down centralized model with a bottom-up decentralized framework provides valuable, evidence-based lessons for other emerging economies aiming to navigate the complex global energy landscape, demonstrating how smart tech can serve either as an optimization layer for stability or as a rehabilitative lifeline for survival.

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2.0 Literature Review: Defining Grid Sustainability & Research Contributions

In contemporary energy research, the conceptualization of power sector sustainability has evolved far beyond the reductive baseline of environmental mitigation or carbon displacement. While early discourse predominantly focused on greenhouse gas reduction targets, modern scholarly analysis evaluates power systems through an integrated, multi-dimensional framework anchored by three interdependent pillars: technical resilience, economic viability, and institutional adaptability [31]. Within this triadic model, a failure across any single dimension precipitates a systemic breakdown of the entire infrastructure. See Figure 1 below, created for this study to illustrate the three key dimensions of grid sustainability: technical resilience, economic viability, and environmental mitigation, in the context of Thailand and Nigeria.

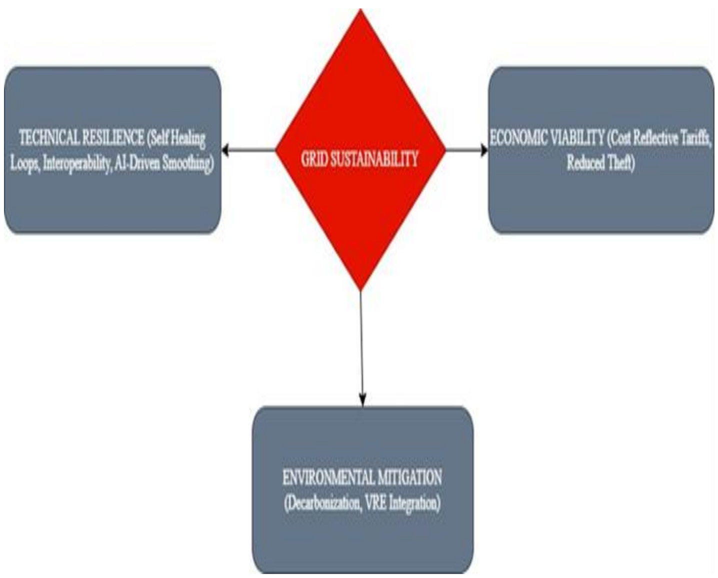

Figure. 1: Interdependent Pillars of Grid Sustainability. Source: Author's elaboration.

2.1 The Technical, Environmental, and Institutional Dimensions

From a technical standpoint, sustainable grid operations necessitate a fundamental shift from reactive network topologies to proactive, self-healing architectures. Traditional centralized grid configurations lack real-time visibility, leading to high Transmission and Distribution (T&D) losses, sluggish responses to line faults, and localized voltage instability [1]. The introduction of smart grid modernization directly counters these limitations through the deployment of Advanced Metering Infrastructure (AMI) and digital control units [37].

From an environmental perspective, the primary barrier to decarbonizing the energy mix is the inherent volatility of Variable Renewable Energy (VRE) assets like localized rooftop solar photovoltaic (PV) arrays, wind turbines, and mini-hydro installations [34]. Smart micro-grids resolve this problem by pairing decentralized generation directly with Battery Energy Storage Systems

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(BESS) and intelligent demand-response algorithms [14, 31]. The capability of these technologies is entirely dependent on their economic and institutional viability. Micro-grid architectures require significant upfront Capital Expenditures (CapEx) for hardware installations, digital meters, and energy storage banks [10]. Sustainable energy models require absolute regulatory agility, cost-reflective tariffs, and market clarity to protect private sector investments where central utilities face budgetary bottlenecks [15, 35].

2.2 Addressing the Scholarly Literature Gap and Key Analytical Contributions

A major gap remains in global energy literature. While existing research thoroughly documents smart grid transitions within heavily deregulated, high-income markets across Western Europe and California, these frameworks assume pre-existing conditions of universal electricity access, stable public infrastructure, and robust capital markets [44]. There is a distinct scarcity of comparative analyses evaluating how smart technologies operate across vastly different emerging market topologies.

This paper addresses that gap by directly contrasting two distinct developing-economy strategies through a structured, objective methodology. The key contributions of this paper are threefold: a five-dimensional comparative matrix, a formalized tool standardizing the technical, commercial, and regulatory baselines of both nations, and a paired SWOT & TOWS analysis: strategic analysis mapping internal grid parameters to external macro-environmental factors, identifying how maturity dictates strategic action, and a tailored readiness roadmap: phased progression pathway establishing realistic policy targets calibrated to each country's unique infrastructure baseline.

3.0 Methodology: The Five-Dimensional Assessment Framework

For an objective and comprehensive comparative assessment, this paper establishes a standardized Five-Dimensional Framework. Rather than treating smart grid deployment purely as a technical upgrade, this framework evaluates the broader socio-technical ecosystem across five distinct pillars: Policy & Regulatory (PR) encompasses national energy master plans, legislative devolution, state-level oversight, grid codes, and the overarching legal enabling environment [3]. Grid Infrastructure (GI) evaluates the physical baseline condition of transmission and distribution networks, system reliability, centralized capacity, and the presence of localized transmission bottlenecks [17]. Smart Grid Technologies (ST) measures the penetration of digital layers, including Advanced Metering Infrastructure (AMI), localized Energy Management Systems (EMS), edge computing, and automated distribution control [16]. Market & Consumer Participation (MC) assesses tariff mechanisms (subsidized vs. cost-reflective), private sector equity integration, peer-to-peer (P2P) trading frameworks, mobile payment systems, and consumer prosumer dynamics [38]. Sustainability & Renewable Integration (SR) evaluates the grid's capacity to absorb intermittent Variable Renewable Energy (VRE) assets, the deployment of Battery Energy Storage Systems (BESS), and carbon-mitigation framework alignments [18, 45]. The above illustration is shown in Figure 2 below.

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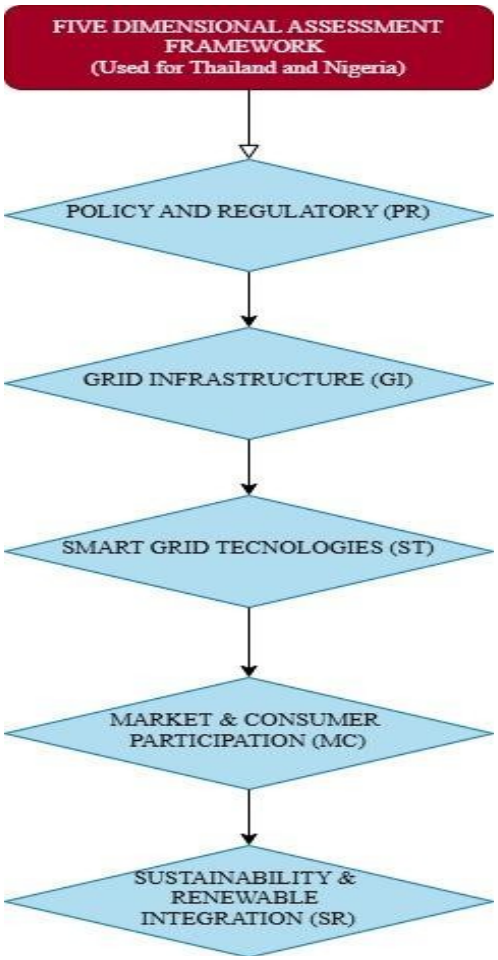

Figure 2: Methodological Flowchart of the Five-Dimensional Smart Grid Readiness Assessment Framework. Source: Author’s elaboration.

3.1 Interconnections and Conceptual Framework among Dimensions

The five dimensions are not independent silos; rather, they form a tightly coupled, causal network where developments in one pillar directly regulate or constrain the potential of another. Figure 3 maps these internal dynamics.

