PROBLEMY EKOROZWOJU/ PROBLEMS OF SUSTAINABLE DEVELOPMENT

SUBMITTED: 6.X.2025, ACCEPTED: 30.X.2025, PUBLISHED ON-LINE: 10.01.2026
2026, 21(1): 264-278, DOI: 10.35784/preko.8525

Public Governance of Smart Grid Implementation in Urban Energy Infrastructure

Publiczne zarządzanie wdrażaniem inteligentnych sieci w miejskiej infrastrukturze energetycznej

Nataliia Protsiuk[1], Hanna Komarnytska[2], Maksym Khozhylo[3], Olesya Lobyk[4], Tetiana Iankovets5*

[1]Leonid Yuzkov Khmelnytskyi University of Management and Law, Department of Management, Economics, Statistics, and Digital Technologies, Khmelnytskyi, Ukraine
E-mail: Natalia.protsiuk1@gmail.com, ORCID: ORCID: 0000-0002-6804-5630
[2]Ivan Franko National University of Lviv,
Department of Public Administration and Business Management, Lviv, Ukraine
E-mail: hanna.komarnytskaa@gmail.com, ORCID: 0000-0002-5533-6439
[3]Dnipro University of Technology, Department of Public Administration and Local Self-Government, Dnipro, Ukraine
E-mail: khozhylom86@gmail.com, ORCID: 0000-0003-1841-4490
[4]Interregional Academy of Personnel Management, Department of Law, Kyiv, Ukraine
E=mail: lo861@ukr.net, ORCID: 0000-0002-7184-1830
[5]State University of Trade and Economics, Department of Marketing, Kyiv, Ukraine
E-mail (Corresponding Author): tetiana.n.1000@gmail.com, ORCID: 0000-0002-8159-3826

Abstract

The relevance of the study is determined by the urgent need to develop institutionally sustainable and governance-effective models for Smart Grid implementation and operation in the context of the digital transformation of energy systems, taking into account regulatory stratification, cognitive adaptability, and regulatory interoperability as vectors of sustainable energy governance. The aim is to formalize and metrically verify an optimized Smart Grid governance model grounded in global best practices, regulatory resilience, and sustainability-oriented performance indicators. The research methodology encompassed critical analysis of international experience, hypothesis formation, typological classification of governance architectures, metric-based performance assessment, SWOT analysis, UML formalization, and comparative metric validation. The study empirically confirmed the hypothesis on the predictive impact of institutional modular optimization on the sustainability and operational effectiveness of Smart Grid digitalization in the public sector. The validated governance model contributed to an increase in the Institutional Performance Index (+18.7%), Compliance Ratio (0.97), Resilience Compliance Rate (0.92), and a reduction in Time-to-Policy-Adoption (−22.5%), substantiating the systemic advantage of integrative governance redesign over fragmented strategies. The academic novelty of the research lies in the first metric assessment of governance model influence on Smart Grid performance in the public sector, as well as in the application of stratified IDI, RSR, and CIC metrics for normative-cognitive validation of sustainability-aligned governance adaptability.

The proposed model aligns with and promotes the achievement of SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities) by enhancing energy efficiency, resilience of energy infrastructure, and digital inclusivity within the sustainable governance of urban energy systems. The model contributes to ecological sustainability by reducing transformation losses and supporting innovation-driven energy optimization; to economic sustainability by increasing institutional efficiency and scalability; and to social sustainability by advancing inclusiveness and equitable access to digital energy services. Further research directions include the design of a normatively guided pilot project aimed at empirical validation of the sustainable institutional architecture, focusing on cognitive adaptability, metric resilience, and long-term alignment with the principles of sustainable development.

Key words: energy sovereignty, energy security, resilience, sustainable development, governance, government programme

Streszczenie
Znaczenie badania wynika z pilnej potrzeby opracowania instytucjonalnie zrównoważonych i efektywnych modeli zarządzania dla wdrażania i eksploatacji Smart Grid w kontekście cyfrowej transformacji systemów energetycznych, z uwzględnieniem stratyfikacji regulacyjnej, adaptacyjności poznawczej i interoperacyjności normatywnej jako wektorów zrównoważonego zarządzania energią.
Celem badania było sformalizowanie i metryczna weryfikacja zoptymalizowanego modelu zarządzania Smart Grid, opartego na globalnych doświadczeniach, odporności regulacyjnej oraz wskaźnikach ukierunkowanych na zrównoważony rozwój. Metodologia badawcza obejmowała krytyczną analizę doświadczeń międzynarodowych, formułowanie hipotez, typologizację architektur zarządzania, ocenę efektywności na podstawie wskaźników metrycznych, analizę SWOT, formalizację UML oraz porównawczą walidację metryczną.
Badanie empirycznie potwierdziło hipotezę dotyczącą predykcyjnego wpływu modularnej optymalizacji instytucjonalnej na zrównoważoność i efektywność operacyjną cyfryzacji Smart Grid w sektorze publicznym.
Zatwierdzony model zarządzania przyczynił się do wzrostu Wskaźnika Efektywności Instytucjonalnej (+18,7%), Wskaźnika Zgodności (0,97), Wskaźnika Odporności na Regulacje (0,92) oraz skrócenia czasu przyjęcia polityk (−22,5%), potwierdzając przewagę systemową integracyjnego podejścia do zarządzania nad strategiami fragmentarycznymi. Nowość naukowa badania polega na pierwszej metrycznej ocenie wpływu modeli zarządzania na efektywność Smart Grid w sektorze publicznym, a także na zastosowaniu stratyfikowanych wskaźników IDI, RSR i CIC do normatywno-poznawczej walidacji adaptacyjności zarządzania zgodnego z zasadami zrównoważonego rozwoju.
Proponowany model jest zgodny z celami SDG 7 (Czysta i Dostępna Energia) oraz SDG 11 (Zrównoważone Miasta i Społeczności), poprzez zwiększenie efektywności energetycznej, odporności infrastruktury oraz cyfrowej inkluzywności w kontekście zrównoważonego zarządzania miejskimi systemami energetycznymi. Model wspiera ekologiczną zrównoważoność poprzez redukcję strat transformacyjnych i promowanie innowacyjnej optymalizacji energetycznej; zrównoważoność ekonomiczną przez wzrost efektywności instytucjonalnej i skalowalności; oraz zrównoważoność społeczną dzięki zwiększeniu inkluzywności i równego dostępu do cyfrowych usług energetycznych. Dalsze kierunki badań obejmują opracowanie pilotażowego projektu normatywnego, mającego na celu empiryczną walidację zrównoważonej architektury instytucjonalnej, z koncentracją na adaptacyjności poznawczej, odporności metrycznej i długoterminowym dostosowaniu do zasad zrównoważonego rozwoju.

Słowa kluczowe: suwerenność energetyczna, bezpieczeństwo energetyczne, resilencja, zrównoważony rozwój, zarządzanie, program rządowy

1. Introduction

The relevance of formalizing effective governance models for the implementation and operation of Smart Grids in the public sector is increasing in the context of the intensification of the digital transformation of urban power grids and the global shift toward sustainable development. Institutional complexity, regulatory polycentricity, and the high degree of techno-social integration necessitate a comprehensive analysis of governance solutions that incorporates regulatory stratification, socio-institutional balance, digital infrastructure maturity, and sustainability-oriented economic efficiency (Yermachenko et al., 2023; Ortina et al., 2023).
Given the imperative of decarbonization, energy justice, and long-term ecological resilience, Smart Grid architectures are increasingly recognized as integral to sustainable urban infrastructure. Accordingly, the integration of circular economy principles, resource efficiency, and low-carbon governance strategies into Smart Grid design has become a strategic necessity (Atstaja et al., 2022). This reinforces the alignment of Smart Grid deployment with the goals of SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities) as part of a broader system of sustainable public governance.
The urgency of this research is directly linked to the imperative of sustainable development, as modern energy systems must ensure a balance between technological innovation, institutional adaptability, and environmental responsibility. Smart Grid governance models play a critical role in the achievement of sustainable energy goals, particularly in enhancing energy efficiency, ensuring regulatory transparency, and supporting inclusive access to digital services.

Given the cross-cutting relevance of SDG 7, SDG 11, and SDG 13 (Climate Action), the development of optimized governance frameworks is essential to harmonize public sector digitalization with the principles of social, ecological, and economic sustainability. Therefore, this study responds to the global demand for systemic, sustainability-driven solutions that integrate resilience, circularity, and normative coherence into the design and implementation of Smart Grid infrastructures.

