REGULATORY AND POLICY CHALLENGES IN THE DIGITAL TRANSFORMATION OF THE POWER SECTOR THROUGH ADVANCED METERING INFRASTRUCTURE IN SOUTH ASIA

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DOI: https://doi.org/10.5281/zenodo.18628400

Keywords
Digital Transformation, Power Sector Reform, Advanced Metering Infrastructure, Smart Grid Policy, Power Line Communication, Pakistan

Article History
Received: 14 December 2025
Accepted: 29 January 2026
Published: 13 February 2026

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Abstract
The digital transformation of the power sector is a key enabler for improving operational efficiency, transparency, and sustainability in electricity utilities. Advanced Metering Infrastructure (AMI) plays a central role in this transformation by enabling real-time data acquisition, loss reduction, demand-side management, and integration of renewable energy resources [1,2]. While extensive technical work exists on AMI communication technologies, comparatively limited attention has been given to the regulatory, institutional, and policy frameworks that critically influence digital transformation outcomes, particularly in developing countries [3,4]. This paper presents a field-based regulatory and policy analysis of large-scale AMI deployment in Pakistan, drawing on direct utility-level implementation experience. The study identifies key regulatory and governance gaps spanning the power and telecom sectors, including communication standards, SIM and spectrum governance, cyber security, data ownership, procurement rigidity, and weak inter-agency coordination. Field evidence demonstrates how regulatory misalignment translates into operational failures such as non-commissioned devices, data loss, communication outages, and delayed digital benefits. Based on observed deployment challenges, the paper proposes actionable policy recommendations to accelerate sustainable digital transformation of the power sector in Pakistan and other comparable developing economies.

INTRODUCTION

Digitalization has become a central strategic objective in the global power sector, motivated by the need to improve operational performance, enhance system transparency, minimize technical and non-technical losses, and advance sustainability objectives. Within this context, Advanced Metering Infrastructure (AMI) is regarded as a core enabler of digital transformation, as it facilitates bidirectional communication, high-resolution consumption monitoring, and increased automation throughout electricity distribution systems [1-5]. AMI solutions serve as an integrative platform connecting grid operations, end users, and data analytics within smart energy systems. In many developing economies, AMI deployment is embedded within wider power sector reform initiatives targeting loss reduction, improved governance, and enhanced revenue collection. Nevertheless, despite the maturity of metering and communication technologies, a significant number of AMI implementations fall short of their intended performance. Emerging evidence from field deployments indicates that, beyond technical limitations, factors such as regulatory preparedness, institutional coordination, and coherent policy frameworks are decisive for successful outcomes [6-7].

Although AMI communication technologies and system architectures have been widely studied, far less empirical work has examined the influence of regulatory and institutional arrangements on AMI performance in developing-country contexts. This study contends that effective digital transformation in the power sector requires not only appropriate technological choices but also well-aligned regulatory and governance frameworks [4]. Using Pakistan as a case study, this paper draws on field-based evidence from large-scale AMI deployments to show how fragmented governance structures, ambiguous institutional responsibilities, and weak regulatory enforcement manifest as operational shortcomings, including uncommissioned meters, communication failures, and compromised data integrity.

This study builds upon the authors' earlier peer-reviewed work on AMI deployment in Pakistan, which primarily investigated communication behavior and system-level performance issues observed during large-scale field implementation [8]. Whereas the previous study emphasized technical and operational aspects, the present work broadens the scope by examining the regulatory, institutional, and policy environments that influence digital transformation outcomes. By explicitly connecting governance structures with field-level performance, this paper provides a complementary, policy-focused perspective to the existing predominantly technical literature.

