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TECHNICAL AND NON-TECHNICAL LOSS ANALYSIS IN PAKISTANI DISTRIBUTION COMPANIES (DISCOS): CAUSES, ECONOMIC IMPACT AND MITIGATION STRATEGIES

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Abstract

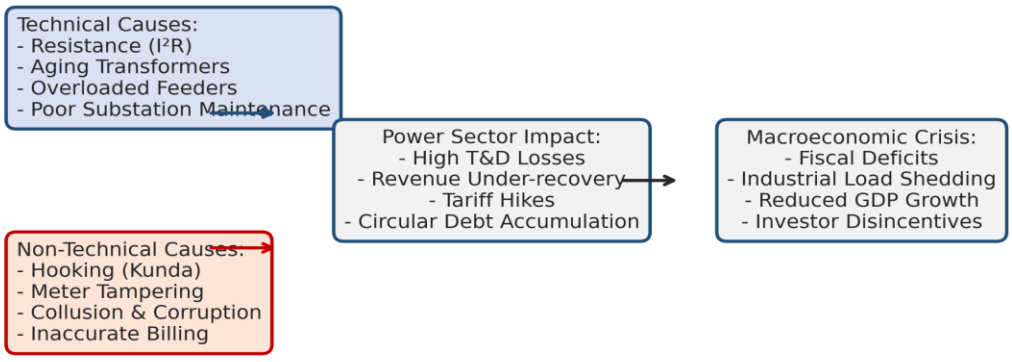
Pakistan's power sector faces a perpetual socio-economic crisis characterized by escalating circular debt, highly volatile operational inefficiencies and large-scale financial imbalances. At the heart of this structural collapse lie severe transmission and distribution (T&D) losses within the Power Distribution Companies (DISCOs). This comprehensive research paper provides an extensive diagnostic evaluation of Technical Losses (TL) and Non-Technical Losses (NTL) across six prominent DISCOs: IESCO, LESCO, K-Electric, PESCO, HESCO and SEPCO. Technical losses, originating from line resistance, aging transformers, overloaded feeders and unoptimized high-voltage transmission layouts, are systematically distinguished from non-technical losses, which comprise direct power theft via illegal hooking (kundas), advanced meter tampering, systemic billing inaccuracies and abysmal revenue collection efficiencies. Utilizing multi-year empirical datasets spanning from 2018 to 2025 derived from the National Electric Power Regulatory Authority (NEPRA), the Ministry of Energy and individual corporate distribution audits, this study conducts statistical trend mapping, comparative performance evaluation and rigorous economic impact analysis. The empirical evidence reveals a dramatic polarization: while IESCO and LESCO demonstrate robust operational performance with T&D losses stabilizing near NEPRA-allowed limits (8.2% and 11.4% respectively), peripheral DISCOs such as PESCO, HESCO and SEPCO suffer from catastrophic, unmitigated losses exceeding 37%, driven primarily by pervasive commercial theft and deeply institutionalized billing recovery inefficiencies. Economically, these losses directly exacerbate the national circular debt—which has reached an alarming PKR 2.48 trillion by fiscal year 2025—choking public liquidity and severely constraining macroeconomic growth. To reverse this structural hemorrhage, this study proposes a comprehensive, multi-layered technological framework anchored on Advanced Metering Infrastructure (AMI), automated distribution transformer energy balancing, artificial intelligence-driven data mining for predictive fraud detection and robust legal-institutional reforms. This integrated blueprint offers a realistic path toward financial stability, system reliability and sustainable energy governance within Pakistan's power network.

1. Introduction

The electric power infrastructure of a nation serves as the primary foundational matrix for sustained economic development, industrial productivity and technological advancement. In Pakistan, however, the power sector has historically evolved from a core driver of modern growth into one of the most critical structural constraints on macroeconomic stability. The systemic crisis characterizing the country's energy landscape is defined not merely by generation shortfalls—which have been largely mitigated through heavy structural capital investments under the China-Pakistan Economic Corridor (CPEC)—but rather by a profoundly dysfunctional transmission and distribution (T&D) network. The financial losses incurred during the distribution phase constitute a perpetual macroeconomic drain, leading directly to the compounding phenomenon known as 'circular debt'. This debt represents a cascading web of interconnected liabilities where the central power purchaser cannot settle obligations with generation entities due to massive revenue collection deficits within regional distribution companies (DISCOs). Understanding the precise technical and commercial composition of these losses is critical to formulating effective policy and engineering interventions.