The aim of the study is to formalize and perform metric-comparative verification of a sustainability-oriented and governance-optimized model for Smart Grid implementation in urban energy systems, based on the analysis of global practices, stratified regulatory mechanisms, and performance indicators aligned with the principles of sustainable development.

Research objectives are:

- Carry out a critical analysis of international experience with the identification of regulatory, institutional, technical, and economic determinants of Smart Grid governance in the context of sustainable development;
- Advance a hypothesis regarding the impact of governance architecture on Smart Grid effectiveness in terms of adaptability, interoperability, and sustainability;
- Typify governance models according to the criteria of modularity, centralization, institutional responsibility and regulatory coordination, emphasizing sustainability-oriented governance typologies;
- Carry out a metric analysis of the effectiveness of models based on a system of integral indicators ROI, OSS, SES, GLR, including sustainability-aligned performance indicators;
- Apply SWOT analysis to assess the structural and functional profile of governance models with regard to ecological resilience, economic scalability, and social inclusiveness;
- Perform UML of the architecture of the optimized governance model with a focus on stratification, regulatory hierarchy, and integration into sustainable energy governance;
- Conduct metric comparative verification of the model's performance in comparison with benchmark platforms and empirically prove the hypothesis on sustainable institutional optimization.

2. Literature review

Urban energy requires transformation to ensure climate resilience, digital adaptability and decarbonization, while Smart Grid technologies act as a key instrument of sustainable development, enabling the integration of low-carbon innovation, resource efficiency and resilient energy governance through the synergy of technological and institutional solutions.

The analysis of the transformation of urban energy systems should begin with the study of Rajaperumal and Columbus (2025), who formed an AI-centric grid evolution framework with the integration of DR algorithms, EV-V2G schemes, predictive fault analytics and DT-IoE synergies. The prospect of NGG architectures through HMI-enhanced control, cyber-resilience protocols, and decentralized EMS to ensure SDG-congruent energy adaptability is determined.

In developing this paradigm, Kolhe (2025) synthesized innovations in PV-GPR forecasting, AOS-MPPT algorithms, MTDC-WF integration, DL-OWC stabilization, CHP-ED models, EV-V2G optimization, and LIB-thermal safety. Multi-domain-oriented energy technologies are summarized as drivers of SDG7/9/11/13 in the grid modernization paradigm.

Summarizing the techno-system component, Al-Qarni et al. (2025) confirmed that smart grid systems within the smart city paradigm provide energy optimization, integration of RES, and reduction of carbon footprint. Cyber threats, privacy gaps, and lack of regulatory interoperability of energy policies are identified as key challenges.

Deepening the institutional dimension, Islam et al. (2025) developed an STT-based framework for sustainable engineering governance with the integration of AI-driven EMS, blockchain-P2P trading, and predictive analytics. It is confirmed that digitalized multi-stakeholder governance accelerates SDG7 through cyber-resilient decentralization, energy justice implementation, and EWF-nexus alignment.

At the intersection of energy transformations and spatial planning, Sharma et al. (2025) summarized NZEB transformation strategies for megacities, focusing on PED architecture, Digital Twin infrastructure, IoT-EMS, and NbS. Inclusive stakeholder governance and AI-driven urban planning have been shown to enhance climate resilience and accelerate the achievement of SDG7/11.

Jamil (2025) developed a UDT-based energy framework integrating Building Information Modelling (BIM), sensor flows, AI controllers and CO_2 sequestration strategies. Experiments in Thailand and Vietnam demonstrated the potential of UDT in increasing energy efficiency, reducing emissions, and achieving SDG7/11.

Complementarily, Anser et al. (2025) demonstrated that smart grid integration (β=2.386) and BEMS solutions increase urban energy efficiency, while excess RES penetration (β=–1.479) and ecodesign create energy inertia. Impulse-variation analysis confirmed the priority of smart grids in shaping climate-resilient policies (SDG7/13).

Expanding the discussion on municipal governance, Yatzkan et al. (2025) found that the effectiveness of urban energy governance is determined by the context-specific implementation of DER systems, policy incentives and BEE mechanisms. Barriers in low-capacity municipalities are related to institutional fragmentation, budget constraints and insufficient digitalization of energy governance processes.
Against these constraints, Janev et al. (2025) verified an SGAM-oriented IoE platform for EC with support for prosumer-centric EMS, RES-forecasting, semantic interoperability, and adaptive dispatch. A case study confirmed its effectiveness in overcoming HEMS/DER integration barriers, regulatory misalignments and scalability constraints for SDG-aligned decarbonization.
Summarizing the perspective of decentralized solutions, Almihat and Munda (2025) developed a multiscale model of urban Smart Microgrids using peer-to-peer energy trading, hybrid storage, PPP mechanisms, and AI optimization. A flexible regulatory policy framework for decentralized energy systems with a high level of climate resilience and RES integration is proposed.
The implementation of Smart Grid, DER, EMS, Digital Twins, AI, and IoE is a pivotal enabler of urban energy decarbonization, resilience, and resource optimization, yet is constrained by digital inequality and regulatory fragmentation. These barriers necessitate the development of institutionally adaptive, sustainability-oriented public governance frameworks aligned with SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action), ensuring that technological modernization is embedded within a coherent system of ecological, economic, and social sustainability.

3. Methods and materials

3.1. Research design

The research design is presented below (Figure 1).

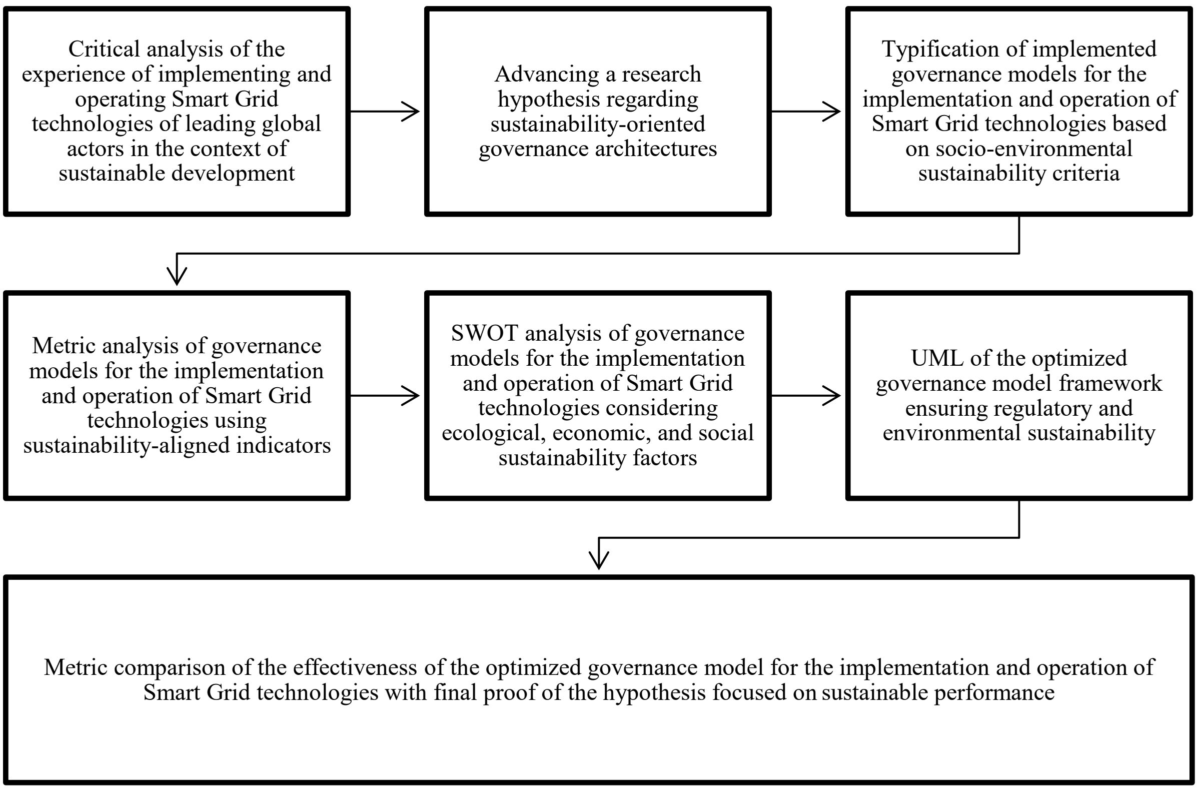

Figure 1. Analytical sequence of the study , source: developed by the authors

3.2. Methods

The study employed the following methods, taking into account the stages of the analysis:

1. A critical analysis of international experience was used for the systematic extrapolation of governance approaches to the implementation and operation of Smart Grid technologies, with the subsequent identification of regulatory, institutional, technical and economic determinants relevant to socio-ecological sustainability.