By systematically connecting observed technical failures with underlying regulatory and policy deficiencies, this study proposes a practical diagnostic framework that is relevant not only for Pakistan but also for other developing power sectors. While the analysis highlights the importance of regulatory and policy reforms in enabling effective AMI deployment, it also acknowledges the structural constraints faced by regulators in developing countries. Regulatory bodies often operate with limited technical capacity and within legal frameworks designed for conventional power systems rather than digital infrastructures [9]. In Pakistan, fragmented responsibilities across the power, telecommunications, and IT regulators stem from historical sectoral divisions rather than an integrated approach to digital governance. These challenges are further compounded by financial limitations, political sensitivity surrounding electricity tariffs, and dependence on incumbent service providers, all of which slow regulatory adaptation. Recognizing these constraints is critical for sequencing reforms, prioritizing high-impact interventions, and minimizing disruption during ongoing AMI implementation efforts.

Although this study centers on AMI deployment in Pakistan, the regulatory and policy challenges identified are broadly characteristic of several South Asian countries, including India, Bangladesh, Nepal, and Uzbekistan. These systems commonly experience fragmented governance structures, weak coordination between power and telecommunications regulators, limited institutional and technical capacity, and procedural delays in digital metering implementation [10-11]. By examining Pakistan as a detailed case study, this paper offers transferable insights for strengthening AMI deployment strategies and regulatory frameworks across the South Asian region.

2. Methodology

This study adopts a field-based observational methodology complemented by utility data analysis to assess regulatory and policy gaps influencing AMI deployment in Pakistan. The approach emphasizes real-world distribution-level operations and systematically links observed performance outcomes to underlying regulatory and institutional frameworks.

Study Area and Scope:
The research was carried out at the Islamabad Electric Supply Company (IESCO), serving approximately 4 million consumers, including about 1.3 million equipped with AMI meters under an ongoing digitalization program. The analysis covers low- and medium-tension distribution networks with single-phase, three-phase, and CT/CTPT metering, and examines both technical performance and regulatory factors influencing meter commissioning, communication reliability, and data integrity.

Data Collection:
1. **Field Observations:** Over a six-month period, field inspections were carried out at transformer stations, distribution lines, and consumer premises to assess meter installation practices, wiring arrangements, and data concentrator unit (DCU) connectivity.

2. **Operational Records:** Utility data from the Head-End System (HES) were analyzed to identify non-commissioned meters, communication failures, transformer-level connectivity issues, and billing inconsistencies.

3. **Stakeholder Interviews:** Structured interviews with utility engineers, field personnel, vendors, and telecom regulators were conducted to capture procedural challenges, regulatory compliance issues, and operational constraints, with recurring themes cross-validated against field observations and system data to link policy gaps to observed inefficiencies.

4. **Telecom and Regulatory Data:** Public regulatory documents issued by the Pakistan Telecommunication Authority (PTA), the National Electric Power Regulatory Authority (NEPRA), and the Ministry of Energy were systematically reviewed to identify policy and regulatory gaps related to AMI communication frameworks, SIM provisioning, spectrum allocation, and data governance.

Data Analysis:
1. Quantitative indicators were derived from HES logs, including incidents of neutral and phase loss, missing transformer identifiers, and PLC signal attenuation.
2. Field observations were cross-validated with utility datasets to confirm the scale and nature of operational failures.
3. Observed technical issues were systematically aligned with existing policy and regulatory frameworks to identify causal links between governance gaps and deployment inefficiencies.
4. International AMI deployment experiences were reviewed comparatively to benchmark regulatory best practices and assess their applicability to the Pakistani context.

Limitations:
1. The analysis is centered on IESCO and may not fully represent operational and regulatory conditions across other distribution utilities in South Asia.
2. Certain observed issues were episodic and influenced by network topology or seasonal load variations, which may limit broader generalization.
3. The study relied on utility-maintained records and field observations; independent third-party measurements were not available for validation.

Overall, this methodological approach enables an integrated assessment of how technical, procedural, and regulatory factors jointly shape AMI deployment performance, providing an empirical foundation for targeted and context-sensitive policy recommendations.

