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Governance of electricity markets under decentralized generation, storage technologies, and smart grid regulation frameworks worldwide

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Abstract

Electricity markets worldwide are undergoing profound structural change driven by the rapid deployment of decentralized generation, advanced storage technologies, and smart grid systems. From a broad governance perspective, these developments challenge the traditional centralized utility model and require new regulatory approaches to ensure efficiency, reliability, equity, and system security. Market governance is increasingly shaped by the interaction between digitalization, prosumer participation, flexible demand, and real-time system management, redefining the roles of regulators, system operators, and market participants. This study examines the governance of electricity markets under decentralized energy architectures, with particular emphasis on the regulatory implications of distributed renewable generation, energy storage integration, and smart grid frameworks. It analyses how contemporary governance models address issues such as market access, tariff design, data governance, interoperability standards, and coordination between transmission and distribution system operators. The study highlights how regulatory instruments including grid codes, flexibility markets, peer-to-peer trading rules, and incentive-based regulation are being adapted to accommodate bidirectional power flows and decentralized decision-making while maintaining system stability. Through a comparative assessment of international regulatory frameworks, the analysis identifies divergent approaches to balancing innovation with oversight, particularly in relation to consumer protection, cybersecurity, and investment incentives. The paper further narrows its focus to the governance challenges posed by storage technologies, which blur the boundaries between generation, consumption, and network services, complicating market classification and remuneration structures. Smart grid regulation is examined as a critical enabler of decentralized markets, facilitating real-time monitoring, automation, and data-driven coordination across the electricity value chain. The findings suggest that effective governance of decentralized electricity markets depends on adaptive regulation, institutional coordination, and regulatory clarity that evolves alongside technological change. The paper contributes to global policy discourse by outlining governance principles capable of supporting resilient, efficient, and participatory electricity markets in the transition toward low-carbon energy systems.

Keywords: Electricity Market Governance; Decentralized Generation; Energy Storage; Smart Grids; Regulatory Frameworks; Power System Transformation

1. Introduction

1.1. Evolution from Centralized to Decentralized Power Systems

Electricity systems were historically developed around centralized power generation and vertically integrated utilities, where generation, transmission, distribution, and retail functions were coordinated within single monopoly entities [1]. This model was justified by economies of scale, high capital intensity, and the technical necessity of real-time balancing in power systems. Regulatory oversight focused primarily on cost recovery, rate-of-return regulation, and universal

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service obligations, with limited scope for competition or consumer choice [2]. Over time, wholesale market liberalization and unbundling reforms introduced competition at the generation and retail levels, yet system architecture largely remained centralized in physical and operational terms [1].

The past two decades have witnessed a gradual but structural shift toward decentralized power systems. The rapid deployment of renewable energy technologies, particularly solar photovoltaics and onshore wind, reduced minimum efficient scale and enabled generation closer to the point of consumption [2]. Advances in digital technologies, automation, and real-time data analytics further weakened the operational dominance of centralized control. At the same time, policy incentives encouraged household and commercial participation in electricity production, transforming passive consumers into active prosumers [3]. Distributed energy resources began to challenge traditional assumptions about unidirectional power flows, predictable load profiles, and central dispatch authority.

This evolution has not replaced centralized systems outright but has resulted in increasingly hybrid electricity architectures. Central generation continues to play a critical role in system adequacy, while decentralized assets contribute flexibility, resilience, and emissions reduction. The coexistence of these models fundamentally alters the governance requirements of electricity markets [4].

1.2. Governance Challenges in the Age of Distributed Energy Resources

The expansion of distributed energy resources introduces complex governance challenges that extend beyond technical system operation. Coordination becomes more demanding as millions of small-scale assets interact dynamically with distribution and transmission networks. Traditional market designs, optimized for large generators and predictable dispatch, struggle to integrate decentralized actors efficiently without increasing transaction costs or operational risk [5]. This creates tension between market efficiency and inclusivity, as regulatory frameworks must balance simplicity with the need to accommodate diverse participation models.

System reliability also emerges as a governance concern rather than solely an engineering issue. Variability in renewable output, coupled with decentralized decision-making, complicates forecasting and real-time balancing responsibilities [6]. Distribution networks, historically passive, now face active system management roles without always having corresponding regulatory authority or incentives. Fragmentation of regulatory competencies between national, regional, and local institutions further exacerbates these challenges [7].

In addition, decentralization raises questions of equity and cost allocation. Network tariffs, legacy infrastructure costs, and system service obligations must be distributed fairly between participants who both consume and produce electricity [8]. Without coherent governance, decentralized markets risk undermining public trust, investment certainty, and long-term system adequacy.

1.3. Objectives, Scope, and Structure of the Article

Against this backdrop, this article examines the governance of electricity markets under conditions of decentralized generation, expanding storage deployment, and smart grid integration. Its primary objective is to analyses how regulatory frameworks and institutional arrangements are adapting to technological change while maintaining core public policy goals such as reliability, efficiency, affordability, and security of supply [9]. Rather than focusing on a single jurisdiction, the article adopts a comparative and conceptual approach to identify common governance patterns and structural tensions.