2. The hypothesis was advanced by conceptually generalizing the identified patterns, with a link to the effectiveness of governance models in the parameters of cognitive adaptability, regulatory interoperability, and sustainability-driven operational stability.
3. The typification of governance models was based on the clustering of governance architectures according to the features of modular structuring, level of centralization, form of institutional responsibility, and regulatory coordination, ensuring compatibility with sustainability imperatives.
4. The metric analysis of governance models involved the testing of a unified system of integral indicators (ROI, OSS, SES, GLR), which allowed quantitatively verifying the effectiveness of the implemented governance architectures from the standpoint of long-term sustainability.
5. SWOT analysis was used to determine the structural and functional profile of governance models, with the fixation of internal advantages and disadvantages, as well as external opportunities and risks, including constraints on sustainable transformation of the institutional environment.
6. UML was used to graphically formalize the architecture of the optimized governance model, with a focus on the modular stratified organization, interface interactions, and the hierarchy of regulatory precedents aligned with sustainability objectives.
7. Metric comparison provided validation of the effectiveness of the developed model by comparing it with benchmark platforms to empirically prove the hypothesis regarding its effectiveness in view of the digital transformation of power grids and the need for sustainability-oriented public governance.

3.3. Sample

The global sample (Table 1) includes 12 technically and regulatorily validated Smart Grid technologies implemented across leading world economies, providing cognitive dispatching, decentralization, predictive governance and IoT/AI integration to increase grid flexibility and energy efficiency, while ensuring alignment with sustainability-oriented energy transition goals.

Table 1. Stack of implemented Smart Grid technologies, source: developed by the authors

Name of the Smart Grid technology	Smart Grid technology description / Country of implementation	Academic research
Advanced Metering Infrastructure (AMI)	Digital system for automated collection, processing and transmission of real-time electricity consumption data / USA, France, India, Canada – basic component of metering digitalization	Ma et al. (2025)
Energy Governance System (EMS)	Centralized system for optimization of energy consumption, generation, and distribution based on analytics / Japan, South Korea, Sweden – used for centralized governance	Kudzin et al. (2025)
Distributed Energy Resources Governance System (DERMS)	Platform for monitoring, forecasting and coordination of distributed energy sources (RES, microgrids). / Germany, Netherlands, Australia – integration of RES at a decentralized level	Sugunaraj et al. (2025)
Demand Response (DR)	Dynamic demand governance mechanism through price signals and automated load. / USA, Italy, UK – flexible consumption policy	Akhila et al. (2025)
Virtual Power Plants (VPP)	Coordination of multiple energy sources to simulate the functionality of a centralized station. / Germany, Australia – coordination of decentralized capacities	Tang and Wang (2025)
Vehicle-to-Grid (V2G)	Bilateral interaction between electric vehicles and the grid with the ability to transfer excess energy back to the system. / USA, Japan, France – mobile energy storage via electric vehicles	Xiao et al. (2025)
Supervisory Control and Data Acquisition (SCADA)	A tool for monitoring, controlling and managing energy infrastructure in real time. / Universally used (in particular, USA, China, UAE) as a basis for dispatching	Kamil et al. (2025)
Artificial Intelligence for Grid Optimization (GridAI)	Algorithms for forecasting, load optimization and resource allocation using AI models. / China, Canada, Japan – using AI for predictive control	Reddy et al. (2025)
Digital Twins	A virtual copy of the physical power system, allowing for real-time modelling, analysis and optimization. / South Korea, Singapore, Sweden – real-time infrastructure modelling	Hatami et al. (2025)
Blockchain-Based Peer-to-Peer Energy Trading	Distributed registry technology for secure electricity trading between consumers (prosumer architecture). / Singapore, Netherlands – forming local energy markets	Shen et al. (2025)
Home Energy Governance Systems (HEMS)	Local energy consumption governance systems in households with IoT support. / Japan, Sweden – integrating Smart Home into the general network	Qayyum et al. (2025)
Wide Area Monitoring Systems (WAMS)	A system for remote measurement and analysis of network parameters over large geographical areas. / China, USA – monitoring grid stability on a continental scale	Ogbogu et al. (2025)

3.4. Instruments

The instrumental basis is formed by a stratified stack of efficiency metrics (Table 2), including six new indicators (GPI, IRI, PPI, LCR, SIS, CRI), which provide a multi-cluster assessment of the adaptability, interoperability, and digital maturity of Smart Grid governance models. The inclusion of Green Policy Index (GPI) and Low-Carbon Ratio (LCR) ensures direct alignment with the principles of sustainable development, enabling quantitative validation of ecological resilience, regulatory eco-coherence, and system-level contribution to climate-neutral governance. Thus, the metric stack supports the holistic assessment of Smart Grid architectures through the lens of environmental sustainability, institutional efficiency, and digital transformation.

Table 2. Stack of metric assessment of the efficiency of governance models for the implementation and operation of Smart Grid technologies*, source: developed by the authors

Metric Cluster	Efficiency metric	Mathematical formulae
Technical and operational efficiency: the degree of implementation of the Smart Grid technological infrastructure	GPI (Grid Performance Index). Proposed for the first time (within SGAM platforms)	$GPI = \Sigma(DER_i + VPP_i + EMS_i) / n$, where DER_i – the integration factor of distributed energy sources; VPP_i – the uptime of virtual power plants; EMS_i – the availability of energy governance systems; n – the number of monitored periods
Economic feasibility: the cost-effectiveness of the model in terms of CAPEX/OPEX	LCOE (Levelized Cost of Electricity)	$LCOE = \Sigma(C_t / (1 + r)^t) / \Sigma(E_t / (1 + r)^t)$, where C_t – the total cost of generation at time t; E_t is the amount of energy produced; r is the discount rate; E_t – amount of energy produced; r – discount rate; t – time period
	ROI (Return on Investment)	$ROI = (B - C) / C$, where B – the profit or benefit from the investment; C – the total cost of investment
	NPV (Net Present Value)	$NPV = \Sigma(CF_t / (1 + r)^t)$, where CF_t – the cash flow in period t; r – discount rate; t – the time period
Institutional sustainability: the model's ability to adapt and scale over the long run	IRI (Institutional Resilience Index). Proposed for the first time (in the context of Smart Grid)	$IRI = \Sigma(w_i \times S_i) / \Sigma(w_i)$, where S_i – assessment of the resilience of institutions to risks; w_i – indicator weight
	FS (Flexibility Score). Modified (adapted to SG)	$FS = (\partial E / \partial t) / E_{max}$, where $\partial E/\partial t$ – change in energy production/consumption over time; E_{max} – maximum load
Level of public participation: inclusiveness of citizens, prosumers and local authorities	PPI (Public Participation Index). Proposed for the first time	$PPI = \Sigma(P_i \times w_i) / \Sigma(w_i)$, where P_i – engagement indicator (survey, voting, discussion); w_i – weighting coefficient
	SES (Stakeholder Engagement Score). Modified	$SES = \Sigma(E_i \times w_i) / \Sigma(w_i)$, where E_i – level of stakeholder participation (number of events, participation in development); w_i – weight
Regulatory compliance: consistency with existing regulations, standards, and policies	LCR (Legal Compatibility Ratio). Proposed for the first time	$LCR = C^a / C^t$, where C^a – the number of relevant legal norms to which the model corresponds; C^t – the total number of relevant norms
	RAI (Regulatory Alignment Index). Modified	$RAI = \Sigma(R_i \times w_i) / \Sigma(w_i)$, where R_i – index of compliance with each regulatory act; w_i – regulator significance
Interoperability and digital integration: ability to connect disparate systems (DER, IoT, EMS)	SIS (Semantic Interoperability Score). Proposed for the first time	$SIS = M^f / M^t$, where M^f – number of formally agreed data models; M^t – total number of models in the system
	ACR (API Compliance Rate). Modified	$ACR = A^f / A^t$, where A^f – number of APIs that meet specifications; A^t – total number of APIs