3. Overview of AMI Communication Technologies

AMI facilitates digital transformation through bidirectional communication between smart meters, data concentrators, and utility head-end systems, using technologies such as power line communication (PLC), RF mesh networks, cellular links, and hybrid architectures [1,5]. PLC utilizes existing distribution lines and is cost-efficient but remains sensitive to network topology, wiring quality, and operational conditions. RF mesh systems offer self-healing features suited to dense deployments, while cellular solutions provide broad coverage at the cost of dependence on public telecom networks, SIM management, and recurring expenses. Hybrid approaches are increasingly adopted to enhance reliability across diverse network environments.

Despite their technical maturity, the field performance of these communication options is strongly shaped by regulatory and institutional factors, including device certification, SIM provisioning, spectrum allocation, data governance, and coordination between power and telecom authorities [4].

4. Regulatory Landscape Relevant to AMI in Pakistan

Pakistan's AMI-driven digital transformation operates under multiple, loosely connected regulatory regimes. Power sector regulation prioritizes tariffs, loss reduction, and performance targets, while telecommunications regulation governs device certification, SIM provisioning, IMEI registration, and machine-to-machine communication. Public procurement frameworks emphasize transparency and competition but lack flexibility for fast-evolving digital systems, and cybersecurity and data protection policies remain fragmented, with no AMI-specific enforcement mechanisms.

The lack of an integrated regulatory framework has led to overlapping mandates, procedural delays, inconsistent implementation, and unclear accountability across utilities—challenges that align with international evidence on AMI governance shortcomings [7, 12]. This regulatory fragmentation underscores the need for a formal institutional coordination mechanism to harmonize approvals, clarify responsibilities, and ensure effective compliance in AMI deployment.

5. Field Evidence from AMI Deployment

Field-level evidence from Advanced Metering Infrastructure (AMI) deployment in Pakistan demonstrates that a substantial proportion of operational failures cannot be attributed solely to technological shortcomings. Instead, these failures are largely rooted in procedural weaknesses, fragmented institutional coordination, and insufficient regulatory clarity. On-site observations and utility data reveal recurring issues such as missing or incorrect transformer identifiers, shared neutral connections, uncommissioned meters, and persistent communication outages. These operational deficiencies align closely with identifiable governance gaps, including the absence of enforceable installation standards, inconsistent commissioning procedures, and delays in SIM provisioning arising from misaligned regulatory mandates between power utilities and telecommunication authorities [1, 13].

The digital transformation of the power sector through AMI is further constrained by the lack of a clearly defined and integrated governance architecture. AMI systems inherently operate at the intersection of multiple regulatory domains, encompassing electricity regulation, telecommunications oversight, information technology policy, and data governance. However, in the current institutional framework, no single authority holds explicit legal responsibility for ensuring the coordinated functioning of these domains. This fragmentation of regulatory oversight creates ambiguity regarding roles, responsibilities, and enforcement authority, resulting in weak accountability mechanisms and coordination failures that utilities are unable to resolve independently [14]. As a consequence, technical issues that could otherwise be addressed through coordinated regulatory action persist and scale across large deployments.

Regulatory design and performance evaluation mechanisms further limit the effectiveness of AMI-based digital transformation. Existing regulatory oversight frameworks remain largely focused on conventional indicators, such as tariff determination, capital expenditure approval, physical infrastructure rollout, and compliance reporting. In contrast, critical digital performance dimensions—including data reliability, communication latency, system interoperability, meter availability, and data completeness—are not systematically incorporated into regulatory assessment or utility performance benchmarks. This structural omission incentivizes utilities to prioritize numerical installation targets and procurement milestones over sustained functional performance, reinforcing a compliance-driven implementation culture rather than a performance-oriented digital transformation strategy. A significant and often overlooked policy failure concerns the legal status of AMI-generated data. Under existing legislative and regulatory frameworks, smart meter data is not explicitly recognized as a critical digital or infrastructure asset. This absence of legal recognition creates uncertainty regarding data ownership, access rights, privacy obligations, retention policies, cybersecurity responsibilities, and liability in cases of data loss, manipulation, or service disruption. Without a clearly defined data governance framework, utilities operate in a regulatory vacuum, relying on ad hoc internal procedures that lack enforceability and consistency. This situation increases institutional risk, undermines consumer trust, and weakens the long-term sustainability of AMI-driven digital power systems.