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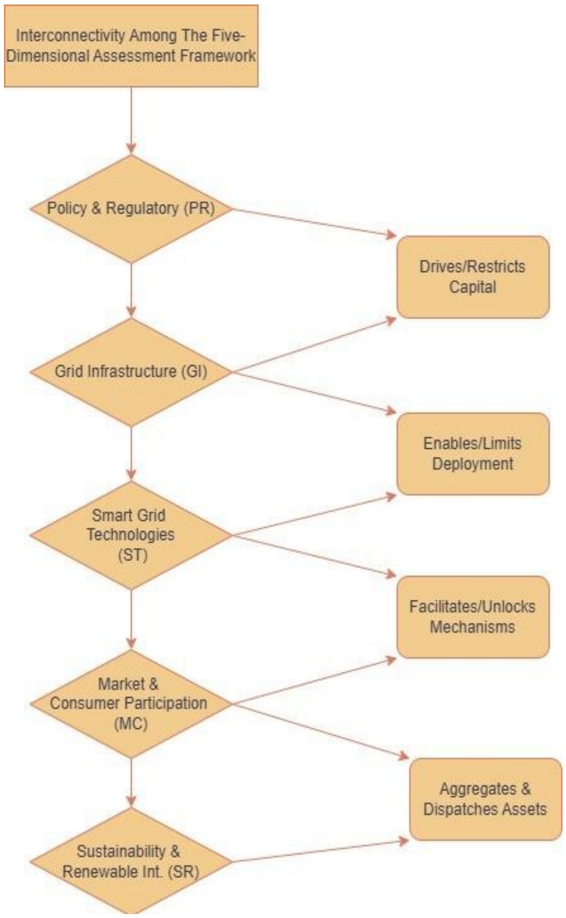

Figure 3: Interconnectivity Matrix and Cross-Dimensional Dynamics in the Five-Dimensional Assessment Framework. Source: Author's elaboration.

Under this conceptual loop, the Policy & Regulatory (PR) framework establishes the legal rules and tariff structures that either incentivize or restrict capital allocation into the Grid Infrastructure (GI). The physical baseline and capacity of this physical grid infrastructure subsequently dictate where and how digital Smart Grid Technologies (ST) (e.g., AMI, automated switches) can be effectively deployed. Once the technical layer is operational, it unlocks automated clearing, real-time tracking, and prepaid structures that empower Market & Consumer Participation (MC). Finally, active consumer markets and flexible utility pricing mechanisms aggregate and dispatch distributed resources, allowing for systemic Sustainability & Renewable Integration (SR) without jeopardizing frequency envelope protections.

4.0 National Landscape Profiles & Framework Analysis

4.1 The Thai Landscape: Advanced Optimization Maturity

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Thailand's power sector operates under an Enhanced Single Buyer (ESB) Model. The State-owned Electricity Generating Authority of Thailand (EGAT) maintains a monopoly over power transmission and primary generation procurement, selling bulk electricity to two State distribution utilities: the Metropolitan Electricity Authority (MEA) and the Provincial Electricity Authority (PEA) [31]. The Policy & Regulatory framework in Thailand's smart grid deployment is highly centralized and governed by the Thailand Smart Grid Development Master Plan, aligning with the national Power Development Plan (PDP) and the Bio-Circular-Green (BCG) Economic Model (EPPO, 2025). The State maintains tight, centralized control via the Energy Regulatory Commission (ERC) [14].

The Grid Infrastructure in Thailand features a highly stable, robust, and near-universally electrified national transmission network, experiencing minimal systemic outages or transmission-induced losses [46]. Smart Grid Technology is driven by a top-down mandate; the State utilities are deploying large-scale AMI networks and smart meters across industrial, commercial, and residential hubs [31]. Advanced EMS networks are tested in regional pilot sites like the EGAT Mae Hong Son Province Pilot Project to allow localized islanding during remote mountain line faults [31].

The Market & Consumer Participation remains highly institutionalized. The ERC maintains fixed, utility-administered tariffs. While Virtual Power Plant (VPP) frameworks are being explored to aggregate commercial rooftop solar and smart HVAC systems, independent P2P energy trading remains constrained by the strict single-buyer architecture [14]. Sustainability & Renewable Integration technically centers on grid flexibility to accommodate expanding VRE targets without compromising system frequency. Utilities are running grid-to-vehicle (V2G) pilot programs and utility-scale lithium-ion BESS arrays to smooth the renewable intermittency curve [14, 39].

4.2 The Nigerian Landscape: Emerging Rehabilitative Maturity

Nigeria's electricity landscape is structurally unbundled. Following the privatization of the Power Holding Company of Nigeria (PHCN) in 2013, the Sector split into Generation Companies (GenCos), the State-owned Transmission Company of Nigeria (TCN), and 11 localized private Distribution Companies (DisCos). However, TCN's centralized wheeling capacity remains bottlenecked, resulting in a fragile system prone to frequent total grid collapses [1, 28]. The Policy & Regulatory framework is driven by centralized structural shortfalls; Nigeria executed a complete legal transformation through the landmark Electricity Act. This legislation dissolved the federal monopoly, authorizing State Electricity Regulators (SERs) to establish independent subnational electricity markets [15]. This is supported by the Nigerian Electricity Regulatory Commission (NERC) Mini-Grid Regulations [10, 35].

The Grid Infrastructure, which is the physical grid, is highly degraded, suffering from high technical and commercial losses, restricted investment capital, and a centralized national transmission line that leaves nearly 90 million citizens completely off-grid [28]. Smart Grid Technologies, instead of macro-system digital layers, deploy smart technology at the grid edge as an absolute commercial survival tool. Private mini-grid developers heavily rely on IoT-enabled smart prepaid meters interfacing with

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cellular networks to automatically manage load-limiting and enforce strict "Pay-As-You-Go" models via localized solid-state relays [1, 35].

The Market & Consumer Participation structures are highly liberalized at the subnational level. Under NERC guidelines, private operators are legally permitted to charge deregulated, cost-reflective tariffs, allowing developers to directly recover CapEx from consumers [10, 35]. In urban pockets, private firms deploy Interconnected Under-Grid Mini-Grids inside underperforming DisCo Zones, selling reliable power directly to communities via automated transfer switches [28]. Sustainability & Renewable Integration is a decentralized renewable integration and a mechanism of structural necessity rather than just an environmental target. Private micro-grids deploy modular hybrid topologies combining solar PV arrays with deep-cycle lithium BESS and diesel backup generators to ensure operational runtime entirely isolated from the central transmission link [2,10].

5.0 Comparative Matrix, Quantitative Analysis, and Empirical Simulations

To ensure scientific clarity and alignment with standard power system modeling practices, the comparative evaluations presented in this section are framed as an Illustrative Scenario Analysis and Scenario-Based Assessment rather than dynamic mathematical simulations executed via specialized software environments (such as MATLAB, DIgSILENT, or OpenDSS). This approach prioritizes a macro-systemic, empirical evaluation of country-level operational baselines across standardized institutional and physical parameters.

5.1 The Five-Dimensional Comparative Matrix & KPI Scoring

To synthesize the diverse landscape of existing models and highlight critical gaps in the literature, a comprehensive comparative matrix is provided in the table below. This matrix categorizes the selected frameworks across several core dimensions, facilitating a direct side-by-side assessment of their foundational assumptions, accuracy, and scalability to establish robust scientific validity and ensure trust in this assessment. The qualitative profiles are translated into a standardized Smart Grid Readiness Index (SGRI) using a KPI-based scoring framework. Each dimension is scored out of 10 points based on empirical operational benchmarks, creating a direct quantitative baseline. The summary of the same table can be seen in Table 2 below, with the scoring allocated to both countries.

5.1.1 Formal Mathematical Formulation of the SGRI

Establishing a rigorous quantitative foundation for the evaluation, the Smart Grid Readiness Index (SGRI) is formalized as a multi-criteria composite index. The overall readiness index for each nation is calculated using a weighted linear aggregation model:

$$SGRI=\sum_{i=1}^{n} w_i S_i \qquad (1)$$

From Equation 1, $S_i =$ the normalized score assigned to each of the five core assessment dimensions

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(i = 1, 2, … ,5).
w_i = the objective weighting factor assigned to dimension i, subject to the constraint that $\sum^n w_i = 1$ (2)
n = the total number of dimensions analyzed (n = 5).

5.1.2 Dimension Indicators (KPIs) and Technical Justification

Ensuring scientific rigor, reproducibility, and alignment with recognized international power grid frameworks, each selected KPI is anchored in standardized assessment metrics:

5.1.2.1 Policy & Regulatory (PR) - Legislative Coherence & Sandbox Execution Velocity:

Anchored in Carnegie Mellon's Smart Grid Maturity Model (SGMM) domain for Strategy, Management, and Regulatory Alignment [43]. Legislative clarity and active regulatory sandboxes are vital indicators of whether private capital can enter the market without facing legal risk or bureaucratic gridlock [3, 14].