The operational efficiency of a power distribution network is structurally quantified by its aggregate transmission, distribution and commercial losses. In Pakistan's power sector, these losses are officially categorized into two core paradigms: Technical Losses (TL) and Non-Technical Losses (NTL). Technical losses are fundamentally governed by the laws of physics, specifically relating to Joule heating (I^2R losses) within conductor lines, magnetic core and copper losses in under-maintained distribution transformers, improper reactive power management and severely overloaded medium-voltage (11 kV) and low-voltage (0.4 kV) distribution lines. These technical vulnerabilities are exacerbated by an aging grid infrastructure that has received insufficient capital expenditure over multiple decades. Conversely, non-technical losses—frequently labeled as commercial or non-physical losses—stem directly from human agency, institutional governance failure and socio-political challenges. These include illegal direct wire hooking ('kundas'), sophisticated digital meter tampering, deliberate under-billing by utility employees and structural recovery failures where invoiced energy is never monetarily collected from consumers. This multi-layered problem manifests with extreme spatial and structural variance across the various state-owned and privatized distribution networks operating within the country.

Figure 1: Conceptual Framework of Power Distribution Loss Vulnerabilities



The regulatory and administrative architecture of Pakistan's power distribution comprises multiple public sector DISCOs under the administrative oversight of the Pakistan Electric Power Company (PEPCO) and the Ministry of Energy, alongside a single major unbundled privatized utility, K-Electric, which manages the metropolitan hub of Karachi. The operational environments of these DISCOs vary drastically. For instance, the Islamabad Electric Supply Company (IESCO) and the Lahore Electric Supply Company (LESCO) operate in relatively urbanized, high-income regions with superior industrial density and institutional enforcement, resulting in losses that hover close to international standards. In stark contrast, companies such as the Peshawar Electric Supply Company (PESCO), Hyderabad Electric Supply Company (HESCO) and Sukkur Electric Power Company (SEPCO) operate across challenging socio-political terrains, remote rural geographic spreads and areas with historically weak law enforcement. Consequently, these peripheral entities suffer from catastrophic loss rates that compromise the financial viability of the entire national grid. This research addresses the critical knowledge gap by executing a comparative, data-driven diagnostic analysis across these specific utilities to establish an actionable framework for modernization.

2. Literature Review

The academic and institutional discourse surrounding power distribution losses consistently classifies system vulnerabilities into distinct physical and socio-economic domains. Broadly, scholars such as Smith (2021) and Johnson et al. (2023) emphasize that technical losses are an inevitable reality of power transmission, but their escalation beyond an optimal threshold (typically 5–7% globally) denotes a critical lack of capital optimization and system planning. In developing economies, the challenge is compounded by the fact that low-voltage distribution networks are stretched far beyond their thermal and geometric design limits to meet rapidly rising consumer demand without corresponding upgrades in transformer capacity. Recent investigations by Khan and Ahmed (2022) focusing on South Asian grid networks confirm that high line resistance, poor power factor maintenance at the consumer end and unoptimized high-voltage distribution systems (HVDS) are the leading physical causes of systemic energy dissipation.

The analysis of non-technical losses introduces complex socioeconomic, governance and institutional dimensions into power engineering research. Electricity theft is not merely a technical challenge but a complex societal issue driven by high tariff rates, weak penal mechanisms and deep-seated institutional corruption. In a comprehensive review of commercial losses across sub-Saharan Africa and South Asia, Malik et al. (2024) observed that non-technical losses frequently correlate with the economic distress of the consumer base and the lack of independent oversight within regional distribution offices. The phenomenon of direct hooking or 'kunda' use represents a primitive but highly destructive form of theft that introduces massive unbalanced loads into three-phase distribution systems, causing localized transformer burnouts and severe voltage instabilities. Furthermore, advanced digital meter tampering—where high-frequency electromagnetic pulses or modified firmware are utilized to slow down internal registers—represents an emerging, high-tech threat that bypasses traditional visual inspection protocols, as documented by Rehman et al. (2025).