The scope of the analysis encompasses market design, regulatory oversight, and actor coordination across transmission and distribution levels. Particular attention is given to the evolving roles of regulators, system operators, and market participants in managing decentralized electricity systems [10]. Energy storage and digital grid technologies are treated as cross-cutting enablers that reshape governance boundaries rather than isolated technical solutions.

The article is structured to progress logically from conceptual foundations to applied governance challenges. Following this introduction, Section 2 outlines the theoretical basis of electricity market governance. Subsequent sections examine decentralized generation, storage integration, smart grid regulation, and comparative international frameworks, culminating in a synthesis of policy implications [11].

2. Conceptual Foundations of Electricity Market Governance

2.1. Market Governance and Regulatory Theory in Electricity Systems

Electricity market governance refers to the set of legal, institutional, and regulatory arrangements through which electricity systems are coordinated, monitored, and steered toward public policy objectives. Unlike conventional commodity markets, electricity markets exhibit natural monopoly characteristics in network infrastructure, extreme sensitivity to imbalance, and limited short-term substitutability [12]. As a result, governance frameworks have historically relied on strong regulatory intervention to correct market failures and ensure system integrity.

Economic regulation theory provides the foundation for understanding these interventions. Traditional approaches emphasised price regulation and cost-based oversight to prevent monopoly abuse. Over time, incentive-based regulation emerged to promote efficiency, innovation, and service quality by aligning private incentives with public goals [13]. Institutional design theory further highlights the importance of clearly defined roles, accountability mechanisms, and coordination between regulatory bodies and market operators.

Public–private coordination is particularly salient in electricity governance. System operators manage real-time technical constraints, while regulators define market rules and long-term investment signals. Effective governance depends on information symmetry, regulatory credibility, and adaptive rule-making capable of responding to technological change [1]. In decentralised contexts, these theoretical foundations are tested by increased actor diversity and system complexity.

2.2. Centralised versus Decentralised Market Architectures

Centralised electricity market architectures are characterised by large-scale generation assets, hierarchical system control, and wholesale markets designed around marginal cost dispatch. Governance mechanisms in such systems prioritise coordination efficiency, central forecasting, and standardised participation rules [2]. Regulatory authority is typically concentrated at the national level, with limited operational autonomy for distribution networks.

By contrast, decentralised architectures distribute generation, flexibility, and decision-making across the system. Local energy markets, distributed storage, and demand response introduce multiple layers of interaction that challenge centralised optimisation models [3]. Governance shifts from command-and-control structures toward facilitative and enabling regulation, where regulators define frameworks rather than direct outcomes.

Hybrid models increasingly dominate contemporary electricity systems. Centralised markets continue to provide bulk energy and capacity adequacy, while decentralised mechanisms supply flexibility and resilience [4]. This coexistence requires governance arrangements capable of managing interfaces between transmission-level markets and distribution-level activities. Poorly aligned architectures risk inefficiencies, double remuneration, or conflicting signals to market participants [5].

Understanding the governance implications of these contrasting architectures is essential for designing regulatory frameworks that accommodate decentralisation without sacrificing system-wide coordination or economic efficiency.

2.3. The Changing Roles of Regulators, System Operators, and Market Actors

Decentralisation fundamentally alters the roles and responsibilities of electricity sector actors. Regulators increasingly act as system designers, tasked with creating adaptive rules that accommodate innovation while safeguarding public interests [6]. This requires greater engagement with data governance, flexibility markets, and performance-based oversight mechanisms.

System operators also face expanded mandates. Transmission system operators must coordinate with distribution system operators managing active networks with bidirectional flows [7]. Distribution operators, in turn, transition from passive asset managers to local system coordinators, raising governance questions around neutrality, market facilitation, and information access [8].

Market actors diversify as prosumers, aggregators, and digital service providers enter the electricity landscape. These actors blur traditional distinctions between producers and consumers, challenging licensing, compliance, and accountability frameworks [9]. Governance systems must therefore manage increased participation without undermining transparency or system security.

Collectively, these evolving roles underscore the need for coherent governance structures that align institutional responsibilities with technical realities. The interaction between regulators, operators, and market participants becomes a central determinant of decentralised electricity market performance [10].

3. Governance Of Decentralised Generation In Electricity Markets

3.1. Regulatory Treatment of Distributed Renewable Energy

The regulatory treatment of distributed renewable energy represents one of the most consequential governance shifts in contemporary electricity markets. Historically, licensing regimes were designed for large, centralised generators and imposed administrative and financial burdens ill-suited to small-scale renewable installations [13]. In response, many jurisdictions introduced simplified permitting, capacity thresholds, and standardised connection procedures to reduce barriers to entry for distributed generators.

Grid access regulation has become a central governance issue as distributed renewable penetration increases. Priority or guaranteed grid access mechanisms were initially adopted to accelerate renewable deployment and support decarbonisation objectives [14]. While effective in early market development, these measures increasingly interact with network congestion, local voltage constraints, and balancing responsibilities. Regulators have therefore begun reassessing priority dispatch rules to ensure system security without discouraging investment [15].