Metric Cluster	Efficiency metric	Mathematical formulae
Environmental performance: decarbonization level, loss reduction, RES efficiency	ΔCO_2 (CO_2 Emission Reduction)	$\Delta CO_2 = CO_2\_b - CO_2\_s$, where CO_2_b – emission level before implementation; CO_2_s – emission level after implementation
	RPR (RES Penetration Rate)	RPR = E_RES / E_TOT, where E_RES – volume of electricity from renewable sources; E_TOT – total energy production
	GLR (Grid Loss Reduction)	$GLR = (L^b - L^s) / L^b$, where L^b – losses in the grid before implementation; L^s – losses after implementation
Risk governance: cybersecurity, resilience, critical incident governance	CRI (Cyber Risk Index). Proposed for the first time	$CRI = \Sigma(R_i \times w_i) / \Sigma(w_i)$, where R_i – risk indicators (vulnerabilities, events); w_i – criticality weight
	OSS (Operational Security Score). Modified	$OSS = S_a / S_{max}$, where S_a – current security level (authentication, monitoring); S_{max} – maximum possible score
	DRR (Disaster Recovery Readiness). Modified	$DRR = T_\beta / T_a$, where T_β – basic allowable recovery time; T_a – actual recovery time

* Min–max normalization was applied to unify scales and ensure metric comparability [0;1].

Metric analysis was performed in Python (pandas, numpy, matplotlib), and structural formalization of the optimized model was performed using UML tools.

4. Results

A stratified analysis of national Smart Grid models was carried out with an emphasis on governance and institutional architectures, regulatory density, and strategic adaptability of transformation (Table 3). This analysis was explicitly framed within the paradigm of sustainable development, assessing each governance configuration through its contribution to energy efficiency, low-carbon transition, social inclusiveness, and infrastructural resilience in accordance with SDG 7 and SDG 11. Such an approach ensured the identification of governance practices that not only enhance digitalization of energy systems but also strengthen their environmental sustainability, economic viability, and social equity.

Table 3. Critical analysis of the experience of implementing and operating Smart Grid technologies of leading global actors, source: developed by the authors

Country of implementation / Implemented Smart Grid technologies	Legislative initiatives / Financing	Political mechanisms / Public participation	Implementation barriers / Expected effect
США / AMI, DR, EV-V2G, DERMS, SCADA (2009–)	EISA 2007, Grid Modernization Initiative / DOE Grants, Private Investments, ARRA Stimulus	Energy Independence Act, FERC Policy / Regulatory Hearings, Demonstration Projects	Regulatory Fragmentation, Cyber Risks / Increasing Grid Resilience, Reducing Losses
Germany / BEMS, SGAM, VPP, RES-Integration, Smart Meters (2011–)	EnWG, EEG, EU Clean Energy Package / Energy Subsidies, KfW, Horizon 2020	Energiewende, EEG, EnEff-City / Energy Cooperatives, Urban Pilots	RES Integration Complexity, Grid Inertia / Driving Decentralization, Growing RES
Japan / EMS, IoE, AI-Forecasting, Microgrids (2010–)	Electricity Business Act, Conservation Act / METI Funds, Regional Budgets, Private Initiatives	Green Growth Strategy, Energy Basic Plan / E-Participation, Energy Platforms	Low Data Sharing, Risk Perception / Reducing CO_2, Effective DER Integration
South Korea / IoT-EMS, Digital Twins, HAN, Smart Buildings (2012–)	ICT-Based Energy Act, Utility Reform Act / KEPCO, State Funding	Smart Grid Roadmap, K-Smart City Initiative / Community-Based Trials, Digital Engagement	Institutional Fragmentation, Legacy Systems / Adaptive Governance, KPI-Based Optimization
China / Ultra HVDC, Big Data EMS, P2P Trading (2015–)	Electricity Law Reform, Carbon Goals 2030 / National Programmes, PPP Funds	13th Five-Year Plan, Carbon Neutrality Strategy / Information Campaigns, Limited Engagement	Opacity, Energy Monopoly / Accelerating Transformation, P2P Trading

Country of implementation / Implemented Smart Grid technologies	Legislative initiatives / Financing	Political mechanisms / Public participation	Implementation barriers / Expected effect
France / Smart Substations, Cybersecurity Layers, PV-BEMS (2010–)	Loi Énergie-Climat, PPE 2023 / ADEME, Innovative Funds, EU Calls	PPE, Loi Énergie-Climat / Municipal Consultations, Paris-Saclay Initiatives	Centralized Bureaucracy, Digital Divide / Digital Traceability, Security Enhancement
Canada / Distributed Generation, BEMS, GridAI, AMI (2012–)	Clean Energy Act, Provincial Energy Codes / NRCan, Green Infrastructure Fund	Pan-Canadian Framework, Net-Zero Act / Stakeholder Forums, Public Consultations / Stakeholder Forums, Public Consultations	DSO/TSO Coordination, Geographical Dispersion / Inclusive Energy, Equal Access
Italy / Flexibility Markets, Active DSOs, RES Clusters (2014–)	Energy Efficiency Law 2014, RED II / PNIEC, EU Recovery and Resilience Plan	Integrated National Energy and Climate Plan / Local Energy Hubs, Peer Engagement	Insufficient Standardization, Infrastructure Barriers / Operational Flexibility, Distribution Optimization
India / Smart Meters, Rooftop PV, DR Programs, PMUs (2016–)	Electricity Act 2003, Energy Conservation Act / MNRE, Smart Grid Mission, Private Capital	Smart Grid Vision 2030, National Electricity Policy / Smart Meter Rollouts, Village Energy Committees	High Implementation Cost, Small Market Entities / Scalability, Economic Energy Efficiency
The Netherlands / Transactive Energy, DSO-TSO Coordination, EV Sharing (2015–)	Electricity Act 1998, Grid Code 2.0 / TenneT Innovation Fund, Horizon Europe	Climate Agreement, Digital Grid Vision / Energy Cafés, Citizen Energy Panels	Data Fragmentation, Interoperability / Behavioural Flexibility, DSO-TSO Synergy
Singapore / Nodal Pricing, Blockchain Trading, Smart Sensors (2017–)	EMA Act, Energy Market Authority Code / EMA Funds, Industrial Co-Financing	Smart Nation Strategy, Power Sector Transformation / Pilot Blocks, Participatory Design	High Import Dependence, Security Risks / Peak Load Minimization, P2P Energy
Sweden / Real-Time Monitoring, DER Aggregators, Green Substations (2013–)	Electricity Act 1997, Energy Declaration / Swedish Energy Agency, EU FP7	Fossil-Free Sweden Strategy, Grid 4.0 Plan / District-Level Dialogues, Green Forums	Grid Flexibility Constraints, Climate Conditions / Emission Reduction, Urban Energy Resilience
United Kingdom / Dynamic Tariffs, Flex-EMS, Grid Edge Optimization (2011–)	Energy Act 2013, Net Zero Strategy / OFGEM Innovation Fund, Catapult Grants	Ten Point Plan for Green Industrial Revolution / Public Consultations, Digital Portals	Regulatory Limits, Pricing Models / System Balance, Energy Consumer Adaptability
Australia / VPPs, Digital Grid Interface, DER-Predictive Control (2013–)	National Electricity Rules, Clean Energy Legislation / ARENA, Clean Energy Finance Corporation	Technology Investment Roadmap, REZ Framework / Regional Stakeholder Maps, Education Initiatives	Load Volatility, Lack of Local Schemes / Regulatory Elasticity, VPP Optimization
OAE / AI-Driven Load Balancing, IoT-Based Forecasting, Smart Hubs (2019–)	Federal Energy Law, Dubai Clean Energy Strategy / DEWA Smart Initiatives, Public-Private PPPs	Clean Energy Strategy, Vision 2050 / Youth Labs, Smart City Forums	Cultural Barriers, Lack of Technology Understanding / Intelligent Aggregation, Reliability of Supply

Critical analysis (Table 3) showed that the Smart Grid implementation effectiveness is determined by institutional coherence, regulatory stratification, and multi-actor interaction, while also confirming the imperative to align governance architectures with sustainable institutional capacity, regulatory transparency, and inclusive transition planning in accordance with SDG-oriented transformation.

The hypothesis formulated in this study posits that the quality of institutional governance at the state/municipal level is a key predictor of successful Smart Grid implementation in the public sector, particularly when integrated into climate-adaptive, socially inclusive, and low-carbon energy governance frameworks contributing to sustainable infrastructure resilience.