Collectively, these findings indicate that the principal constraints on effective AMI deployment in Pakistan are not rooted in technological limitations alone, but rather in systemic governance and regulatory deficiencies. Overcoming these challenges requires a transition from fragmented, sector-specific regulation toward an integrated digital governance framework that aligns power sector objectives with telecommunications regulation, data governance standards, and institutional accountability mechanisms. In the absence of such regulatory coherence, continued investment in AMI technologies is unlikely to fully realize gains in operational efficiency, transparency, and long-term sustainability.

Field observations further reveal that several large-scale communication failures stem from procedural and installation deficiencies rather than inherent weaknesses of PLC technology. Loss of neutral or phase continuity at the data concentrator level frequently renders entire downstream meter groups non-communicative, highlighting the lack of standardized installation and maintenance practices. The use of dissimilar conductor materials at joints promotes oxidation and carbon formation under environmental exposure, significantly degrading PLC signal propagation. Additionally, infrastructure modifications—such as transitions between bare conductors and multi-core cables—introduce impedance mismatches that can reduce signal strength by more than half, leading to widespread communication loss. These effects are exacerbated on long low-tension feeders without intermediate aggregation points, where signal attenuation further constrains reliable data transmission.

A persistent institutional challenge observed during AMI deployment is the non-commissioning of meters caused by missing, delayed, or incorrect transformer identification data. The absence of timely GIS-based transformer IDs prevents proper logical mapping of meters and data concentrator units within the head-end system, leaving otherwise operational devices permanently offline. This issue is further exacerbated when transformer replacements or load reconfigurations are not reflected in system records, leading to misassigned assets and compromised data integrity.

Another critical field-level issue relates to the informal practice of sharing the neutral conductor between adjacent distribution transformers to mitigate local voltage instability, often as an alternative to implementing proper earthing through adequate ground excavation. This non-compliant practice, enabled by weak enforcement of distribution and earthing standards, introduces unintended parallel paths for PLC signal propagation. As a result, meters connected to one transformer may intermittently communicate with the data concentrator of a neighboring transformer through the shared neutral, undermining transformer-level segregation within the AMI architecture. This signal leakage directly affects the accuracy of transformer-wise energy accounting, resulting in distorted loss calculations and misleading performance indicators. Collectively, these observations reinforce that many operational failures arise from regulatory and procedural deficiencies rather than technological constraints. Figure 1 provides a consolidated overview of the key operational issues identified during AMI deployment at IESCO, highlighting the relative scale of meter populations affected by each failure mode.

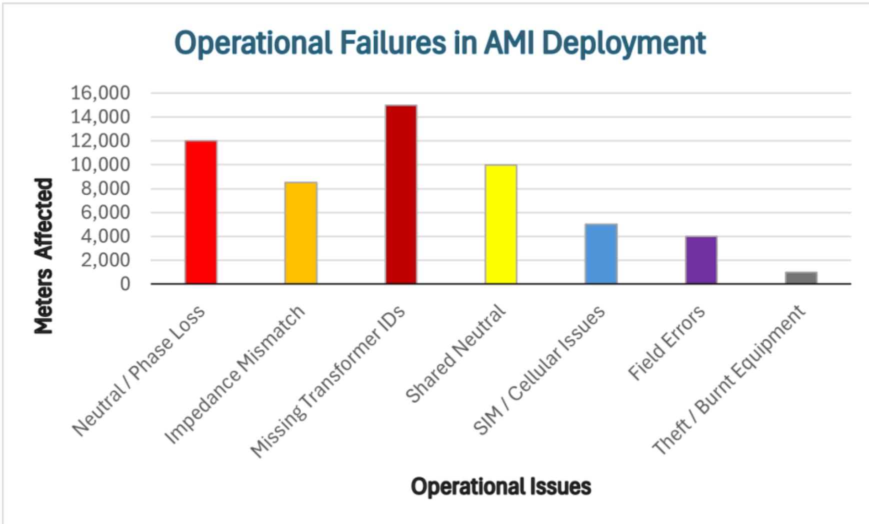

Figure 1 Field-level operational issues in AMI deployment at IESCO.