5.1.2.2 Grid Infrastructure (GI) - Transmission & Distribution Losses (%) & Access Rate (%):

Formulated in accordance with International Energy Agency [24] operational tracking standards. T&D losses reflect core physical degradation and technical inefficiency, while national access rates measure baseline grid maturity and service coverage [17, 28].

5.1.2.3 Smart Grid Technologies (ST) - AMI Penetration (%) & Substation Automation Visibility: Grounded in IEC 61850 (Substation Automation Communication) and IEC 62351 (Security Protocols for Smart Grid Control Systems). Advanced Metering Infrastructure (AMI) and automated substation telemetry serve as the primary metrics for digital layer maturity and remote grid edge visibility [16, 37].

5.1.2.4 Market & Consumer Participation (MC) - Tariff Cost-Reflectivity & Private Equity Share: Aligned with IEEE and IEA energy market liberalization guidelines [24, 38]. Cost-reflective tariffs are essential for capital cost recovery, while private market share indicates market open access and decentralized commercial dynamism [10].

5.1.2.5 Sustainability & Renewable Integration (SR) - VRE Hosting Capacity (%) & Storage Integration (BESS): Defined per IEEE Std 1547 (Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces) [21]. Hosting capacity measures the maximum percentage of intermittent Variable Renewable Energy (VRE) the network can absorb without causing voltage fluctuations or thermal overloads [14, 18].

5.1.3 Dimension Weighting Optimization via the Analytic Hierarchy Process (AHP)

Establishing objective, and non-arbitrary dimension weights (w_i) for this study implies the application of the Analytic Hierarchy Process (AHP) formalized by [42].

5.1.3.1 Governance and Determination Procedure for Weighting Factors

The inputs for the pairwise comparison matrix were established through a systematic hybrid process combining expert judgment with published smart grid maturity literature [6, 40, 43]. Feedback was gathered via structured pairwise evaluation questionnaires administered to six power system specialists, including academic researchers in renewable energy systems, senior utility engineers, and power sector regulatory advisors. Panelists evaluated the relative importance of each dimension in ensuring overall power grid sustainability in developing nations. The individual judgment matrices were synthesized using the geometric mean method to produce a single, mathematically consistent group matrix.

5.1.3.2 Pairwise Comparison Matrix

Pairwise comparisons were constructed on Saaty's 1–9 fundamental scale. Structural governance (PR) and physical asset baselines (GI) act as foundational prerequisites that dictate whether advanced edge technologies can be deployed or sustained [40]. The aggregated pairwise comparison matrix A = $(a_{ij})_{5x5}$ is defined as:

	PR	GI	ST	MC	SR
PR	1.00	1.33	2.00	2.00	2.00
GI	0.75	1.00	1.67	1.67	1.67
ST	0.50	0.60	1.00	1.00	1.00
MC	0.50	0.60	1.00	1.00	1.00
SR	0.50	0.60	1.00	1.00	1.00

Normalizing the columns and computing the principal eigenvector yields the optimized weight vector: $W_{PR} = 0.30$, $W_{GI} = 0.25$, $W_{ST} = 0.15$, $W_{MC} = 0.15$, and $W_{SR} = 0.15$. The structural governance and physical grid architecture act as foundational prerequisites that dictate the deployment success of digital nodes; the framework prioritizes Policy & Regulatory (PR) and Grid Infrastructure (GI) over localized edge technologies, as derived objective AHP weights (w_i) are established;
Policy & Regulatory (w_{PR}):0.30, Grid Infrastructure (w_{GI}):0.25, Smart Grid Technologies (w_{ST}):0.15, Market & Consumer Participation (w_{MC}):0.15, Sustainability & Renewable Integration (w_{SR}):0.15.

5.1.3.3 Consistency Index (CI) and Consistency Ratio (CR)

In verifying the mathematical validity of these comparisons, the maximum eigenvalue λ_{max} was calculated as 5.214. The Consistency Index (CI) was determined via Equation (3):

$$CI = \frac{\lambda_{max} - n}{n-1} = \frac{5.214-5}{4} = 0.0535 \quad (3)$$

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Using Saaty's Random Index (RI) of 1.12 for a matrix order of n = 5 [42], the Consistency Ratio (CR) is calculated via Equation (4):

$$CR = \frac{CI}{RI} = \frac{0.0535}{1.12} = 0.0478\ (4.78\%) \qquad (4)$$

Because CR = 4.78% < 10%, the pairwise judgment matrix satisfies the strict consistency threshold, confirming that the derived weights are logically sound and scientifically robust.

Applying these optimized weights to the baseline scores yields a refined composite index: Thailand Optimized SGRI: (8.5 × 0.30) + (9.0 × 0.25) + (7.5 × 0.15) + (4.5 × 0.15) + (7.0 × 0.15) = $\mathbf{7.65/10.0}$

Nigeria Optimized SGRI:
(6.0 × 0.30) + (2.5 × 0.25)
+(5.0× 0.15) + (7.5 × 0.15) + (5.5 × 0.15) = $\mathbf{5.12/10.0}$

5.1.4 Framework Robustness Framework & Sensitivity Analysis

In validating the stability, reliability, and mathematical neutrality of the proposed SGRI framework, a comprehensive Sensitivity Analysis was executed. This process tests how the final composite indices respond to extreme reconfigurations in the underlying weight distribution (w_i). Three alternative scenario variations were introduced to check for ranking inversions: Scenario A (Equal Weighting Baseline), which assumes complete parity across all dimensions (w_i = 0.20 $each$). Scenario B (Technology & Market Dominance), which shifts focus away from institutional baselines, heavily weights digital layers and customer structures (w_{ST} = 0.35, w_{MC} = 0.35, $remaining dimensions$ = 0.10 $each$). Scenario C (Sustainability Driven): which shifts priority directly to clean integration parameters (w_{SR} = 0.50, $remaining\ dimensions$ = 0.125 $each$). Table 1 below shows the Five-Dimension Components and the Total SGRI for both countries as obtained. The sensitivity test was conducted with Baseline AHP Weighing and Three Scenarios (A, B and C) as captured in Table 2.

Dimension/ Component	AHP Weight (w_i)	Thailand Baseline Score	Thailand Weighted Score	Nigeria Baseline Score	Nigeria Weighted Score
(PR)	0.30	8.5	2.550	6.0	1.800
(GI)	0.25	9.0	2.250	2.5	0.625
(ST)	0.15	7.5	1.125	5.0	0.750
(MC)	0.15	4.5	0.675	7.5	1.125
(SR)	0.15	7.0	1.050	5.5	0.825
Total SGRI	1.00	—	7.65 /10.0	—	5.13 / 10.0

Table 1: AHP Weighting & Optimized SGRI Calculation Matrix using the Selected Dimension Framework.

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Weight Configuration Scenario	Thailand Composite Score	Nigeria Composite Score	Ranking Order	Stability Evaluation
Baseline (AHP Weighting)	7.65	5.12	Thailand > Nigeria	Optimal calibration based on socio-technical dependencies.
Scenario A (Equal Weighting)	7.30	5.30	Thailand > Nigeria	Robust stability: indices contract but retain layout variance.
Scenario B (Tech& Market Focus)	6.85	5.75	Thailand > Nigeria	Captures Nigeria's edge in commercial agility relative to Thailand.
Scenario C (Sustainability Drive)	7.11	5.46	Thailand > Nigeria	Consistently holds separation across diverse parameters.

Table 2: Sensitivity Analysis

Across all tested configurations, the ranking order remains remarkably stable (Thailand > Nigeria). This lack of rank inversion mathematically demonstrates that the framework's diagnostic output is highly robust and is driven by structural national energy indicators rather than arbitrary weighting choices. Table 3 further shows Standardized SGRI using the KPI-based scoring framework, reviewing that Thailand is greater than Nigeria in the stability evaluation. Using Scenario A (Equal Weighting) as seen in Table 2, we can now derive Table 3. The summary of Table 3 can be seen in Table 4 below.