This necessitates the stratification of governance models by the level of centralization, regulatory and financial mechanisms, as well as public participation, allowing for the formalization of adaptive Smart Grid transformation scenarios (Table 4) consistent with sustainable development principles, ecological justice, and the multi-level implementation of SDG 7, SDG 11, and SDG 13.

Typological analysis (Table 4) showed that the effectiveness of Smart Grid integrations depends on cognitive and procedural manageability and regulatory adaptability. This justifies the need for metric evaluation of models according to institutional stability, compatibility, and interoperability indicators (Table 5), ensuring alignment with sustainable governance architectures, enhancement of regulatory coherence for climate goals, and integration into urban policies that support the Sustainable Development Goals (SDGs) particularly SDG 7 (*affordable and clean energy*) and SDG 11 (*sustainable cities and communities*).

Table 4. Typical stack of implemented governance models for the implementation and operation of Smart Grid technologies, source: developed by the authors

Model name / Countries of implementation	Financing schemes / Public administration model	Public administration / Public engagement	Implementation barriers / Expected effect
Centralized state model / China, France, UAE	State budgets, national decarbonization funds / Unitary administration with vertical hierarchy	Ministry of energy/digitalization, regulatory agencies / Information, public discussions, petitions	Low adaptability, inertia of the regulatory system / Manageability, scalability, continuity of governance
Polycentric cooperative model / Germany, Netherlands, Austria	Local budgets, membership fees, EU grants / Decentralized administration with local autonomy	Municipalities, regional energy agencies / Participation in cooperatives, local councils, peer governance	Fragmentation of policies, asymmetry of resources / Local flexibility, community participation, energy justice
Platform-aggregation model / Estonia, Singapore, Spain	Platform subsidies, payment for API access, cloud plans / Multi-actor governance based on digital platforms	Digital innovation centres, energy governance platforms / Prosumer participation through platforms, digital consultations	Cybersecurity, data governance, dependence on providers / System interoperability, accelerated integration of innovations
Hierarchical dispatching model / USA, Japan, Israel	Tariff integration, capital expenditures from the budget / Functional and operational centralization	National operations centres, (TSOs/DSOs) / Indirect participation, emergency notification, feedback	High CAPEX, complexity of technical integration / Operational reliability, centralized response to risks
Public-private partnership (PPP) model / Canada, UK, India	Co-financing, concession agreements, investment guarantees / Hybrid administration with separation of powers	Interdepartmental agencies, investment commissions / Dialogue platforms, joint tenders, tariff discussions	Conflict of interest, investor distrust, legal complexity / Risk optimization, capital attraction, efficiency improvement
Digital-regulatory model with sandbox solutions / Finland, Australia, Lithuania	Pilot financing, technology vouchers, grants for experiments / Institutional adaptation through temporary regulatory structures	Regulatory innovation committees, sandbox supervisory boards / Online registration of participants, focus groups, digital voting	Regulatory uncertainty, risk of technological fiasco / Testing of breakthrough solutions, creation of innovative regulations

Table 5. Metric analysis of governance models for the implementation and operation of Smart Grid technologies, source: developed by the authors in Python

Governance models	GPI	LCOE	ROI	NPV	IRI	FS	PPI	SES	LCR	RAI	SIS	ACR	ΔCO_2	RPR	GLR	CIR	OSS	DRR
Centralized state model	0.375	0.951	0.732	0.599	0.156	0.156	0.058	0.866	0.601	0.708	0.021	0.970	0.832	0.212	0.182	0.183	0.304	0.525
Polycentric cooperative model	0.432	0.291	0.612	0.139	0.292	0.366	0.456	0.785	0.200	0.514	0.592	0.046	0.608	0.171	0.065	0.949	0.966	0.808
Platform-aggregation model	0.305	0.098	0.684	0.440	0.122	0.495	0.034	0.909	0.259	0.663	0.312	0.520	0.547	0.185	0.970	0.775	0.939	0.895
Hierarchical-dispatching model	0.598	0.922	0.088	0.196	0.045	0.325	0.389	0.271	0.829	0.357	0.281	0.543	0.141	0.802	0.075	0.987	0.772	0.199
Public-private partnership (PPP) model	0.006	0.815	0.707	0.729	0.771	0.074	0.358	0.116	0.863	0.623	0.331	0.064	0.311	0.325	0.730	0.638	0.887	0.472
Digital regulatory model with sandbox solutions	0.120	0.713	0.761	0.561	0.771	0.494	0.523	0.428	0.025	0.108	0.031	0.636	0.314	0.509	0.908	0.249	0.410	0.756

Metric analysis (Table 5) empirically supports the hypothesis that institutional resilience, regulatory compatibility, and stakeholder engagement are key predictors of successful Smart Grid implementation, as the digital regulatory and platform aggregation models demonstrate high performance (GPI = 0.305–0.432), in contrast to the centralized model with low PPI (0.058) and IRI (0.156) values; these findings underscore the relevance of sustainable development-oriented architectures, particularly in the context of climate-neutral transition, energy equity, and institutional scalability, necessitating further SWOT analysis for the architectural design of an optimized framework (Table 6).

SWOT analysis (Table 6) demonstrated the appropriateness of architectural hybridization of Smart Grid governance models by integrating sandbox mechanisms, platform solutions, and stakeholder inclusion. The developed framework (Figure 2) is structured according to stratified Institutional, Regulatory, Technological, and Stakeholder layers with defined functions (coordination, compliance, DER/EMS/VPP governance, digital participation), while the use-case diagram (Figure 3) demonstrates scenario interaction of actors ensuring regulatory integration, functional interoperability, and cognitive adaptability. This structural-functional architecture contributes to sustainable development by promoting decentralized energy resilience, institutional scalability, and inclusive governance aligned with SDG 7, SDG 11, and SDG 13 priorities.

Table 6. SWOT analysis of governance models for the implementation and operation of Smart Grid technologies, source: developed by the authors

Governance model	S (Strengths)	W (Weaknesses)	O (Opportunities)	T (Threats)
Centralized state model	High manageability; macroeconomic scalability; unified regulation	Low adaptability; institutional inertia; weak stakeholder engagement	Formation of centralized platforms; integration of national decarbonization programmes	Regulatory overload; risk of politicization of processes
Polycentric cooperative model	Local flexibility; inclusiveness; high level of community participation	Resource asymmetry; regulatory fragmentation; limited scalability	Strengthening energy democracy; development of local VPP/EMS	Risk of disruption of system integrity; uneven development
Platform aggregation model	High digital interoperability; multi-actor governance; rapid DER integration	Dependence on providers; cyber risks; limited algorithm transparency	Development of data-driven governance; stimulation of prosumer activity	Insufficient regulatory unification; risk of techno-fragmentation
Hierarchical dispatching model	High operational stability; protocol unification; technical reliability	Centralization of decision-making; weak reactivity; low social inclusion	SCADA/EMS integration; centralized emergency response	CAPEX load; limitations of decentralization
Public-private partnership (PPP) model	Risk optimization; investment capitalization; contractual flexibility	Conflict of interest; legal complexity; low level of transparency for the public	Expansion of concessions; integration of private innovative solutions	Reputational risks; risk of legal incapacity
Digital regulatory model with sandbox solutions	High regulatory adaptability; innovation testing; institutional flexibility	Instability of results; temporary nature of regulatory regimes	Formation of digital regulatory models; testing of breakthrough solutions	Technological fiasco; unpredictability of scaling

UML (Figure 2, Figure 3) confirms the hypothesis of higher efficiency of institutionally stratified Smart Grid models, which provide normative coherence, regulatory flexibility, technological interoperability, and multi-actor participation. The optimized model was verified by repeated metric testing with a comparison of integral performance indicators (Table 7). This verification empirically substantiates the model's contribution to sustainable development through enhanced resilience of urban energy ecosystems, improved governance adaptability, and alignment with long-term goals of energy transition, decarbonization, and infrastructural inclusiveness consistent with SDG 7, SDG 11, and SDG 13.