Telecommunications regulation constitutes an additional structural constraint on effective AMI deployment. Existing regulatory frameworks are primarily designed for consumer and commercial telecommunications services and do not differentiate utility-operated machine-to-machine (M2M) communication from general-purpose connectivity. As a result, AMI communication components are subjected to regulatory requirements that are poorly aligned with their role as part of critical national infrastructure. Utilities typically lack the institutional authority to seek tailored regulatory provisions or exemptions, leading to prolonged approval processes, procedural delays, and recurring operational inefficiencies.

Cellular communication plays a pivotal role in AMI functionality; however, its effectiveness is tightly constrained by network coverage, spectrum availability, and regulatory governance. In contexts such as Pakistan, nationwide 5G deployment has yet to materialize, while legacy 2G and 4G networks continue to exhibit uneven and unreliable coverage, particularly in rural and remote areas. Consequently, a substantial share of cellular-enabled smart meters remains persistently offline. These challenges are compounded by recurring cellular and internet service disruptions, which—during 2025 alone—caused repeated interruptions to AMI data acquisition, billing processes, and real-time operational visibility.

Beyond cellular limitations, spectrum regulation poses significant barriers to non-cellular AMI communication technologies. Internationally, RF mesh and other low-power IoT systems for smart metering are typically designed to operate within the 863–920 MHz sub-GHz band, which offers favorable propagation characteristics for utility-scale networks. In contrast, the Pakistan Telecommunication Authority designates only the narrower 920–925 MHz band as licence-exempt, subject to stringent constraints on transmission power, duty cycle, and interference. This regulatory misalignment compels utilities and vendors to alter hardware designs, restrict operational frequencies, or pursue additional regulatory approvals for equipment originally developed for wider sub-GHz allocations. Such adaptations increase deployment complexity, elevate interoperability risks, and significantly raise implementation costs, ultimately undermining the scalability and reliability of AMI systems.

The absence of a clear national framework for eSIM technology introduces significant operational risk in AMI deployment. While eSIMs can reduce tampering, fixed operator profiles create network lock-in and prevent post-deployment migration to better coverage. Advanced capabilities such as remote SIM provisioning and profile switching remain unsupported due to regulatory and commercial constraints, leaving utilities without mechanisms to ensure long-term connectivity.

AMI rollout is further delayed by multi-layered cellular regulatory requirements, including device type approval, IMEI registration, and compliance certification, which significantly slow large-scale deployment. In parallel, limited diversity in national optical fiber infrastructure—dominated by a single provider—creates a systemic single point of failure, undermining redundancy for AMI data centers. These structural constraints highlight the need for regulatory reforms that enable flexible connectivity, streamlined approvals, and diversified communication infrastructure to support reliable digital power systems.

Public procurement regulations further intensify AMI deployment challenges by treating digital power systems as static hardware assets rather than evolving digital platforms. Emphasis on lowest-cost selection and fixed specifications limits performance-based evaluation, modular upgrades, and lifecycle optimization, often resulting in vendor lock-in and restricted interoperability. While such controls were originally intended to ensure transparency and prevent misuse of public funds, they now require careful recalibration to support digital adaptability without undermining accountability.

Regulatory gaps extend beyond procurement to interoperability, risk allocation, and long-term governance. Interoperability standards remain largely advisory, allowing proprietary implementations that constrain future integration. At the same time, regulatory and contractual frameworks place disproportionate operational risk on utilities, with limited vendor accountability for post-deployment performance. Approval processes prioritize capital expenditure and installation milestones, offering little regulatory support for ongoing system optimization, cybersecurity investment, or data analytics, thereby weakening long-term sustainability.