Market participation rules further illustrate the evolving governance landscape. Distributed renewable producers are gradually transitioning from fixed feed-in remuneration schemes toward market-based participation models, including net billing and direct market access [16]. This shift reflects a broader regulatory objective of exposing decentralised generators to price signals while maintaining revenue stability. However, uneven implementation across jurisdictions creates governance asymmetries that affect investment behaviour and cross-border market integration [17].

Overall, the regulatory treatment of distributed renewable energy demonstrates the tension between facilitative governance and system coordination. Effective frameworks must balance accessibility, transparency, and operational responsibility as decentralised generation becomes a structural component of electricity systems.

3.2. Prosumers, Peer-to-Peer Trading, and Local Energy Markets

The emergence of prosumers marks a significant departure from traditional consumer roles in electricity markets. Prosumers simultaneously generate, consume, and sometimes store electricity, challenging regulatory frameworks premised on clear functional separation [18]. Governance responses initially focused on enabling self-consumption through simplified connection rules and compensation mechanisms for surplus generation.

Beyond individual participation, peer-to-peer trading and local energy markets represent more collective governance innovations. These models allow participants to exchange electricity locally using digital platforms, often outside conventional wholesale market structures [19]. Regulators face the challenge of enabling experimentation while ensuring consumer protection, system integrity, and compliance with market principles. As a result, many peer-to-peer arrangements operate within regulatory sandboxes or pilot frameworks designed to limit systemic risk [20].

Local energy markets also raise questions of institutional coordination. Distribution system operators play a critical role in facilitating local transactions while maintaining network neutrality. Governance frameworks must therefore define clear boundaries between market facilitation and network operation to avoid conflicts of interest [21]. Additionally, data access and settlement arrangements become central governance concerns as transaction volumes increase.

While prosumer-led markets enhance participation and local optimisation, their integration into broader electricity systems remains uneven. Governance mechanisms must ensure that local innovation complements, rather than fragments, system-wide efficiency and reliability objectives [22].

3.3. Network Charges, Tariff Design, and Cost Allocation

As decentralised generation expands, network charges and tariff design become central governance instruments for ensuring equity and efficiency. Traditional volumetric tariffs, based on energy consumption, are increasingly misaligned with cost drivers in systems where users both consume and export electricity [23]. This creates revenue adequacy risks for network operators and raises concerns about cost shifting between participant groups.

Regulators have responded by exploring alternative tariff structures, including capacity-based charges, time-of-use pricing, and locational signals. These approaches aim to reflect network utilisation more accurately while preserving incentives for decentralised investment [24]. However, tariff reform remains politically sensitive, particularly where changes affect residential consumers.

Cost allocation governance also intersects with social equity considerations. Households without access to distributed generation may bear a disproportionate share of legacy network costs if tariff reforms are poorly designed [13]. Regulators must therefore balance economic efficiency with fairness and public acceptance.

The governance of network charges serves as a critical link between decentralised participation and system sustainability. Well-designed tariffs can align individual behaviour with system needs, while poorly coordinated reforms risk undermining trust and long-term investment signals.

Table 1 Comparative overview of tariff and network charge approaches for decentralised generation across selected jurisdictions

Jurisdiction	**Export remuneration approach**	**Self-consumption / bill offset**	**Network charge approach for decentralised generators**	**Notable features / recent direction**
Great Britain (UK)	Wholesale-linked export (via supplier "export tariffs"; not a universal regulated feed-in tariff). Embedded generators may also receive Transmission Embedded Export Tariff (EET) credits in relevant zones. [1–3]	Self-consumed energy reduces imports at retail price (supplier tariff), while exports are paid separately (supplier contract).	DUoS (distribution use of system) and TNUoS (transmission network use of system) methodologies apply; reforms have shifted residuals toward fixed/asset-based charges to reduce distortionary incentives. Ongoing DUoS SCR reform workstream. [1,4]	"Embedded benefits" have been progressively re-shaped (notably around residual charging and embedded export signals). DUoS charging reform is explicitly underway. [1,4]
Germany	EEG feed-in tariff / market premium: legally defined remuneration for eligible PV exports; rates adjust over time and by system size/segment. [5,6]	Widespread prosumption: self-consumption offsets retail purchases; export receives EEG-set remuneration (if eligible).	Network charges exist across the system; policy debate includes how producers/prosumers should contribute to grid tariffs as DER penetration rises. [6]	Recent documentation highlights tariff levels for small rooftop PV and continuing adjustments to remuneration. [5]
Australia (NEM states/territories)	Move from simple net metering toward export pricing / export tariffs (including proposals/approvals enabling DNSPs to charge for exports) alongside dynamic export management. [7,8]	Self-consumption reduces imported kWh at retail rates; exports credited/charged depending on DNSP/export tariff design and retailer plans.	DNSPs may deploy export tariffs and Dynamic Operating Envelopes (DOE) or flexible export limits to manage hosting capacity and congestion. [7,8]	Regulatory materials explicitly contemplate export tariffs and DOE-style operating limits to better align DER exports with network constraints. [7,8]
California (USA)	Net Energy Metering / Net Billing: CPUC describes transition to Net Billing Tariff (often called NEM 3.0) where export compensation is not retail netting and is tied to avoided-cost style values; annual true-up and "net surplus compensation" concepts exist. [9]	Imports are billed at retail; exports earn credits under the applicable NEM/NBT rules rather than simple 1:1 retail netting.	Interconnection rules and tariff structures vary by utility; CPUC overview highlights program structure, including treatment of surplus and customer-generator conditions. [9]	Policy emphasis has shifted toward time-differentiated export value under net billing (moving away from full retail netting). [9]
South Africa	Emerging net billing / export tariff practices (often municipal/Eskom tariff schedules; compensation frameworks are becoming more formalised). [10,11]	Self-consumption offsets imports; exported energy may be credited under approved municipal/Eskom	Tariff schedules and municipal wheeling frameworks govern how embedded generators and third-party transactions interact with network charges and wheeling fees. [10–12]	National/municipal guidance documents show active development of wheeling and embedded generation tariff structures, with increasing