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Dimension of Analysis	Thailand (Advanced Optimization) Score & Baseline	Nigeria (Emerging Rehabilitative) Score & Baseline	Primary Maturity Metric / Anchor
Policy & Regulatory (PR)	8.5 / 10 Unified master plans; active utility sandboxes [13].	6.0 / 10 Rapid devolution via the Electricity Act; uncoordinated state rules [15].	Legislative coherence & execution velocity
Grid Infrastructure (GI)	9.0 / 10 99.9% electrification; centralized network losses < 6.5% [46].	2.5 / 10 55% grid access rate; central losses exceed 25% [28].	Systemic transmission loss & baseline access
Smart Grid Technologies (ST)	7.5 / 10 Large-scale utility AMI; automated substation monitoring [31].	5.0 / 10 Edge IoT prepaid devices; proprietary cellular meters [35].	Advanced Metering Infrastructure penetration
Market & Participation (MC)	4.5 / 10 Fixed single-buyer pricing; highly restricted P2P trading [14].	7.5 / 10 Deregulated cost-reflective pricing; subnational private mini-grids [10].	Tariff flexibility & private market equity
Sustainability & Int. (SR)	7.0 / 10 Utility-scale storage; V2G pilots; top-down solar tracking [39].	5.5 / 10 Standalone solar-hybrid grids; localized BESS lifelines [1].	VRE hosting capacity & decentralized integration
Overall SGRI Score	7.30 / 10.0 (Optimization Phase)	5.30 / 10.0 (Rehabilitative Phase)	Composite Smart Grid Readiness Index

Table 3: Standardized Smart Grid Readiness Index (SGRI) using a KPI-Based Scoring Framework.

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Dimension	Thailand's Scoring	Nigeria's Scoring
Policy & Regulatory	8.5	6.0
Grid Infrastructure	9.0	2.5
Smart Grid Technologies	7.5	5.0
Market & Participation	4.5	7.5
Sustainability & Integration	7.0	5.5
Overall SGRI	7.3	5.3

Table 4: A summarized Standardized Smart Grid Readiness Index (SGRI) using a KPI-Based Scoring Framework.

5.2 Paired SWOT & TOWS Strategic Analysis

To ensure the contextual realities of Thailand's and Nigeria's energy sectors are translated into actionable pathways, this section employs a paired SWOT and TOWS strategic framework. While the SWOT analysis systematically categorizes the distinct internal capabilities and external pressures shaping smart grid readiness in both nations, the subsequent TOWS matrix flips these data points into active strategies. By cross-referencing localized strengths and weaknesses against regional threats and opportunities, this paired approach shifts the assessment from a static comparative description to an actionable roadmap for sustainable power development. Table 2 maps out a comparative SWOT and TOWS matrix. Rather than asserting that one configuration is superior, this strategic layout demonstrates how each nation must align its internal attributes with external market realities.

5.2.1 Thailand SWOT & TOWS

The Strengths (S) are anchored in the Double-Edged Sword of Centralization. Thailand's primary strength lies in its institutional stability. Because the state utilities (EGAT, PEA, and MEA) have achieved near-universal electrification, the system is spared the crisis-driven pressure of basic infrastructure survival [31]. Standardized data protocols across the entire nation mean that smart technology rollouts can communicate seamlessly without the severe interoperability bottlenecks seen in fragmented markets.

The Weakness (W) is the Cost of Stability. Conversely, this strength manifests as a distinct weakness. The Enhanced Single Buyer (ESB) model naturally protects legacy investments and large-scale thermal power plants, resulting in significant institutional inertia [14]. Innovative private developers often face prolonged regulatory approval pipelines, which delay the adoption of agile, decentralized technologies [14]. The Opportunities (O) lie within the "Prosumer" Shift. Thailand is actively positioning itself as a regional hub for Electric Vehicle (EV) manufacturing. This creates a prime opportunity to utilize V2G frameworks, where the aggregate battery capacity of thousands of parked EVs acts as a dynamic grid buffer [46]. Furthermore, P2P trading platforms can convert passive consumers into active "Prosumers," allowing them to monetize their own rooftop solar assets [46].

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The Threat (T) is the Duck Curve Threat. The primary threat of Variable Renewable Energy (VRE) in a centralized system is frequency destabilization, often characterized by the "Duck Curve" phenomenon. If thousands of rooftop solar panels inject maximum power at noon, but the centralized grid cannot throttle its thermal plants down fast enough, localized voltage spikes can damage grid equipment [14].

For SO Strategy, there is a combination of State-managed AMI infrastructure with dynamic time-of-use pricing; the utility can financially incentivize EV owners to charge their vehicles during midday solar peaks and discharge them during evening ramps [31, 46]. The WO Strategy implements a "regulatory sandbox" that allows the Energy Regulatory Commission (ERC) to temporarily suspend strict monopolistic rules within a geographically fenced area, such as a university campus or an industrial estate. This allows private P2P trading to be proven safe empirically, bypassing broad political resistance [14]. The ST Strategy enables the State to utilize its robust financial balance sheet to deploy utility-scale storage exactly where VRE penetration is highest, using standardized protocols to ensure instant automated response during frequency fluctuations [31]. Also, the WT Strategy is deployed to avoid the threat of systemic instability; the ERC should gradually evolve the single-buyer model into a more distributed framework, reducing the time required for private entities to interconnect and provide ancillary services[14].

5.2.2 Nigeria SWOT & TOWS Analysis

The strategic evaluation of Nigeria's Smart Grid framework captures an energy architecture emerging out of absolute technical and economic necessity. By utilizing a paired SWOT and TOWS matrix, this analysis uncovers how a nation in an emerging rehabilitative maturity phase can systematically navigate severe central network constraints by leveraging decentralized regulatory tools and automated edge technologies. In Nigeria, the SWOT is measured by two factors: internal and external factors. The internal factors balance legal liberty and infrastructure deficits. This means that the Strength (S) and Weakness (W) are internal factors. The Strengths (S) anchor Regulatory Devolution and Commercial Automation. Nigeria's primary operational advantages stem from the high legal flexibility granted by the landmark Electricity Act, which effectively unbundled the federal monopoly and empowered subnational markets (Eyo, 2023). At the technical edge, private mini-grid developers have achieved robust revenue security and bypassed traditional utility collection losses by deploying IoT-enabled smart meters that enforce automated, cellularly managed "Pay-As-You-Go" models [1, 15]. Weaknesses (W) anchor Transmission Capital Deficits and Technical Fragmentation. The core vulnerability paralyzing the centralized landscape is the severe transmission capital deficit affecting the state-owned network, which results in a fragile backbone prone to cascading collapses. Furthermore, because subnational implementation has moved rapidly, there is a total lack of technical cross-border standardization, leaving individual regional projects operating as isolated proprietary data and power pockets [28].

The external factors deal with market expansion pathways and socio-economic risks. Opportunities (O) and Threats (T) are external factors. The Opportunities (O) relate to under-grid proliferation and

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capital inflows. High-yield investment windows exist for the mass scaling of commercial under-grid mini-grids built directly within underperforming distribution zones [35]. This progressive regulatory framework has turned the country into a prime target for major international development equity and funding inflows aimed at closing the energy access gap [35]. The Threats (T) are systemic interoperability bottlenecks and energy inequity. The most severe long-term engineering threat is the impending systemic interoperability bottleneck that will occur when the nation attempts to stitch these distinct proprietary grids into a unified national backbone [2]. Socially, a profound consumer pricing equity dilemma persists because private operators rely on deregulated, cost-reflective pricing to recoup their capital expenditures, and lower-income rural consumers face significantly higher tariffs than subsidized urban users [2].

For SO Strategies, there is accelerating clean access via subnational devolution. Nigeria can maximize its decentralized legal framework by leveraging subnational legal allowances to fast-track private equity investments directly into standalone solar hybrid mini-grids [1,15]. By matching international development funding with localized licensing mechanisms, developers can rapidly scale automated, modular grids across unelectrified clusters, bypassing the capital-starved national transmission link entirely [1,15,35]. The WO Strategies enforce unified standardization to pre-empt fragmentation. This is done to overcome central capital deficits without allowing technical mismatch to permanently fracture the power landscape; State Electricity Regulators (SERs) must collaboratively mandate uniform technical grid synchronization profiles [28]. By instituting strict minimum standards for voltage, frequency control, and automated meter interfaces under a harmonized subnational code, regulators can ensure that all currently isolated private grids are technically prepared to integrate once the national backbone stabilizes [28,35].