At the operational level, fragmented cybersecurity oversight, unclear data migration governance, and the absence of mandated digital capacity-building further undermine system reliability. Field-level issues—including poor asset-data synchronization, non-standard installation practices, inadequate coordination among contractors, and weak resilience planning—compound technical failures. Consumer protection frameworks also lag behind digital realities, with smart meter disputes still governed by legacy rules. Collectively, these findings demonstrate that AMI performance is shaped as much by regulatory coherence and institutional discipline as by technology itself. Quantitative evidence from IESCO illustrates how these governance gaps translate into non-commissioned meters, communication failures, and measurable billing losses, underscoring the urgent need for integrated regulatory reform.

Table 2. Comparison of international AMI regulatory practices, outcomes, and lessons relevant for Pakistan.

Regulatory / Policy Gap	No. of Meters Affected	No. of Transformers Affected	Estimated Operational / Billing Impact	Linked Regulatory Domain
Neutral loss / phase loss at DCU	12,000	60	Moderate revenue loss, manual data collection	NEPRA / Power Utility Installation Standards
Non-standard wiring / impedance mismatch	8,500	45	PLC signal degradation, partial data loss	NEPRA / Power Utility Technical Codes
Missing / incorrect transformer IDs in HES	15,000	75	Non-commissioned meters, inaccurate loss calculation	NEPRA / Utility IT Governance
Shared neutral causing signal leakage	10,000	50	Transformer-wise energy misallocation, billing errors	NEPRA / Utility Technical Standards
Cellular coverage gaps / SIM provisioning issues	5,000	60	Meters offline, delayed billing	PTA / Telecom Regulation
Procedural errors in field (wrong meter installation / disconnection)	4,000	25	Localized data loss, communication failures	NEPRA / Utility Training & SOPs
Theft / burnt meters / DCUs	1,000	10	Asset loss, temporary service disruption	NEPRA / Security & Asset Management Policies

6. Key Policy and Regulatory Gaps Identified

Based on extensive field observations during AMI deployment in IESCO Pakistan, several specific regulatory and policy gaps have been identified that directly impact operational performance:

1. **Absence of AMI-specific communication and installation standards**
   - Non-standard wiring, mixed conductor types, and improper neutral connections caused PLC signal degradation and meter communication failures.
   - Lack of enforceable technical codes allows vendor-specific installations, reducing interoperability and long-term reliability.

2. **Weak coordination between power utilities and telecom regulators**
   - Cellular connectivity and eSIM provisioning suffered from regulatory misalignment.
   - Multi-layered PTA approvals, IMEI whitelisting, and restricted frequency bands caused delays in meter commissioning and reduced network reliability.

3. **Unclear legal framework for AMI data ownership and access**
   - Missing or incorrect transformer IDs, shared neutral paths, and non-commissioned meters highlight the absence of legally defined custodianship of AMI data.

o No explicit rules on data retention, access, or liability create operational uncertainty and risk to billing accuracy.

4. **Inflexible procurement and lifecycle policies**

o Current procurement rules treat AMI systems as static hardware assets, preventing iterative upgrades, modular expansions, or hybrid communication solutions.

o This rigidity limits utilities' ability to adapt to evolving digital technologies or correct system-wide issues post-deployment.

5. **Insufficient institutional capacity and workforce training**

o Field staff errors, such as incorrect meter installation, improper disconnection practices, or failure to update system records, caused widespread operational disruptions.

o Regulators provide no mandatory frameworks for staff certification, training, or competency in digital power systems.

6. **Fragmented cybersecurity and infrastructure oversight**

o No single authority governs cybersecurity for AMI, leaving systems vulnerable to tampering, theft, and service disruptions.

o Dependency on single fiber providers (PTCL) and limited spectrum flexibility increases operational risk.

7. **Limited enforcement of interoperability and post-deployment performance**

o Interoperability standards are advisory; vendors can deploy closed systems, leading to vendor lock-in.

o Utilities face minimal regulatory incentives to maintain system performance, resulting in long-term degradation of AMI functionality.