		arrangements where available.		formalisation in municipal contexts. [11,12]
Philippines	Net metering under the Renewable Energy Act framework: customer-generators can export surplus to the distribution utility under program rules. [13,14]	Net metering offsets consumption over the billing period according to national rules; typically aimed at small systems (program-defined limits). [13,14]	Distribution frameworks define charges (including distribution wheeling charges terminology in regulatory materials) and technical/program requirements. [13,15]	The DOE (Department of Energy) describes net metering as a fully implemented mechanism under the RE Act; wheeling/charges terminology appears in formal rule sets. [13–15]
Singapore	Excess solar can be paid for (mechanism depends on consumer contestability and arrangements), with exports typically settled commercially/under regulated frameworks rather than classic net metering. [16]	Onsite solar offsets consumption first; surplus exported may be remunerated based on the applicable consumer category/market arrangement.	Grid connection/service charges apply; export settlement depends on market contestability status and arrangements with the relevant parties. [16]	

4. Governance Implications of Energy Storage Integration

4.1. Storage Technologies and Market Role Ambiguity

Energy storage technologies introduce profound governance challenges due to their multifunctional nature. Storage can act as generation when discharging, as load when charging, and as a provider of system services such as frequency regulation and congestion management [14]. This role ambiguity complicates regulatory classification and market integration.

Historically, electricity regulation relied on functional distinctions between generation, consumption, and network activities. Storage disrupts these categories, exposing gaps in licensing regimes, grid codes, and market participation rules [15]. Governance frameworks must therefore evolve beyond asset-based classification toward service-based regulation.

The system value of storage is context-dependent, varying by location, time, and market design. Centralised storage assets may support transmission-level balancing, while distributed storage enhances local flexibility and resilience [16]. Without coherent governance, these benefits risk being underutilised or double-counted.

As storage deployment accelerates, regulatory clarity becomes essential to avoid investment uncertainty and market distortion. Governance responses increasingly recognise storage as a cross-cutting system resource rather than a discrete technology category [17].

4.2. Regulatory Classification and Market Access for Storage Assets

Regulatory classification directly determines storage access to electricity markets. In some jurisdictions, storage is treated as generation, subjecting it to licensing and market participation rules designed for power plants [18]. In others, storage is classified as a network asset, raising concerns about competitive neutrality and unbundling compliance.

Ownership models represent a particularly sensitive governance issue. Allowing system operators to own storage assets may enhance system optimisation but risks crowding out competitive providers [19]. Conversely, restricting ownership can limit deployment where market incentives are insufficient. Regulators must therefore balance efficiency, competition, and system security objectives.

Market access rules further shape storage participation. Storage assets increasingly seek access to multiple markets, including energy, capacity, and ancillary services [20]. Governance frameworks must accommodate such stacking of revenues without enabling arbitrage that undermines market integrity.

Clear regulatory classification is critical for unlocking storage's system value. Ambiguity increases transaction costs, delays investment, and complicates coordination between system operators and market participants [21].

4.3. Remuneration Mechanisms and Flexibility Markets

Remuneration mechanisms are central to the governance of storage integration. Traditional energy-only markets often fail to reflect the full system value of flexibility, prompting the development of dedicated flexibility markets and capacity mechanisms [22]. Storage assets are well positioned to participate in these arrangements due to their rapid response capabilities.

Flexibility markets operate at both transmission and distribution levels, creating new governance interfaces. Distribution-level flexibility procurement enables local congestion management but requires coordination with wholesale markets to avoid conflicting signals [23]. Regulators increasingly act as arbiters between overlapping market layers.

Performance-based remuneration is gaining prominence as governance frameworks shift toward valuing outcomes rather than assets. Storage compensation is increasingly linked to availability, response time, and system contribution [24]. This approach aligns private incentives with public system needs but requires robust monitoring and verification mechanisms.

Effective remuneration governance ensures that storage supports reliability and efficiency without distorting competition. As flexibility becomes a defining feature of electricity markets, governance frameworks must continue evolving to reflect its strategic importance.