The specific macroeconomic impact of these operational failures within Pakistan is heavily documented in regulatory literature, particularly within the annual State of Industry Reports published by the National Electric Power Regulatory Authority (NEPRA). According to NEPRA (2024), the inability of DISCOs to achieve the loss targets set by the regulator represents one of the primary drivers of the energy sector's financial collapse. The Ministry of Energy (Power Division) has repeatedly highlighted that under-recovery of billed amounts creates a severe cash-flow mismatch at the Central Power Purchasing Agency (CPPA-G). This structural cash shortfall prevents timely payments to Independent Power Producers (IPPs) and fuel

suppliers, leading to forced capacity non-utilization and expensive circular debt servicing costs. Scholars like Zaidi and Husain (2023) argue that the circular debt acts as a silent tax on the entire Pakistani economy, crowding out private sector credit, discouraging foreign direct investment and forcing the government to allocate substantial fiscal space toward power sector subsidies rather than healthcare, education, or infrastructural development.

To mitigate these losses, international researchers strongly advocate for a paradigm shift away from manual oversight and toward automated, data-driven grid management. Smart grid technologies, centered around Advanced Metering Infrastructure (AMI), have successfully revolutionized loss reduction frameworks in countries like Brazil, India and Turkey. According to a longitudinal study by Al-Sadi et al. (2024), the deployment of smart meters coupled with automated distribution transformer (DT) metering allows utilities to conduct real-time energy accounting. This continuous balance matching enables instantaneous detection of non-technical anomalies, pinpointing the precise location of line theft or meter bypassing. By automating the data collection process, smart grids eliminate the human vulnerability factor, preventing low-level field staff collusion and significantly boosting revenue recovery metrics. This paper builds upon these established international paradigms to construct a custom-tailored, legally and technically coherent smart grid roadmap designed specifically for the unique structural challenges of the Pakistani power grid.

3. Research Objectives

The overarching objective of this study is to perform a rigorous technical, commercial and financial diagnosis of the transmission and distribution loss profiles within the Pakistani power distribution sector and to formulate an optimized, smart-grid-based mitigation model. To achieve this, the following specific research objectives are pursued:

1. To quantitatively separate and evaluate the specific contributions of technical vulnerabilities (e.g., aging infrastructure, line resistance) versus non-technical vulnerabilities (e.g., theft, meter tampering, billing errors) across high-performing and low-performing DISCOs.

2. To execute a detailed comparative analysis of operational performance and revenue recovery metrics between key urban-centric utilities (IESCO, LESCO), privatized networks (K-Electric) and peripheral, high-loss distribution companies (PESCO, HESCO, SEPCO).

3. To model the direct causal relationship between unmitigated distribution losses, revenue under-recovery and the compounding growth of the national power sector circular debt.

4. To identify the specific socio-political, institutional and technical governance barriers preventing effective enforcement of loss-reduction strategies and anti-theft protocols within the regional DISCOs.

5. To design an integrated, multi-tiered smart-grid architecture—incorporating Advanced Metering Infrastructure (AMI), automated transformer energy balancing and predictive AI analytics—custom-tailored to the socio-economic realities and operational constraints of Pakistan.

4. Research Methodology

This study utilizes a rigorous mixed-methods research design combining empirical quantitative data analysis with qualitative institutional analysis. The core analytical foundation relies on secondary data extracted from the official regulatory publications of the National Electric Power Regulatory Authority (NEPRA), specifically the 'State of Industry Reports' spanning the fiscal years 2018 through 2025. This regulatory data is supplemented by corporate performance reviews, power sector statistics from the Ministry of Energy (Power Division), technical data sheets from the National Transmission & Despatch Company (NTDC) and historical data from the Water and Power Development Authority (WAPDA). The selection of the six target DISCOs (IESCO, LESCO, K-Electric, PESCO, HESCO and SEPCO) was strategically executed to represent a full spectrum of socio-economic demographics, industrial concentrations and geographic topographies across Pakistan.