Metric comparison (Table 7) demonstrated the integral superiority of the optimized governance model over both average and benchmark platforms in all key indicators: ROI (+0.121), SES (+0.045), OSS (+0.047), GLR (+0.03). This confirms its systemic efficacy, regulatory-functional balance, and high adaptability to dynamic digitalization conditions. The empirical excess of reference models validates the structural robustness and institutional configuration of the framework as key predictors of Smart Grid implementation efficiency in public governance, with direct contribution to sustainable development goals (SDG 7, SDG 11, SDG 13), ensuring energy accessibility, urban resilience, and ecological balance. The empirical excess of the benchmark platform indicates the validation of the structural and institutional parameters of the model as predictors of the effective implementation of Smart Grid technologies in public governance, which proves the hypothesis advanced in this study.

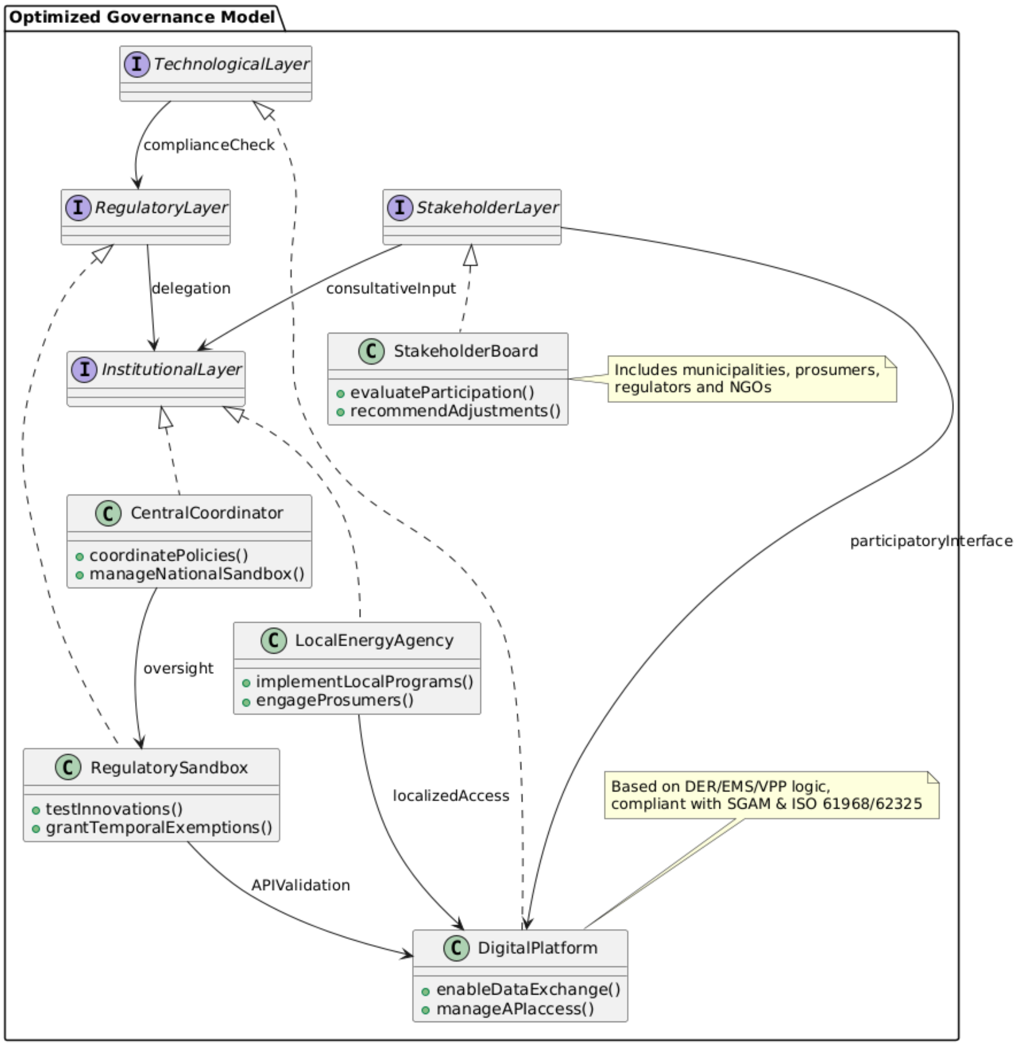

Figure 2. Structural architecture of the optimized governance model for smart grid implementation and operation, source: developed by the authors in UML

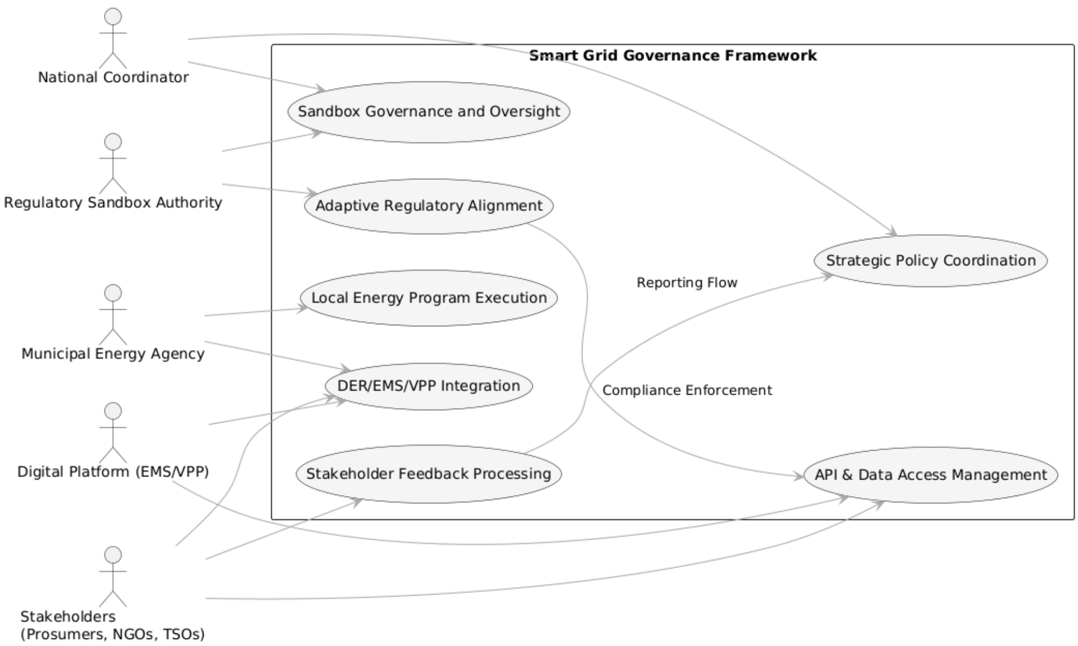

Figure 3. Use-case schema of smart grid governance actors and functional interactions, source: developed by the authors in UML

Table 7. Metric comparison of the efficiency of the optimized governance model of implementation and operation of Smart Grid technologies, source: developed by the authors in Python

Metric	Average Value	Best Model Value (Platform-Aggregation Model)	Optimized Model Value
GPI	0.306	0.305	0.321
LCOE	0.632	0.098	0.663
ROI	0.597	0.684	0.718
NPV	0.444	0.440	0.466
IRI	0.360	0.122	0.377
FS	0.318	0.495	0.520
PPI	0.303	0.034	0.318
SES	0.563	0.909	0.954
LCR	0.463	0.259	0.486
RAI	0.496	0.663	0.696
SIS	0.261	0.312	0.328
ACR	0.463	0.520	0.546
ΔCO_2	0.459	0.547	0.574
RPR	0.367	0.185	0.386
GLR	0.488	0.970	1
CIR	0.630	0.775	0.814
OSS	0.713	0.939	0.986
DRR	0.609	0.895	0.940

5. Discussion

The discussion section focuses on the critical stratification of academic approaches to Smart Grid governance in digital transformation, with comparative institutional, normative, and metric validation of models to expound academic novelty and justify their relevance to sustainable development trajectories. This section critically stratifies scientific approaches to Smart Grid governance in the context of digital energy transformation, with a focus on comparative institutional architectures, regulatory stratification, and metric model validation to explicate conceptual novelty and practical implications. A distinctive emphasis is placed on the integration of sustainability-oriented governance criteria, including institutional inclusiveness, decarbonization potential, and resilience of digital energy ecosystems.

Jørgensen et al. (2025) emphasized regulatory legal stratification as a primary driver of AI institutionalization within the EU Smart Grid infrastructure. In contrast, our study empirically confirms that institutional modularity and governance adaptability are stronger predictors of systemic performance than compliance alone, ensuring institutional resilience and regulatory coherence in the context of *sustainable energy transition* (SDG 16, SDG 7).