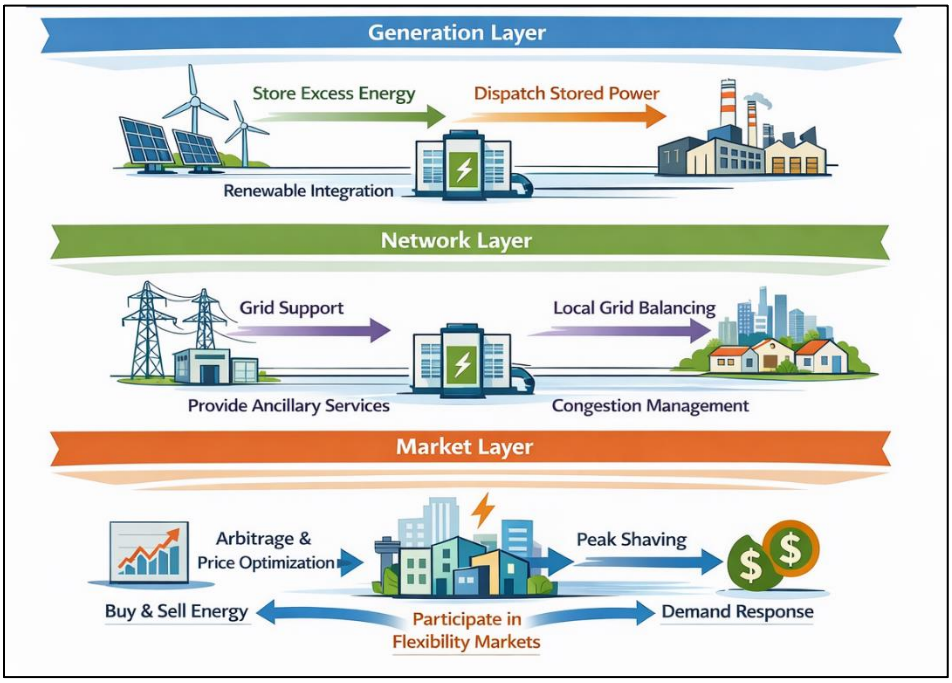

Figure 1 Illustrative schematic of storage participation across generation, network, and market layers

5. Smart Grids as A Governance Enabler for Decentralised Markets

5.1. Smart Grid Architecture and Regulatory Relevance

Smart grid architecture represents a foundational shift in how electricity systems are governed, monitored, and coordinated. Unlike traditional grids built around passive infrastructure and periodic data reporting, smart grids integrate advanced sensors, automated control systems, and real-time communication technologies across generation, network, and consumption layers [22]. This digital infrastructure enhances system observability, enabling regulators and system operators to move from retrospective oversight toward proactive governance.

From a regulatory perspective, smart grids expand governance capacity by improving information symmetry between market participants and oversight institutions. Granular data on network conditions, load behaviour, and distributed resource performance allows regulators to design more targeted interventions and refine market rules [23]. Distribution system operators, in particular, gain enhanced visibility over local networks, supporting their evolving role as active system managers rather than asset custodians.

Smart grid deployment also reshapes accountability structures. Automated decision-making and algorithmic control introduce new governance questions regarding transparency, auditability, and regulatory supervision [24]. Regulators must ensure that digital control systems align with public policy objectives and remain subject to oversight, even when operational decisions occur at machine speed.

Overall, smart grid architecture functions as an institutional enabler rather than merely a technical upgrade. Its regulatory relevance lies in its capacity to support decentralised coordination, enable new market designs, and strengthen oversight in increasingly complex electricity systems [25].

5.2. Data Governance, Interoperability, and Cybersecurity

As electricity systems become data-intensive, governance increasingly depends on robust data management frameworks. Smart grids generate vast volumes of operational, commercial, and consumer data, raising questions about ownership, access rights, and permissible use [26]. Effective data governance is essential to ensure fair competition, protect consumer interests, and support regulatory monitoring.

Interoperability represents a critical governance concern. Decentralised markets rely on seamless communication between devices, platforms, and system operators across multiple layers of the electricity system [27]. Without common standards, fragmented digital ecosystems risk creating barriers to entry and undermining system efficiency. Regulators therefore play a key role in promoting open standards and preventing vendor lock-in.

Cybersecurity introduces additional regulatory complexity. Increased digital connectivity expands the attack surface of electricity systems, transforming cybersecurity from a technical issue into a governance priority [28]. Regulators must define minimum security requirements, incident reporting obligations, and coordination mechanisms between energy authorities and national security institutions.

Balancing innovation with risk mitigation remains a central governance challenge. Excessively prescriptive rules may stifle technological development, while insufficient safeguards expose critical infrastructure to systemic threats. Data governance frameworks must therefore evolve alongside smart grid deployment, ensuring trust, resilience, and institutional legitimacy in decentralised electricity markets [29].

5.3. Incentive-Based Regulation and Performance-Oriented Grid Oversight

Smart grids enable a shift from asset-based regulation toward performance-oriented governance models. Traditional regulatory frameworks rewarded capital investment in physical infrastructure, often incentivising network expansion regardless of utilisation [30]. In contrast, smart grid capabilities allow regulators to focus on outcomes such as reliability, efficiency, flexibility, and service quality.