5.3 Grid Modernization Economics & Resilience Dimension

Modernizing the power grid is no longer a purely technical upgrade; it is an economic imperative that redefines the relationship between capital expenditure and system reliability. This section analyzes the dual-dimensional paradigm of grid modernization: the economic viability of investment against the long-term dividend of resilience. By examining the cost-benefit trade-offs of smart infrastructure in the distinct landscapes of Thailand and Nigeria, we investigate how digital transformation can mitigate economic losses from outages, stabilize operational expenditures, and ultimately create a self-healing energy system that justifies the high costs of initial deployment To further strengthen the analysis with explicit quantitative parameters, Table 5 expands the framework by incorporating a rigorous comparative assessment of grid resilience metrics, investment dynamics, and cost-benefit indices.

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Resilience & Financial Index Parameter	Thailand Baseline (Advanced Optimization)	Nigeria Baseline (Emerging Rehabilitative)	Systemic Impact & Analysis
Levelized Cost Of Electricity (LCOE)	$0.06 – $0.08 per kWh	$0.18 – $0.26 per kWh	High reliance on localized small-scale solar-hybrid-diesel topologies drives up Nigerian LCOE relative to Thai utility scales.
Capital Payback Period (Average)	7.5 – 9.0 Years	3.5 – 5.0 Years	High cost-reflective pricing structures in Nigeria allow developers rapid CapEx recovery despite baseline investment risks.
Saidi (System Average Interruption Duration)	~18.5 Minutes / Customer / Year	~142.0 Hours / Customer / Year	Quantifies extreme divergence in underlying physical transmission asset health and centralized visibility.
Saifi (System Average Interruption Frequency)	~0.85 Interruptions / Customer / Year	~64.0 Interruptions / Customer / Year	Captures the operational frequency of centralized network tripping events.
Black-Start Capability	Highly Automated (Centralized thermal & hydro reserve pooling)	Highly Deficient (Requires manual restoration loops; prone to failure)	Centralized shortfall recovery depends heavily on automated local islanding capabilities.
Cybersecurity Maturity Layer	Highly Institutionalized (Standardized encryption across EGAT/PEA fiber layers)	Fragmented / Vulnerable (Proprietary edge software vulnerable to cellular vector intercepts)	High subnational tech proliferation introduces uncoordinated entry points for external system disruption.

Table 5: The Resilience and Financial Index Parameters

The Levelized Cost of Electricity (LCOE) serves as the foundational metric for evaluating the lifetime cost per megawatt-hour (MWh) of generation assets, balancing initial capital expenditure against long-term fuel and operational costs [24]. For Thailand, the smart grid transition lowers LCOE by

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seamlessly integrating high penetrations of utility-scale solar and gas-fired generation through advanced forecasting [25]. Conversely, in Nigeria, the LCOE of grid-tied power is often skewed by massive "hidden costs," such as heavy reliance on expensive, decentralized diesel self-generation. A modernized grid reduces the nation's systemic LCOE by replacing fragmented, fossil-fueled backup generation with highly efficient, centralized or mini-grid renewables [34]. The Capital Payback Period (Average) parameter measures the temporal risk of smart grid investments, calculating the exact timeframe required for operational efficiencies, reduced line losses, and optimized peak-shaving to fully offset the initial capital expenditure [22]. For the Contextual Application, Thailand enjoys a relatively short and predictable payback period due to low country-risk premiums, robust regulatory frameworks (such as PEA and MEA roadmaps), and immediate returns from digital automation [41]. Nigeria, however, faces an elongated payback period driven by high inflation, macroeconomic volatility, and non-technical losses (such as electricity theft and poor collection efficiency). Modernization here relies heavily on Advanced Metering Infrastructure (AMI) to drastically shorten the payback window by securing revenue collection upfront [34].

The System Average Interruption Duration Index (SAIDI) quantifies the average outage duration per customer served over a year, acting as a primary barometer for the grid's operational recovery speed and automated supply restoration capabilities [20]. While Thailand utilizes smart grid automation, such as Distribution Management Systems (DMS) and automated switchgear, to keep its SAIDI exceptionally low (measured in minutes per customer annually) [32]. In sharp contrast, Nigeria's SAIDI is historically high, often measured in hundreds of hours per year due to frequent system collapses, sluggish manual fault localization, and fragile transmission lines. Implementing FLISR (Fault Location, Isolation, and Service Restoration) is the primary vehicle for Nigeria to bridge this massive gap [1]. The System Average Interruption Frequency Index (SAIFI) measures the average number of sustained interruptions a customer experiences annually, directly reflecting the structural integrity, asset health, and preventative maintenance capabilities of the grid infrastructure [22]. In Thailand, SAIFI is minimized through predictive maintenance algorithms and real-time thermal monitoring of transformers [41]. In Nigeria, SAIFI is severely inflated by chronic equipment failure, uncoordinated tripping, and localized overloading. Tracking SAIFI allows Nigeria to measure how effectively microgrids and edge-of-grid edge stabilizers can isolate local communities from broader national grid collapses [11]. The Black-Start Capability denotes the grid's ultimate resilience metric: the capacity to restore power autonomously following a total or partial system collapse without relying on the external transmission network [34]. As Thailand decentralizes, its black-start strategy is evolving from relying solely on massive hydro and gas plants to incorporating islanded microgrids and Battery Energy Storage Systems (BESS) that can bootstrap local grids [12]. For Nigeria, where total grid collapses (system collapses) occur multiple times a year, robust black-start capability is a critical national security priority. Incorporating smart, automated black-start protocols into Nigeria's domestic hydro stations and upcoming regional solar-plus-storage mini-grids is essential to breaking the cycle of prolonged, nationwide blackouts [9].

The Cybersecurity Maturity Layer evaluates the grid's defensive posture, assessing its ability to detect, isolate, and neutralize cyber-physical attacks targeting Operational Technology (OT) systems like

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SCADA, smart meters, and wide-area monitoring [23]. As Thailand's grid becomes deeply digitized, its cyber-attack surface expands exponentially, requiring a sophisticated, zero-trust cybersecurity maturity framework to protect its massive IoT and smart meter architecture [33]. For Nigeria, the cybersecurity layer represents a critical opportunity for "secure-by-design" leapfrogging. As Nigeria begins to build out its digital architecture from the ground up, it can integrate modern cryptographic protocols and secure communication networks directly into its new infrastructure, bypassing the legacy security flaws that older, retrofitted grids globally are forced to manage [7]. To visually capture the structural baseline variations modeled in Table 6, the allocation of electrical capacity across the centralized-to-decentralized models of the various operation segments used for both countries is illustrated in Table 6.

Operational Model Segment	Thailand Share (%)	Nigeria Share (%)	Architectural Classification
Centralized Bulk Utility	85.0	30.0	High-voltage transmission grid (EGAT vs. TCN)
Interconnected Under-Grid	12.0	25.0	Virtual Power Plants (VPPs) / Commercial Franchises
Standalone Islanded / Off-Grid	3.0	45.0	Remote micro-grids / Private industrial & diesel self-generation

Table 6: The Allocation of Electrical Capacity across the Centralized-to-Decentralized Spectrum.

Furthermore, Table 7 simulates the systemic recovery velocities of both national systems when exposed to an identical generation or transmission shortfall (such as a localized substation trip or a fuel supply disruption), tracking the operational fallout.

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Time Step (T)	Thailand Grid Availability (%)	Nigeria Grid Availability (%)	Systemic Event Context
0	100.0	100.0	Normal baseline steady-state operations
1	100.0	100.0	Normal baseline steady-state operations
2	85.0	35.0	Shortfall Event Initiated: Localized substation failure
3	95.0	10.0	Thailand spins up reserves; Nigeria suffers cascading grid collapse
4	100.0	5.0	Thailand fully self-heals; Nigeria reaches the bottom of systemic blackout
5	100.0	15.0	Nigeria attempts black-start procedures; grid islanding occurs
6	100.0	30.0	Slow step-by-step restoration of high-priority urban feeders
7	100.0	50.0	Private backup generators carry the balance of the local load
8	100.0	70.0	Regional networks slowly synchronize back onto the transmission link
9	100.0	90.0	Generation units stabilize; system approaches full re-coupling
10	100.0	100.0	Grid fully restored to pre-fault baseline status

Table 7: The Systemic Recovery Velocities of both National Systems when Exposed to an Identical Generation or Transmission Shortfall.