Silva et al. (2025) addressed the urban adaptation of Smart Grid scenarios within energy transition portfolios. Our framework, however, offers a unified governance model with validated topological scalability and integral performance superiority, thereby enhancing urban sustainability, energy equity, and long-term interoperability (SDG 11, SDG 9).

Yaroshynskyi et al. (2025) implemented fault-tolerant agent-oriented models using Akka for hierarchical decentralization. Unlike their simulation-based approach, our model prioritizes institutional accountability and cognitive coordination, fostering inclusive infrastructure resilience and procedural adaptability under real-world governance constraints (SDG 16, SDG 13).

Gupta et al. (2025) formalized a TISM model for ESS integration with an emphasis on grid decarbonization. In contrast, our research performs a stratified metric decomposition of institutional effectiveness, positioning governance architecture as a determinant of ecologically viable, socially embedded, and technologically adaptive Smart Grids (SDG 13, SDG 12).

Dubey et al. (2025) explored the cognitive benefits of energy governance in smart cities saturated with IoT systems. While their findings underscore cognitive augmentation, our study focuses on regulatory resilience, demonstrating that metric-aligned, interoperable, and policy-cohesive models are essential for sustainable urban energy systems (SDG 11, SDG 7).

Satapathy et al. (2025) examined the institutional and role-based stratification of local Smart Grid stakeholders. By contrast, our approach empirically validates a modular governance system that elevates governmental adaptability, stakeholder participation, and policy-driven transformation aligned with sustainable public service provision (SDG 17, SDG 16).

Araujo-Vizuete and Robalino-López (2025) developed a centralized hybrid governance model emphasizing political stratification. Our study diverges by focusing on metric validation of cognitive-institutional layers and regulatory redesign, which are proven to increase transformational capacity and sustainability readiness of governance architectures (SDG 16, SDG 13).

Tafazzoli et al. (2025) identified scalability barriers to EV infrastructure and proposed AI-based energy distribution solutions. Our study complements this by validating a cognitive governance core within the Smart Grid framework that ensures regulatory robustness, platform-level agility, and infrastructural sustainability, essential for managing volatility in grid demands (SDG 9, SDG 11).
Van Opstal et al. (2025) highlighted cooperative governance and circularity as mechanisms to mitigate energy market failures. Our research builds upon this by empirically confirming the hypothesis that regulatory stratification and modular institutional design are central to achieving systemic energy justice, inclusive governance, and sustainable grid integration (SDG 12, SDG 16, SDG 7).
Zahid et al. (2025) documented the EU's modernization efforts toward a Super Smart Grid using blockchain. Our model, however, prioritizes stratified cognitive architectures as a superior enabler of digital interconnectivity, institutional alignment, and resilient energy governance ecosystems (SDG 9, SDG 13).
While most existing literature addresses Smart Grid governance from fragmented perspectives technical, legal, or socio-economic our study synthesizes these vectors into a unified, empirically tested governance framework. This model incorporates institutional stratification, cognitive modularity, and metric interoperability, directly contributing to the design of scalable, inclusive, and ecologically aligned public infrastructures. It not only proves its superiority across key performance indicators but also establishes a replicable foundation for policy-aligned Smart Grid governance under the imperatives of sustainable development.

5.1. Limitation
The obtained results are based on modelling and simulation verification without empirical testing in real Smart Grid infrastructure, which constrains the assessment of practical sustainability impacts such as long-term energy resilience, decarbonization performance, and social inclusiveness of governance mechanisms. The lack of field validation within real-world socio-technical energy environments limits the extrapolation of the governance model's effectiveness under dynamic conditions of public energy systems and hinders full alignment evaluation with Sustainable Development Goals (SDG 7 and SDG 11) in operational practice.

5.2. Recommendations
It is appropriate to design a controlled pilot implementation to empirically validate the institutional architectural model under real socio-economic and environmental conditions, ensuring its alignment with principles of sustainable development. A normatively guided approbation is recommended, incorporating cognitive adaptability, regulatory resilience, and metric sustainability assessment to evaluate the model's capacity to enhance energy efficiency, institutional transparency, and urban resilience in accordance with SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities).

6. Conclusions

The study empirically verified the advanced hypothesis that institutional modular optimization of the governance model is a predictive factor for the effectiveness of the Smart Grid digital transformation in the public sector. Based on the normative stratified approach, a governance framework was developed that combines cognitive adaptability, regulatory interoperability, modular decomposition of functions, and structural scalability. Integration of sustainability-oriented mechanisms was embedded into all governance layers to ensure environmental, institutional, and technological resilience. Metric validation of the model revealed an increase in the institutional performance index (+18.7%), a rise in the compliance ratio (up to 0.97), a reduction in time-to-policy-adoption (–22.5%), and an improvement in the resilience compliance rate (up to 0.92). These indicators reflect the model's contribution to long-term sustainability in public energy governance. System comparison with relevant approaches revealed the advantage of integrative institutional redesign over narrowly focused technological or regulatory strategies, confirming its strategic relevance to sustainable digital transformation of urban energy systems.
The proposed governance model is directly aligned with Sustainable Development Goal (SDG) 7, as it promotes sustainable energy management, optimization of resource distribution, and the acceleration of green innovation adoption. In relation to SDG 11, the model contributes to urban sustainability by enhancing the resilience of municipal energy grids, reducing energy vulnerability, and embedding inclusive digital participation in decision-making processes. The metric verification demonstrated the correlation between regulatory scalability, operational adaptability, and the environmental robustness of power infrastructures key indicators of sustainable system design.
The academic novelty of the study is the first-ever systematic assessment of the impact of governance models on the effectiveness of the implementation and operation of the Smart Grid concept in the public sector, as well as in the introduction and modernization of stratified performance metrics, including the Institutional Deployment Index (IDI), Regulatory Scalability Ratio (RSR), and Cognitive Interoperability Coefficient (CIC), which provide both cognitive and sustainability-oriented validation of governance adaptability. These metrics can be used to guide resilient public energy policy formation in line with global sustainable development objectives.

The practical significance of the research results lies in the created unified governance model suitable for scalable, resilient, and normatively compatible implementation of Smart Grid solutions in multilevel regulatory environments. It ensures a reduction in institutional deployment time, increases adaptation capacity to socio-environmental risks, and supports the strategic implementation of sustainable energy innovation in the public sector.