Incentive-based regulation links operator remuneration to measurable performance indicators. These may include reductions in outage duration, efficient integration of distributed resources, or improved congestion management [22]. Smart grids provide the data infrastructure necessary to monitor such metrics accurately and in near real time.

Performance-oriented oversight also supports innovation by granting operators flexibility in how they achieve regulatory objectives. Rather than prescribing specific technologies, regulators define desired outcomes and allow market actors to determine optimal solutions [31]. This approach aligns governance with the dynamic nature of decentralised systems.

However, performance-based regulation requires careful design. Metrics must be transparent, verifiable, and resistant to manipulation. Regulators must also ensure that incentives do not encourage cost externalisation or compromise long-term system resilience. When properly implemented, incentive-based governance leverages smart grid capabilities to align private behaviour with public electricity system goals.

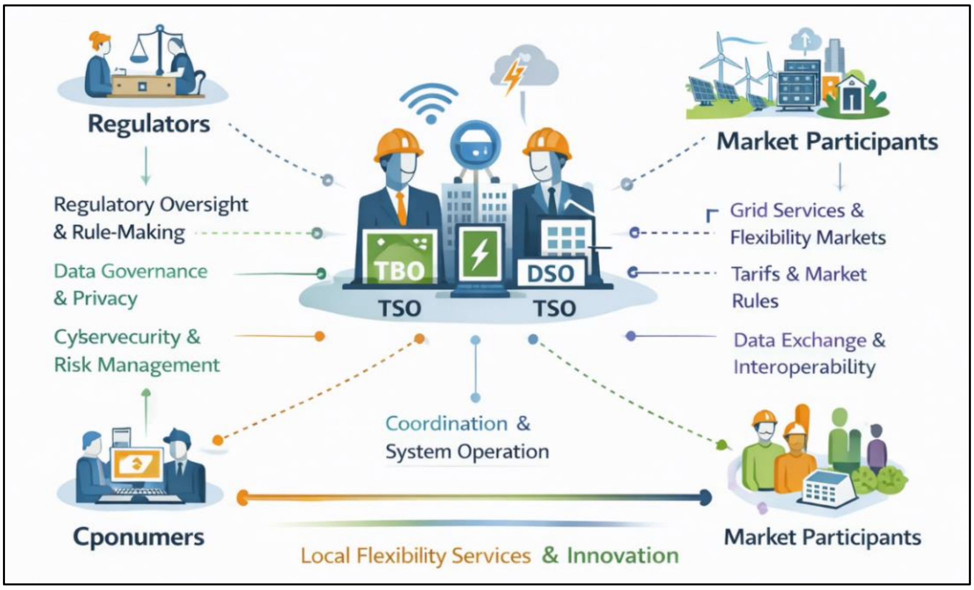

Figure 2 Smart grid-enabled governance interactions between regulators, DSOs, TSOs, and market participants

6. Comparative International Governance Frameworks

6.1. Europe: Distribution-Centric Governance and Market Integration

European electricity governance is characterised by a strong emphasis on market integration alongside increasing decentralisation. Regional market coupling mechanisms enable cross-border trade, while national regulators oversee the integration of distributed resources within harmonised legal frameworks [23]. Distribution system operators play a growing role in facilitating flexibility and coordinating local markets.

Governance arrangements emphasise coordination between transmission and distribution levels. Regulatory initiatives promote data sharing, standardisation, and neutrality to prevent discrimination against decentralised participants [24]. At the same time, European frameworks seek to align decentralised innovation with broader market integration objectives, avoiding fragmentation across member states.

The European approach reflects a governance balance between central coordination and local empowerment. Decentralised generation and flexibility are encouraged, but within a structured institutional framework that preserves market efficiency and system security [25].

6.2. North America: State-Level Experimentation and Market Diversity

In North America, electricity governance exhibits significant diversity due to the prominence of state and provincial regulatory authority. Decentralisation has progressed unevenly, with some jurisdictions adopting advanced distribution-level market reforms while others retain conventional utility models [26]. This regulatory pluralism fosters experimentation but complicates coordination.

State regulators often act as policy laboratories, testing new tariff structures, market participation rules, and utility business models [27]. However, fragmented governance can create inconsistent incentives and regulatory uncertainty for market participants operating across jurisdictions.

Regional transmission organisations provide some coordination at the wholesale level, but distribution-level governance remains highly localised. The North American experience illustrates both the strengths and limitations of decentralised regulatory authority in managing technological change [28].

6.3. Asia-Pacific: Rapid Deployment and Centralised Coordination Models

Asia-Pacific electricity systems are shaped by rapid demand growth and large-scale infrastructure expansion. Governance frameworks often prioritise central coordination to ensure system adequacy and investment certainty [29]. Decentralised generation and smart grids are deployed within centrally planned policy objectives.

Regulators play a directive role in steering technology adoption, often through national development strategies. While decentralisation is expanding, governance remains anchored in strong central institutions that manage system planning and market rules [30].