5.3.1 Calibration and Assumptions of the Illustrative Scenario Analysis

The step-by-step grid shortfall simulation presented in Table 7 is an illustrative, scenario-based model designed to highlight functional differences in system resilience and recovery dynamics between centralized optimization and decentralized rehabilitative architectures. While structured as a

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qualitative scenario exercise, the simulation parameters, specifically the magnitude of availability drops and recovery step timelines, are empirically grounded in and calibrated against historical power sector performance reports.

Specifically, Thailand’s rapid recovery curve reflects operational reliability baselines where automated spinning reserves and SCADA-driven distribution management systems isolate local faults within minutes, maintaining system availability above 85% [5,13,32]. Conversely, Nigeria’s steep drop (collapsing to 10% availability at T=3) and multi-stage recovery steps simulate historical system disturbance events documented by the Nigerian Electricity Regulatory Commission and the Transmission Company of Nigeria, where cascading transmission trips require manual black-start sequences and extensive regional synchronization [1, 28, 35]. This scenario analysis serves to demonstrate how physical asset maturity dictates recovery velocity under severe operational stress.

A technical shortfall in Thailand's centralized network triggers automated spinning reserves and digital Demand Response (DR) protocols via AMI, keeping the overarching voltage envelope intact. Conversely, an identical generation shortfall in Nigeria's centralized network regularly propagates into systemic transmission collapses. This failure loop acts as the primary economic catalyst for private consumers to fully decouple from the national grid, willingly accepting the higher consumer tariffs of independent smart mini-grids to secure operational runtime [1,10]. The above Tables can further be illustrated in graphs and charts below.

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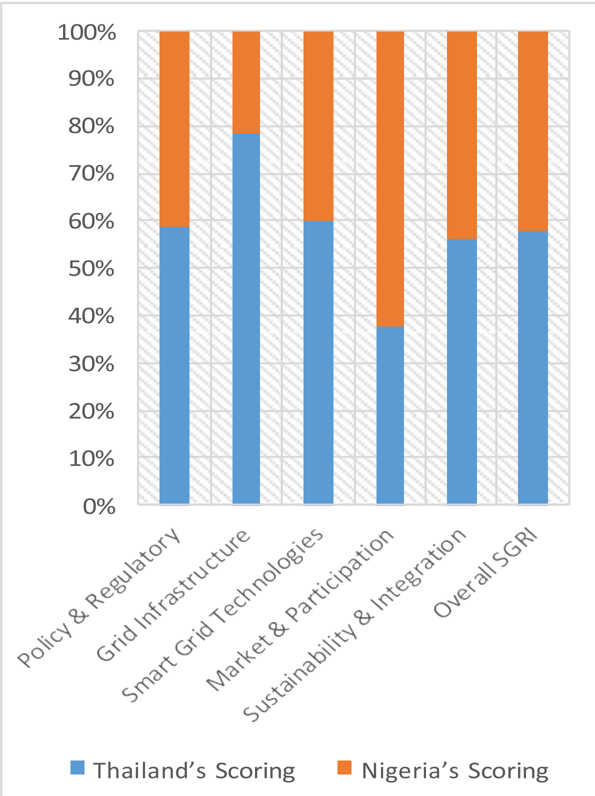
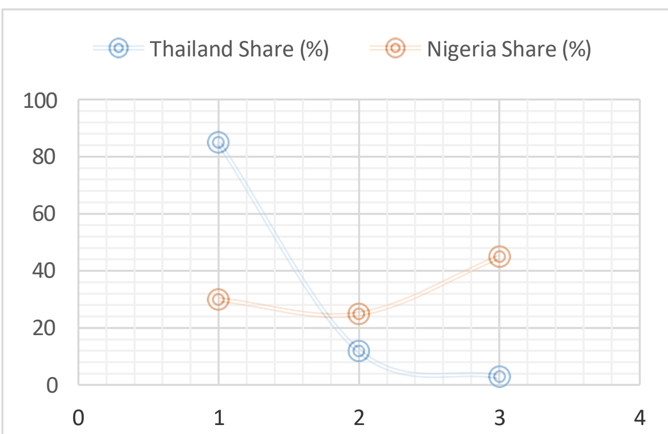


Graph 1: Bar Chart of Standardized Smart Grid Readiness Index (SGRI) using a 100% KPI-Based Scoring Framework.



Graph 2: Graph of Allocation of Electrical Capacity across the Centralized-to-Decentralized Spectrum Share within Thailand and Nigeria.

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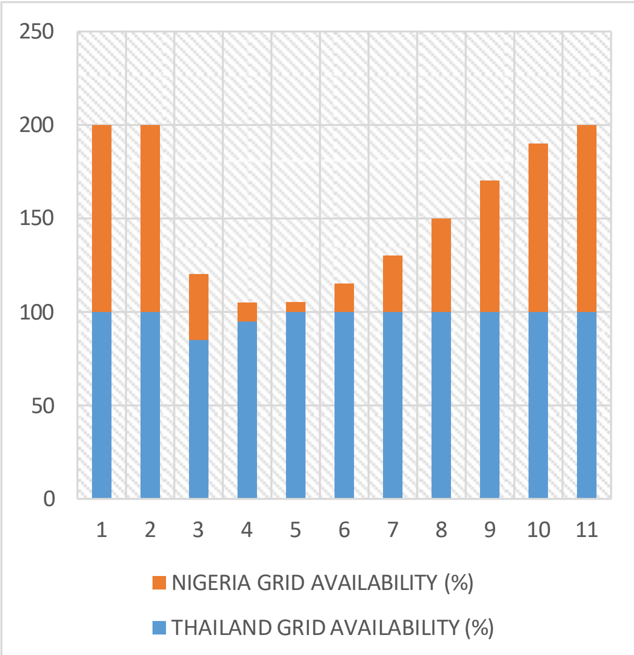
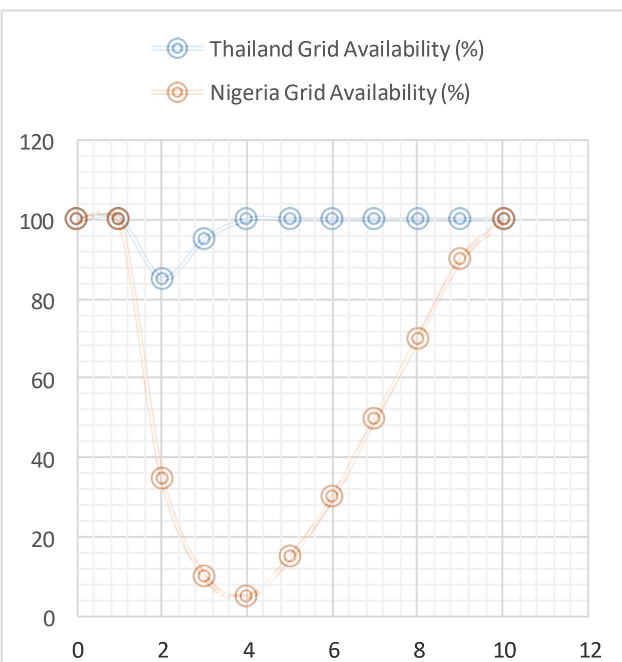


Graph 3a: Bar Chart of System Shortfall Response and Grid Resilience Simulation for Thailand and Nigeria.



Graph 3b: Graph of System Shortfall Response and Grid Resilience Simulation for Thailand and Nigeria.

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From the above Charts and Graphs, the structural divergence between the two nations begins at the foundational level, as illustrated in Graph 1 (Bar Chart of Standardized Smart Grid Readiness Index). Utilizing a 100% Key Performance Indicator (KPI)-based scoring framework as obtained from Table 4. Thailand exhibits a significantly higher SGRI due to sustained public investment in automated sub-transmission systems and cyber-physical security layers [5]. Conversely, Nigeria's lower SGRI, as shown in Graph 1, highlights critical gaps in institutional readiness, legacy infrastructure decay, and a lack of unified digital standards, restricting the country to a reactive grid management posture [48].