These gaps translate directly into operational inefficiencies, increased costs, data reliability risks, and delayed realization of digital benefits , as summarized in Table 1.

7. International Comparison

International experience shows that successful large-scale AMI deployment depends on integrated regulatory frameworks that treat smart metering as critical national infrastructure rather than a standalone technology initiative. Jurisdictions that have realized sustained AMI benefits have aligned electricity regulation with telecommunications policy, cybersecurity governance, and data protection regimes, thereby reducing institutional fragmentation and implementation risk.

In the European Union, harmonized standards and regulatory mandates define interoperability, data governance, and lifecycle management requirements. Utilities are required to meet minimum functional performance criteria—such as data availability and communication reliability—before AMI investments are reflected in tariffs, with post-deployment audits ensuring continued system performance. Italy's nationwide rollout further illustrates lifecycle-oriented regulation, where AMI is recognized as an evolving digital platform, enabling continuous upgrades under regulated cost-recovery mechanisms. Similarly, the United Kingdom adopted a centralized governance model through a dedicated data and communications entity, ensuring standardized connectivity, cybersecurity, and consumer protection across utilities.

Nordic countries emphasize legally defined data ownership and access rights, allowing AMI data to be systematically leveraged for network planning, demand management, and integration of distributed energy resources. In East Asia, particularly China and South Korea, AMI deployment has been embedded within national smart grid strategies, supported by pilot-based validation, phased scaling, and close coordination among utilities, telecom operators, and manufacturers.

Across these cases, common regulatory principles include outcome-based performance evaluation, enforceable interoperability standards, post-deployment oversight, and mechanisms for continuous system evolution. By contrast, Pakistan's AMI deployment remains governed by fragmented, sector-specific regulations, with limited lifecycle oversight and weak enforcement of interoperability. As a result, AMI implementation is treated largely as a procurement exercise rather than a long-term digital transformation process. Adapting international best practices—particularly integrated oversight, lifecycle-oriented regulation, and cross-sector coordination—offers a clear pathway to addressing Pakistan's regulatory gaps and improving AMI performance.

Table 1. Quantitative assessment of regulatory and policy gaps observed during AMI deployment at IESCO.

Country / Region	Regulatory Approach	AMI Results	Key Lesson for Pakistan
European Union	Common technical and data rules across countries	Stable AMI systems with accurate meter data	Use uniform AMI standards and enforce interoperability
Italy	Regulation covers full AMI life cycle, upgrades, and cost recovery	Stable long-term operation and continuous system upgrades	Regulate AMI beyond installation to ensure sustained performance
United Kingdom	Central authority coordinates utilities and telecom operators	Secure, standardized, and consumer-protected AMI networks	Create a central body for AMI coordination and oversight
Nordic Countries	Clear laws on data ownership and data access	Better demand forecasting and smart grid integration	Clearly define AMI data ownership and sharing rules
China	Pilot projects tested before large-scale rollout	Fewer failures during rapid national deployment	Make pilot testing mandatory before full deployment
South Korea	Strong coordination between utility, telecom, and regulator	Highly reliable AMI and local technology growth	Support joint regulation, local testing, and R&D

8. Policy Recommendations

To enable effective digital transformation of the power sector through AMI, regulatory interventions must move from principle-based guidance to explicit operational requirements. The following recommendations specify concrete regulatory actions:

1. Mandate outcome-based performance indicators for AMI approval and evaluation

Regulatory should require utilities to report standardized AMI performance indicators as part of tariff filings and project evaluations. These indicators should include meter reading success rate, data completeness, communication latency, system availability, loss reduction impact, and consumer service improvements. Regulatory approval and future cost recovery should be explicitly linked to achieving minimum performance thresholds rather than completion of installation milestones alone.

2.

3. **Issue a binding national AMI communication, installation, and interoperability code**
The Ministry of Energy, in coordination with Electric power regulatory authority, should publish a mandatory technical code defining approved communication technologies, installation practices, interoperability standards, scalability limits, and redundancy requirements for AMI systems. Compliance with this code should be a prerequisite for project approval, vendor selection, and system expansion.