This approach enables rapid deployment but may limit local experimentation. Asia-Pacific governance models highlight the trade-offs between speed, coordination, and flexibility in decentralised electricity transitions [31].

Table 2 Comparison of decentralized electricity governance models across regions (pre-2022 context)

Region / jurisdiction	**Governance archetype (pre-2022)**	**Key regulator(s)**	**System / market operator role**	**Network ownership and operation**	**Governance treatment of decentralised generation**
Great Britain (UK)	Liberalised electricity market with regulated monopoly networks	Office of Gas and Electricity Markets	National system operation coordinated under industry codes; distribution networks operated under RIIO price control framework	Privately owned Distribution Network Operators (DNOs)	Decentralised generation governed through connection agreements, Distribution Use of System (DUoS) charging, and supplier-led export arrangements (including early SEG framework introduced in 2020). Embedded generation benefits recognised but under review.
Germany	Federal regulatory model with strong renewable support regime	Bundesnetzagentur	Multiple TSOs coordinate system balancing; DSOs manage local networks under national rules	Mixed ownership (private utilities, municipal Stadtwerke)	Decentralised generation integrated primarily via the Renewable Energy Sources Act (EEG) using feed-in tariffs or market premiums; priority dispatch and cost socialisation embedded in governance.
California (USA)	State-regulated investor-owned utility model with restructured wholesale market	California Public Utilities Commission	Independent System Operator manages wholesale market and system reliability; retail tariffs set by regulator	Investor-owned utilities own and operate distribution networks	Decentralised generation governed mainly through Net Energy Metering (NEM 1.0 / NEM 2.0), with retail-rate netting and standardized interconnection (Rule 21). Governance emphasis on customer-sited generation uptake.
Australia (National Electricity Market)	National electricity governance framework with multi-institutional oversight	Australian Energy Regulator; Australian Energy Market Commission	Australian Energy Market Operator manages market operation and power system security	Distribution and transmission networks operated by regulated Network Service Providers (public and private)	Decentralised generation treated largely as price-taking embedded generation, supported via retail feed-in tariffs and technical connection standards; export volumes generally unmanaged beyond static limits.
South Africa	Vertically integrated utility with emerging regulatory accommodation	National Energy Regulator of South Africa	System operation dominated by national utility	Predominantly state-owned (Eskom), with municipal distributors	Decentralised generation governed through municipal approvals, standard tariff schedules, and pilot wheeling frameworks; policy still evolving with limited national-level harmonisation pre-2022.
Philippines	Hybrid liberalised retail model with regulated distribution utilities	Energy Regulatory Commission	Wholesale Electricity Spot Market operates alongside bilateral contracting	Privately owned and cooperative distribution utilities	Decentralised generation incorporated via net-metering rules under the Renewable Energy Act, allowing small customer-generators to export surplus to distribution utilities at regulated rates.

7. Cross-Cutting Challenges and Emerging Governance Risks

7.1. Regulatory Fragmentation and Institutional Coordination Failures

Across regions, one of the most persistent governance challenges in decentralized electricity systems is regulatory fragmentation. As responsibilities are distributed among national regulators, regional authorities, and local institutions, misalignment frequently emerges between market rules, network regulation, and system operation [30]. Fragmentation is particularly evident at the transmission–distribution interface, where coordination failures can lead to inefficient investment signals and operational conflicts.

Institutional silos also limit the effectiveness of decentralised governance. Energy regulators, data protection authorities, and cybersecurity agencies often operate under distinct mandates, complicating integrated oversight of digitalised electricity systems [31]. Without formal coordination mechanisms, regulatory responses to decentralisation risk becoming reactive and inconsistent.

These challenges are not confined to any single governance model. Even highly integrated systems experience coordination failures when institutional frameworks lag behind technological change. Addressing fragmentation therefore requires not only regulatory harmonisation but also adaptive governance structures capable of evolving alongside decentralised electricity markets [32].

7.2. Equity, Access, and Distributional Impacts of Decentralization

Decentralisation raises important equity and distributional concerns that extend beyond market efficiency. Access to distributed generation, storage, and smart technologies is uneven across income groups and regions, creating the risk of energy inequality [33]. Households unable to invest in decentralised assets may face higher network charges or reduced service quality if governance frameworks fail to address cost redistribution.

Social acceptance of decentralised electricity reforms depends on transparent governance and perceived fairness. Tariff reforms, flexibility incentives, and digital participation mechanisms must account for vulnerable consumers to avoid exacerbating existing disparities [34]. Regulators increasingly recognise that decentralisation is not socially neutral and requires complementary policy interventions.

Integrating equity considerations into electricity governance strengthens legitimacy and long-term system resilience. Without deliberate attention to access and distributional impacts, decentralised markets risk undermining public trust and political support for broader energy transitions [35].

8. Future Directions for Electricity Market Governance

8.1. Toward Adaptive, Technology-Neutral, and Resilient Governance Frameworks

Future electricity market governance must evolve toward adaptive and technology-neutral frameworks capable of accommodating rapid decentralisation and digitalisation. Regulators will increasingly act as system architects, focusing on outcomes rather than prescriptive rules [30]. Governance models must integrate market design, network regulation, and data oversight within coherent institutional structures. Flexibility, interoperability, and resilience should guide regulatory evolution, ensuring that innovation aligns with public policy objectives. By embedding adaptability and coordination into governance frameworks, electricity markets can remain efficient, inclusive, and secure as decentralised systems continue to expand [31].