This readiness gap directly dictates the structural distribution of power assets shown in Graph 2 (Graph of Allocation of Electrical Capacity across the Centralized-to-Decentralized Spectrum Share) as obtained from Table 6. Thailand's capacity profile demonstrates a well-regulated, centralized-dominant model that gradually absorbs utility-scale distributed energy resources (DERs) without compromising transmission integrity [5]. In sharp contrast, Nigeria's capacity share displays a highly fragmented topology. Due to the chronic unreliability of its centralized network, Nigeria is experiencing an aggressive, consumer-driven shift toward the decentralized end of the spectrum, bypassing traditional utility frameworks out of operational necessity rather than centralized planning [48].

The real-time operational consequences of these structural differences are validated by the simulation results in Graph 3a and Graph 3b (System Shortfall Response and Grid Resilience Simulation), both obtained from Table 7. As demonstrated in the simulation models, the injection of an identical technical shortfall triggers profoundly different transient responses in each national network. In Thailand, a centralized contingency immediately activates automated spinning reserves and digital Demand Response (DR) protocols orchestrated via widespread Advanced Metering Infrastructure (AMI). The automated shedding of non-critical loads and rapid frequency stabilization keep the overarching voltage envelope intact, preventing localized faults from expanding into wider system disturbances [5]. Conversely, an identical generation shortfall within Nigeria's centralized network regularly propagates into systemic transmission collapses. The absence of automated load balancing, combined with sluggish manual spinning reserve activation, causes a rapid degradation of the frequency and voltage profiles, pushing the system past critical stability thresholds [48].

As captured in contemporary literature, this failure loop serves as the primary economic catalyst for private commercial and industrial consumers to fully decouple from the national grid. High-value consumers willingly accept the significantly higher levelized cost of electricity (LCOE) and consumer tariffs associated with independent, smart solar-hybrid mini-grids purely to secure predictable operational runtime and shield their operations from grid-induced financial losses [1, 10].

5.4 Architectural Divergence & Generalizable Global Lessons

5.4.1 Underlying Drivers of Dimensional Divergence

The comparative results highlight a systemic trade-off between centralized stability and subnational agility:

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5.4.1.1 Grid Infrastructure (GI) vs. Market Participation (MC) Trade-Off: Thailand scores exceptionally high in Grid Infrastructure (9.0/10) due to decades of sustained state-led capital investment, achieving near-universal electrification and low T&D losses [46]. However, this centralized structure breeds institutional inertia, resulting in a lower Market Participation score (4.5/10) because state utilities naturally protect single-buyer monopolies [14]. In contrast, Nigeria's severe physical infrastructure deficit (2.5/10) forced a radical legal response: the Electricity Act of 2023. This legislative devolution unlocked market pricing and subnational private equity, resulting in a significantly higher Market Participation score (7.5/10) [10, 15].

5.4.1.2 Smart Tech Deployment Contexts (ST): In Thailand, AMI (7.5/10) is deployed top-down as an optimization layer to manage VRE intermittency and EV loads [31]. In Nigeria, smart edge technology (5.0/10) is deployed bottom-up as a survival mechanism, utilizing cellular IoT meters for prepaid revenue enforcement and islanded microgrid load management [1, 35].

5.4.2 Lessons and Transferability for Developing Economies

These divergent pathways offer actionable lessons for emerging economies across Sub-Saharan Africa, Southeast Asia, and Latin America:

5.4.2.1 Match Policy Mechanisms to Infrastructure Baseline: High-income modernization paradigms cannot be directly copied into fragile grid environments. Nations with centralized networks but high renewable targets (e.g., Vietnam, Malaysia, Colombia) should follow Thailand's top-down master planning while introducing regulatory sandboxes to prevent utility inertia.

5.4.2.2 Devolve Regulation to Bypass Infrastructure Bottlenecks: Countries facing severe transmission constraints and low access rates (e.g., DRC, Myanmar, Mozambique) should emulate Nigeria's legal devolution model (Electricity Act), empowering subnational entities to license private mini-grids with cost-reflective tariffs to attract off-grid private capital [15, 30].

5.4.2.3 Mandate Upfront Interoperability Standards: To avoid long-term technical fragmentation, developing nations expanding off-grid systems must mandate uniform synchronization and communication standards (e.g., IEC 61850 interfaces) from day one. This ensures that isolated microgrids can seamlessly integrate into a unified national grid when physical networks expand [16,28].

5.4.3 Engineering, Policy, and Transferable Lessons

5.4.3.1 Engineering Implications

The contrast between Thailand's centralized optimization and Nigeria's decentralized bottom-up approach highlights fundamental engineering trade-offs in power system design:

(1) Centralized Stability vs. Single Points of Failure: Thailand demonstrates that high centralized grid

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stability (9.0/10 GI score) allows efficient integration of large-scale renewable assets and high-power quality. However, as VRE penetration grows, centralized topologies require sophisticated dynamic frequency controls, real-time thermal monitoring, and automated distribution management systems (HDMS/FLISR) to prevent "Duck Curve" voltage instability [14, 32]. Engineering investments must focus on substation automation and utility-scale BESS to preserve inertia.

(2) Edge-Driven Resilience vs. Technical Fragmentation: Nigeria proves that where central transmission networks suffer structural failure (2.5/10 GI score), edge-of-grid technologies, such as solid-state relays, IoT prepaid meters, and cellular telemetry, can build autonomous, self-sustaining microgrid islands [1, 35]. The primary engineering challenge of this model is technical fragmentation. Without upfront technical standards governing voltage vectors, frequency tolerances, and communication protocols (e.g., IEC 61850, IEEE 1547), integrating these isolated microgrid islands into a future unified backbone will cause major phase synchronization failures and power quality degradation [16, 28].

5.4.3.2 Policy and Regulatory Implications

(1) Regulatory Flexibility as a Catalyst for Capital: Nigeria's Electricity Act of 2023 demonstrates that legal devolution can unblock stalled power sectors by removing federal monopolies and granting subnational regulators (SERs) authority to issue mini-grid licenses and approve deregulated, cost-reflective tariffs [10, 15]. This framework proves that private capital will flow into high-risk environments if cost recovery is legally protected, despite severe physical infrastructure deficits.

(2) Preventing Monopolistic Stagnation via Sandboxes: Thailand's experience reveals that established centralized power sectors, while physically reliable, suffer from regulatory path-dependency and utility inertia that stifle decentralized innovation [14, 36]. Policy frameworks in such contexts must incorporate active regulatory sandboxes and legal exemptions to allow peer-to-peer (P2P) energy trading, private virtual power plants (VPPs), and third-party energy service models to operate outside rigid single-buyer structures [13, 38].

5.4.3.3 Generalized Lessons for Developing Countries

From these comparative insights, generalizable principles emerge for power system modernization across developing nations in Sub-Saharan Africa, Southeast Asia, and Latin America [19, 27]:

(1) Staged Infrastructure-Match Strategy: Developing nations must explicitly categorize their power system maturity before selecting technical and policy instruments. Nations with near-universal electrification (Access Rate >85%) should adopt top-down optimization pathways modeled after Thailand, emphasizing utility-scale BESS, AMI, and demand response [40]. Conversely, nations with low access rates (<60%) and fragile central networks should adopt rehabilitative bottom-up pathways, legalizing subnational private microgrids and decentralized cost-reflective tariffs [15, 48].

(2) Mandated Upfront Interoperability Codes: Countries launching decentralized, off-grid access drives must immediately enact technical grid connection codes mandating standard inverter interfaces

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and communication protocols. This ensures that decentralized mini-grid investments built today can operate as grid-interactive Virtual Power Plants (VPPs) tomorrow, preserving long-term asset value [4].

(3) Balancing Commercial Viability and Social Equity: While cost-reflective tariffs are essential to attract private off-grid developers, governments must introduce targeted cross-subsidization mechanisms to protect low-income rural prosumers, preventing multi-tier energy access inequalities [2, 38].