4. **Introduce lifecycle-based regulatory approval and cost-recognition mechanisms**
Regulatory frameworks should require utilities to submit lifecycle management plans covering software updates, firmware upgrades, communication optimization, analytics development, and system resilience measures. Electric power regulatory authority should recognize lifecycle-related OPEX and reinvestment costs in tariffs only when utilities demonstrate ongoing system performance improvements and compliance with lifecycle obligations.

5. **Enforce periodic post-deployment technical, cybersecurity, and data integrity audits**
Regulators should mandate independent post-deployment audits at defined intervals (e.g., annually or biennially) to assess communication reliability, data accuracy, cybersecurity controls, interoperability, and system resilience. Continued regulatory approval and cost recovery should be contingent on satisfactory audit outcomes and timely corrective actions.

6. **Create fast-track and long-term regulatory pathways for AMI communication assets** Telecommunication authority, in coordination with power-sector regulators, should establish simplified type-approval, spectrum-use, and lifecycle management procedures specifically for utility-owned AMI communication devices and M2M SIMs. These procedures should address SIM longevity, replacement, roaming constraints, and service continuity over the expected lifespan of AMI systems.

7. **Legally define AMI data ownership, custodianship, and structured data-sharing mechanisms**
Regulatory instruments should explicitly assign ownership of AMI-generated data to utilities while defining custodial responsibilities for data security, quality, and access control. Secure and standardized data-sharing protocols should be mandated to allow controlled use of AMI data by regulators and other public institutions for planning, forecasting, and policy analysis.

8. **Implement a staged regulatory approval process for pilot and full-scale AMI deployments**
Regulators should require AMI projects to proceed through clearly defined pilot and scale-up phases. Pilot approvals should include measurable technical and operational benchmarks, and transition to full deployment should be permitted only after independent verification of pilot performance, scalability, interoperability, and cybersecurity readiness.

9. **Institutionalize permanent inter-agency coordination mechanisms for digital power projects**
A formal coordination platform should be established involving Electric power regulatory authority, the Ministry of Energy, Telecom Authority, cybersecurity authorities, and utilities. This platform should be responsible for resolving cross-sector regulatory issues, aligning approval timelines, and issuing joint guidance for digital infrastructure projects.

10. **Introduce regulatory incentives for local innovation, testing, and capacity development**
Regulators should allow preferential evaluation, pilot funding recognition, or tariff incentives for projects that include local testing, domestic R&D participation, and industry–academia collaboration. Such incentives would support development of local expertise, reduce long-term

technology dependence, and improve system adaptability.
Each recommendation directly addresses regulatory failures observed during field deployment.

9. Conclusion

This paper shows that Pakistan's power sector digital transformation through AMI is constrained primarily by regulatory and institutional misalignment rather than limitations in technological maturity. Field-based evidence demonstrates that gaps in policy coherence, inter-agency coordination, and procedural enforcement directly result in non-commissioned meters, communication failures, data integrity issues, and associated financial inefficiencies. Addressing these challenges requires integrated regulatory frameworks, standardized implementation practices, and strengthened institutional capacity. Continuous performance monitoring and periodic regulatory review are therefore essential to ensure adaptability to evolving digital technologies and sustained system effectiveness. The findings offer insights that are applicable not only to Pakistan but also to other developing countries undertaking large-scale digital transformation of their power sectors.

Acknowledgment

The authors extend their deepest gratitude to the Islamabad Electric Supply Company (IESCO) for its invaluable support in conducting this study. The provision of field access, Hybrid communication data, and technical insights from IESCO's AMI Telecom Team significantly contributed to the quality and accuracy of the findings. The collaboration and dedication of the engineers and staff involved in the AMI project are sincerely appreciated.

Statements & Declaration

Funding

The authors declare that no funds, grants, or other financial support were received during the preparation of this manuscript.

Conflict of Interest

The authors have declared there is no conflict of interest.

Ethical Approval

Not applicable

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