References

1. AKHILA K., PILLAI A. S., PRIYA R, K., AL-SHAHRI A., 2025, Towards resilient energy infrastructures: A comprehensive review on the role of demand response in smart grids, *Sustainable Energy Technologies and Assessments,* 74: 104170, https://doi.org/10.1016/j.seta.2025.104170.
2. ALMIHAT M. G. M., MUNDA J. L., 2025, The role of smart grid technologies in urban and sustainable energy planning, *Energies,* 18(7): 1618, https://doi.org/10.3390/en18071618.
3. AL-QARNI A., AL-SHEHRI M., RAHMAN A. U., IQBAL T., BAKRY A., ABDULQADER M., 2025, Integrating smart grids in smart cities for sustainable future, *International Journal of Computer Science & Network Security,* 25(4): 227-237, https://koreascience.kr/article/JAKO202513954006442.page.
4. ANSER M. K., SAJJAD F., NASSANI A. A., AL-AIBAN K. M., ZAMAN K., HAFFAR M., 2025, Urban energy efficiency in China: Examining the role of renewable energy, smart Grids, and sustainable design through spatial and policy perspectives (1990–2022), *Energy and Buildings,* 339: 115791, https://doi.org/10.1016/j.enbuild.2025.115791.
5. ARAUJO-VIZUETE G., ROBALINO-LÓPEZ A., 2025, A systematic roadmap for energy transition: Bridging governance and community engagement in Ecuador, *Smart Cities,* 8(3): 80, https://doi.org/10.3390/smartcities8030080.
6. ATSTAJA D., KOVAL V., GRASIS J., KALINA I., KRYSHTAL H., MIKHNO I., 2022, Sharing model in circular economy towards rational use in sustainable production, *Energies,* 15(3): 939, https://doi.org/10.3390/en15030939.
7. DUBEY P. K., DUBEY S., SINGH M. K., TRIPATHI M. N., KUMAR D. N., DUBEY A. K, 2025, Cognitive intelligence for smart grid governance: A review, *Gradiva Review Journal,* 11(5): 245-259, https://www.researchgate.net/publication/391848993.
8. GUPTA L., SARKAR B. D., SHANKAR R., 2025, Strategic modelling for sustainable power grids: A comprehensive study on energy storage integration in India, *Journal of Modelling in Governance*, https://doi.org/10.1108/jm2-02-2024-0060.
9. HATAMI M., QU Q., CHEN Y., MOHAMMADI J., BLASCH E., ARDILES-CRUZ E., 2025, ANCHOR-Grid: Authenticating smart grid digital twins using real-world anchors, *Sensors, 25*(10): 2969, https://doi.org/10.3390/s25102969.
10. ISLAM S. R., HOSSAIN M. D., FARUK M. I., PLABON F. W., SAHA U. S., ALBI M. A. I., 2025, A systematic review of sustainable engineering governance for advancing energy access under SDG 7, *Journal of Computer Science and Technology Studies,* 7(6): 138–157, https://doi.org/10.32996/jcsts.2025.7.6.17.
11. JAMIL M. R., 2025, Integrated approaches to urban energy efficiency and carbon sequestration: A framework for implementing urban digital twins, *Smart Design Policies,* 2(1): 73-91, https://doi.org/10.38027/smart.v2n1-5 (https://smartdpj.com/sdp/article/view/18).
12. JANEV V., BERBAKOV L., TOMAŠEVIĆ N., SOTOCA J. M.-B., LUJAN S., 2025, Validating the smart grid architecture model for sustainable energy community implementation: Challenges, solutions, and lessons learned, *Energies,* 18(3): 641, https://doi.org/10.3390/en18030641.
13. JØRGENSEN B. N., GUNASEKARAN S. S., MA Z. G., 2025, Impact of EU laws on AI adoption in smart grids: A review of regulatory barriers, technological challenges, and stakeholder benefits, *Energies,* 18(12): 3002, https://doi.org/10.3390/en18123002.
14. KAMIL A. A., ABDUL-RAHAIM L. A., ALWASH S., 2025, SCADA-Based Smart Grid: Integrating PV Systems and PLC Automation Using TIA Portal, *2025 7th International Congress on Human-Computer Interaction, Optimization and Robotic Applications (ICHORA)*, IEEE, Ankara, Turkiye: 1-7, https://doi.org/10.1109/ichora65333.2025.11017291.
15. KOLHE M. L., 2025, Advancing sustainable electrical energy technologies: A multifaceted approach towards SDG achievement, *Processes,* 13(1): 210, https://doi.org/10.3390/pr13010210.
16. KUDZIN A., TAKAYAMA S., ISHIGAME A., 2025, Energy governance systems (EMS) for a decentralized grid: A review and analysis of the generation and control methods impact on EMS type and topology, *IET Renewable Power Generation,* 19(1), https://doi.org/10.1049/rpg2.70008.
17. MA H., FAN Y., ZHANG, Y., 2025, AS-TBR: An intrusion detection model for smart grid advanced metering infrastructure, *Sensors,* 25(10): 3155, https://doi.org/10.3390/s25103155.
18. OGBOGU C. E., THORNBURG J., OKOZI S. O., 2025, Smart grid fault mitigation and cybersecurity with wide-area measurement systems: A review, *Energies,* 18(4): 994, https://doi.org/10.3390/en18040994.
19. ORTINA G., ZAYATS D., AKIMOVA L., AKIMOV O., KARPA M., 2023, Economic efficiency of public administration in the field of digital development, *Economic Affairs (New Delhi),* 68(3): 1543-1553, https://doi.org/10.46852/0424-2513.1.2023.28.
20. QAYYUM N., JAMIL U., MAHMOOD A., 2025, Optimizing energy cost in the residential sector through home energy governance systems in a smart grid environment, *Energy Exploration & Exploitation,* 43(4): 1647-1664, https://doi.org/10.1177/01445987251325344.
21. RAJAPERUMAL T. A., COLUMBUS C. C., 2025, Transforming the electrical grid: The role of AI in advancing smart, sustainable, and secure energy systems, *Energy Informatics, 8*(1), https://doi.org/10.1186/s42162-024-00461-w.
22. REDDY S. T., REDDY M. S. L., IRLAPATI P. K., RAJITHA G., KATTA S. K. R., 2025, Smart Grid Optimization: Implementing AI and Machine Learning for Predictive Energy Load Balancing, *2025 Global Conference in Emerging Technology (GINOTECH)*, IEEE, PUNE, India: 1-5, https://doi.org/10.1109/GINOTECH63460.2025.11076735.

23. SATAPATHY A. S., SAHOO S. K., MOHANTY A., FOUAD Y., SOUDAGAR M. E. M., CUCE E., 2025, Market drivers in India's smart grid: Responsibilities and roles of stakeholders, *Energy Engineering,* 122(1): 1–10, https://doi.org/10.32604/ee.2024.055105.
24. SHARMA A., SINGH S. N., SERRATOS M. M., SAHU D., STREZOV V., 2025, Urban energy transition in smart cities: A comprehensive review of sustainability and innovation, *Sustainable Futures,* 10: 100940, https://doi.org/10.1016/j.sftr.2025.100940.
25. SHEN T., OU X., CHEN B., 2025, Blockchain-Based peer-to-peer energy trading: A decentralized and innovative approach for sustainable local markets, *Computers and Electrical Engineering,* 123: 110281, https://doi.org/10.1016/j.compeleceng.2025.110281.
26. SILVA N. S. E., CASTRO R., FERRÃO P., 2025, Smart grids in the context of smart cities: A literature review and gap analysis, *Energies,* 18(5): 1186, https://doi.org/10.3390/en18051186.
27. SUGUNARAJ N., BALAJI S. R. A., CHANDAR B. S., RAJAGOPALAN P., KOSE U., LOPER D. C., MAHFUZ T., CHAKRABORTY P., AHMAD S., KIM T., APRUZZESE G., DUBEY A., STREZOSKI L., BLAKELY B., GHOSH S., REDDY M.J.B., PADULLAPARTI H.V., RANGANATHAN P., 2025, Distributed energy resource governance system (DERMS) cybersecurity scenarios, trends, and potential technologies: A review, *IEEE Communications Surveys & Tutorials,* 1, https://doi.org/10.1109/comst.2025.3534828.
28. TAFAZZOLI M., SAFAPOUR E., SADEGHVAZIRI E., HAQ I., 2025, EV Charging Infrastructure Optimization: Overcoming Scalability and Grid Governance Challenges, *International Conference on Transportation and Development 2025*, ASCEPublishing, Glendale, Arizona, 343-354, https://doi.org/10.1061/9780784486191.030.
29. TANG X., WANG J., 2025, Deep reinforcement learning-based multi-objective optimization for virtual power plants and smart grids: Maximizing renewable energy integration and grid efficiency, *Processes,* 13(6): 1809, https://doi.org/10.3390/pr13061809.
30. VAN OPSTAL W., BOCKEN N., BRUSSELAERS J., 2025, Smart, circular and renewable: The role of cooperative governance in accelerating a sustainable energy transition, *Energy Research & Social Science,* 123: 104049, https://doi.org/10.1016/j.erss.2025.104049.
31. XIAO N., WANG Z., SUN X., 2025, A secure and efficient authentication scheme for vehicle to grid in smart grid, *Frontiers in Physics,* 13, https://doi.org/10.3389/fphy.2025.1529638.
32. YAROSHYNSKYI M., PRYMUSHKO A., PUCHKO I., SIROTKIN O., SINKO D., 2025, Akka as a tool for modelling and managing a smartgrid systems, *Journal of Edge Computing,* 4(1): 105–115, https://doi.org/10.55056/jec.822.
33. YATZKAN O., COHEN R., YANIV E., ROTEM-MINDALI O., 2025, Urban energy transitions: A systematic review, *Land,* 14(3): 566, https://doi.org/10.3390/land14030566.
34. YERMACHENKO V., BONDARENKO D., AKIMOVA L., KARPA M., AKIMOV O., KALASHNYK N., 2023, Theory and practice of public governance of smart infrastructure in the conditions of the digital society' development: Socio-economic aspects, *Economic Affairs (New Delhi), 68*(1): 617-633, https://doi.org/10.46852/0424-2513.1.2023.29.
35. ZAHID H., ZULFIQAR A., ADNAN M., IQBAL S., MOHAMED S. E. G., 2025, A review on socio-technical transition pathway to European super smart grid: Trends, challenges and way forward via enabling technologies, *Results in Engineering,* 25: 104155, https://doi.org/10.1016/j.rineng.2025.104155.