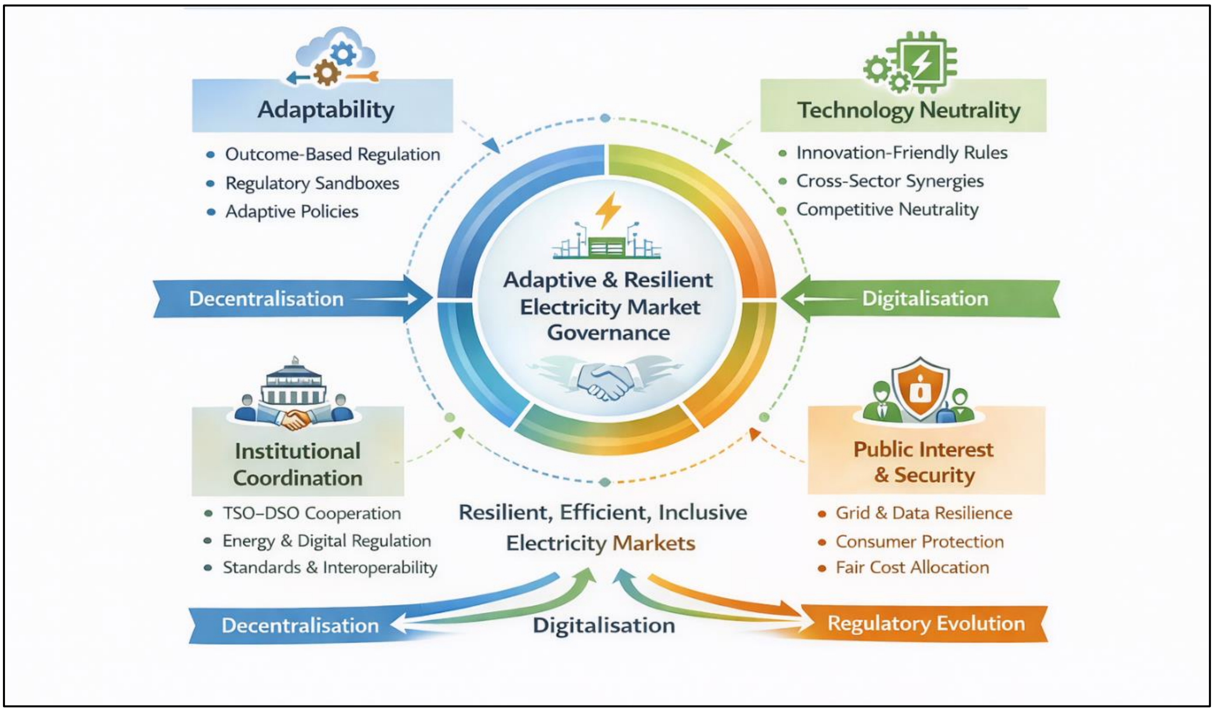

Figure 3 Forward-looking governance framework for decentralised electricity markets

9. Conclusion

9.1. Synthesis of Key Governance Insights

This article has examined how electricity market governance is being reshaped by the combined expansion of decentralised generation, energy storage, and smart grid technologies. Across these domains, a central insight is that technological decentralisation fundamentally alters governance requirements without eliminating the need for system-wide coordination. Distributed renewable energy challenges traditional licensing, dispatch, and market participation rules, while prosumer engagement and local markets introduce new forms of bottom-up participation that must be aligned with overarching system objectives. Energy storage further complicates governance by blurring functional boundaries between generation, consumption, and network services, requiring service-based regulatory approaches rather than rigid asset classifications.

Smart grids emerge as a critical governance enabler, providing the data, visibility, and control capabilities necessary to manage decentralised complexity. However, their effectiveness depends on robust regulatory oversight, data governance, and performance-oriented incentives. Comparative analysis across regions demonstrates that there is no single governance model for decentralised electricity systems. Instead, successful frameworks share common features: institutional coordination across system levels, regulatory adaptability, and clear allocation of roles and responsibilities. Collectively, these insights underscore that governance, rather than technology alone, is the decisive factor in determining whether decentralised electricity systems deliver efficiency, resilience, and public value.

9.2. Policy Implications and Research Directions

From a policy perspective, electricity governance frameworks must prioritise adaptability, coordination, and inclusiveness as decentralisation accelerates. Regulators should focus on outcome-based rules that support flexibility, ensure fair cost allocation, and preserve system reliability while enabling innovation. Strengthening coordination between transmission and distribution governance, as well as between energy and digital regulators, is particularly important.

Future research should examine the long-term performance of decentralised market designs, the distributional impacts of tariff reform, and the governance implications of increasing automation and algorithmic control. Comparative empirical studies will be essential for identifying best practices as electricity systems continue to evolve.

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