6.0 Policy Recommendations and Phased Implementation Roadmap

6.1 Maturity-Based Policy Recommendations

Smart grid modernization is not a uniform blueprint; it must be adapted to fit local infrastructural realities. The comparison between Thailand and Nigeria provides distinct cross-border policy lessons derived from their specific grid maturity phases:

6.1.1 Recommendations for Nigeria (Emerging Rehabilitative Phase)

While the current subnational de-monopolization model successfully drives rapid energy deployment, Nigeria's Federal and State Regulators must collaboratively draft strict, nationwide Grid Code Interoperability Standards [15, 35]. These technical guidelines should mandate that all private IoT meters, inverters, and switchgear deployed by mini-grid developers match minimum synchronization profiles [1, 35]. This proactive step ensures that when the national transmission network eventually stabilizes and expands, these isolated microgrid islands can convert into grid-tied VPP assets without requiring complete hardware overhauls [28]. Additionally, State Regulators must establish targeted tariff cross-subsidization mechanisms to resolve the equity dilemma affecting lower-income rural consumers [1].

6.1.2 Recommendations for Thailand (Advanced Optimization Phase)

To fully tap into the potential of its smart grid infrastructure, Thailand should gradually introduce elements of market deregulation. The ERC should create legal pathways for peer-to-peer (P2P) localized energy trading outside the strict boundaries of the state utilities [14]. By permitting private industrial parks and residential prosumers to buy and sell energy directly to one another via secure localized platforms, Thailand can stimulate private capital to achieve its net-zero objectives far faster than relying solely on utility-led investments [13, 31].

6.2 Phased Strategic Roadmap

Both nations can be guided through their next logical development steps without imposing unrealistic technological requirements; the following phased roadmap isolates targeted objectives based on infrastructure maturity as seen in Fig. 4 below. The roadmap isolates targeted objectives based on infrastructure maturity, drawing upon established principles of sequential grid evolution [6, 43]. This prevents the imposition of unrealistic technological requirements on underdeveloped operating environments [40].

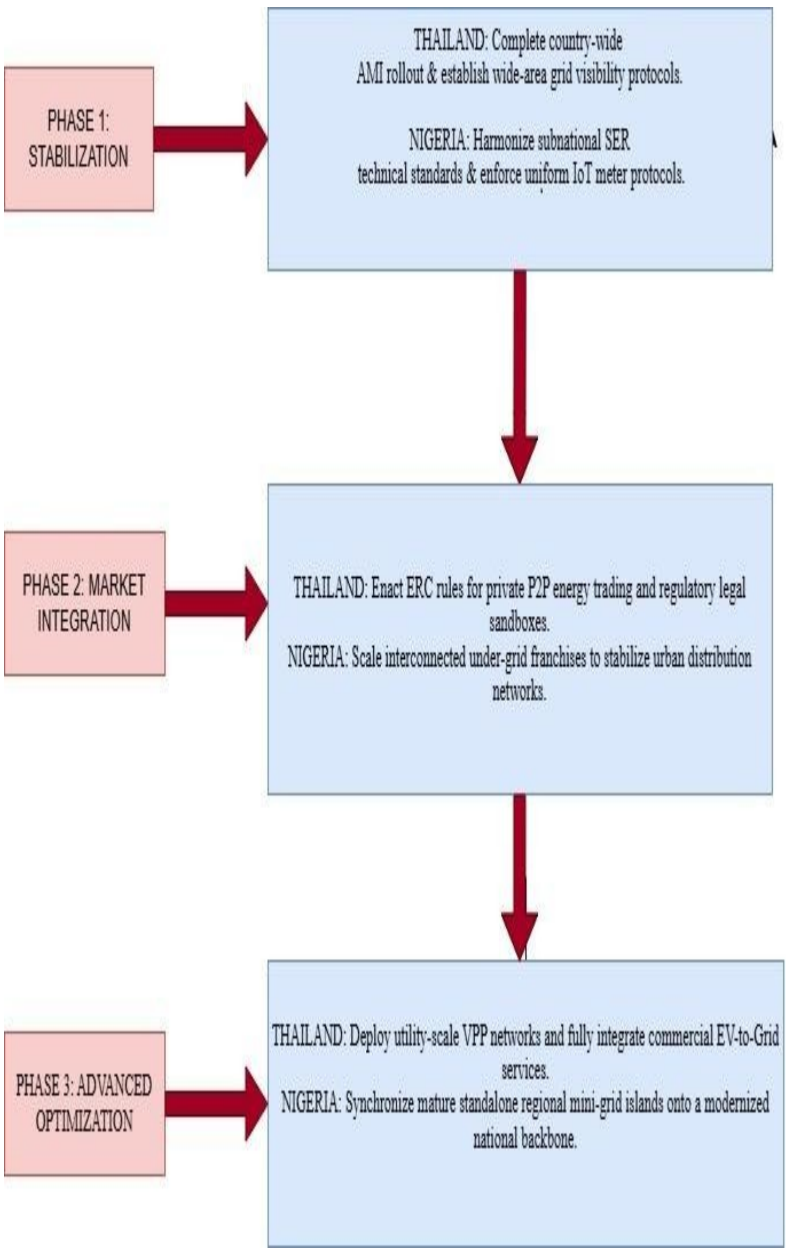

Figure 4: Comparative Strategic Roadmap for Smart Grid Modernization across Phased Objectives in Thailand and Nigeria. Source: Author's elaboration.

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6.3 Limitations and Future Research Directions

6.3.1 Study Limitations

While this study provides a systematic, multi-dimensional assessment of smart grid readiness in emerging economies, several analytical limitations should be acknowledged:

(i) Reliance on Secondary and Empirical Macro Data: The quantitative SGRI scoring, AHP weighting inputs, and scenario recovery calibrations rely on published public utility performance reports, regulatory documents, international energy databases (e.g., IEA, World Bank), and scholarly literature. High-frequency primary telemetry (such as direct PMU sensor streams or real-time AMI log files) was not directly integrated into the analysis.
(ii) Geographical Scope Constraints: The empirical analysis focuses on two selected case study nations (Thailand and Nigeria). While these countries serve as representative archetypes for optimization-driven and rehabilitative smart grid pathways, localized institutional nuances, distinct fuel mixes, or regional political economics in other developing regions (e.g., Latin America or Central Asia) may require tailored index adjustments.
(iii) Absence of Dynamic Power System Simulations and Field Validation: The transient resilience and recovery velocity evaluations presented in Section 5.3 are structured as illustrative, scenario-based macro simulations calibrated against historical grid outage metrics. The study does not include dynamic electromagnetic transient (EMT) power flow modeling or physical hardware-in-the-loop (HIL) field validation using specialized computational software (such as MATLAB/Simulink, DIgSILENT PowerFactory, or OpenDSS).

6.3.2 Directions for Future Research

To address these limitations and build upon the analytical framework established in this study, future research should explore the following avenues:

(i) Dynamic Electromagnetic Transient (EMT) Power Simulations: Execute detailed dynamic power system simulations using tools like DIgSILENT PowerFactory or OpenDSS to mathematically model exact voltage stability limits, frequency drop profiles (df/dt), and dynamic fault ride-through capabilities under high VRE penetration across both grid models.
(ii) Primary Telemetry and Field-Level Validation: Integrate real-time AMI smart meter log files, SCADA event logs, and Phasor Measurement Unit (PMU) data streams from active pilot sites in Thailand and subnational mini-grids in Nigeria to empirically validate field-level SAIDI, SAIFI, and customer load-shedding behaviors.
(iii) Framework Expansion across Expanded Geographical Datasets: Apply the multi-criteria SGRI scoring framework to a broader sample of emerging power systems across Sub-Saharan Africa, Southeast Asia, and Latin America to validate the cross-regional generalizability of the optimization-

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versus-rehabilitative taxonomy.

(iv) Empirical Cyber-Physical Vulnerability Assessments: Perform targeted cyber-physical security stress tests on cellular-connected IoT smart meters and edge control units in decentralized microgrids to analyze potential attack vectors in rapidly digitizing, uncoordinated energy markets.

7.0 Conclusion

In conclusion, both models offer valid, highly innovative pathways toward grid sustainability when aligned with their respective developmental contexts. Thailand proves that a highly centralized, utility-led model can achieve world-class grid resiliency and clean asset aggregation when backed by robust master planning [13, 13]. Concurrently, Nigeria proves that legal devolution and market liberalization can transform smart micro-grids from simple peripheral tech into resilient, self-funding lifelines capable of expanding basic energy access under challenging institutional constraints [10, 15]. Ultimately, sustainable grid evolution is not achieved by replicating a single superior blueprint, but by systematically executing policy and technological updates calibrated to a nation's unique grid maturity profile.

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