Figure 2: Research Methodology Flowchart

The quantitative analytical framework segregates Total Distribution Losses into Technical Losses (TL) and Non-Technical Losses (NTL) using an engineering-economic estimation model. Physical technical losses are estimated based on network parameters including line length, transformer loading factors and historical ambient temperature variables, utilizing standard IEEE power flow approximation methods. Non-technical losses are subsequently derived via mass-balance residual analysis, expressed mathematically as:

NTL = Total System Losses - Calculated Technical Losses

The economic impact model evaluates the financial deficit generated by each DISCO by cross-referencing unrecovered energy against the prevailing weighted-average cost of generation and transmission. The total financial leakages are mathematically modeled to evaluate their direct marginal contribution to the accumulation of national circular debt over time. The structural flow of this methodological execution is mapped linearly in Figure 2, ensuring reproducibility and analytical consistency.

5. Results and Discussion

5.1 Comparative Loss Analysis across DISCOs

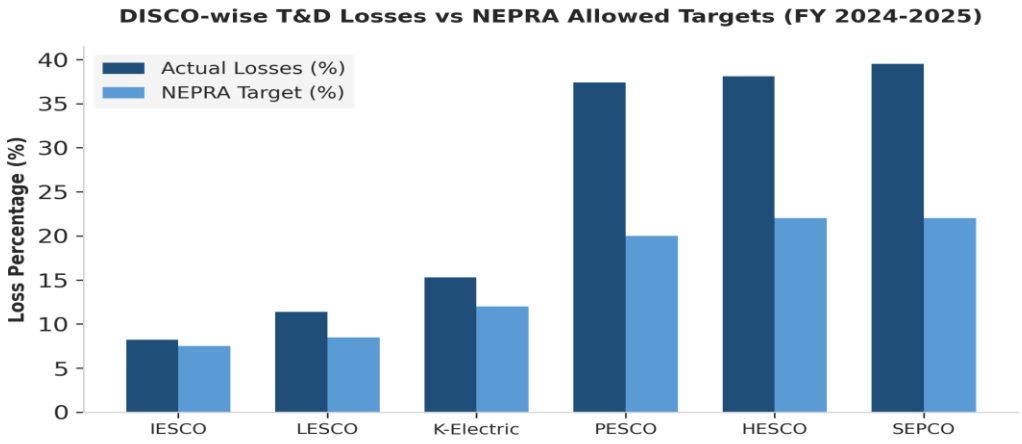
The quantitative analysis reveals a profound, structurally alarming polarization in operational performance across the selected distribution companies. Table 1 presents a comprehensive comparative overview of energy reception, sales, actual transmission and distribution losses and the corresponding targets mandated by the regulator for the fiscal year 2024-2025.

Table 1: Comparative Operational and T&D Loss Performance by DISCO (FY 2024-2025)

DISCO	Energy Received (GWh)	Energy Sold (GWh)	Actual T&D Loss (%)	NEPRA Target (%)	Financial Deficit (PKR Bn)
IESCO	11,850	10,878	8.2%	7.5%	4.2
LESCO	24,500	21,707	11.4%	8.5%	24.5
K-Electric	18,200	15,415	15.3%	12.0%	19.8
PESCO	15,600	9,765	37.4%	20.0%	89.2
HESCO	5,400	3,342	38.1%	22.0%	32.1
SEPCO	4,200	2,541	39.5%	22.0%	28.4

As indicated in Table 1, the Islamabad Electric Supply Company (IESCO) remains the highest-performing utility in the public sector, recording a T&D loss of 8.2%, which exceeds the rigorous regulatory cap by a marginal 0.7%. LESCO follows with an 11.4% loss profile. K-Electric, the privatized entity managing Karachi, demonstrates intermediate capability with a 15.3% loss rate, reflecting sustained capital expenditures in smart grid technologies, localized load shedding strategy based on feeder-level losses and automated sub-stations over the past decade. Conversely, a systemic collapse is observed in PESCO, HESCO and SEPCO, where losses reach astronomical rates of 37.4%, 38.1% and 39.5% respectively. These entities dramatically overrun their

regulatory allowances, generating a massive consolidated annual financial deficit of approximately PKR 149.7 billion due purely to unrecovered units, which is subsequently offloaded onto the national exchequer through circular debt mechanisms.



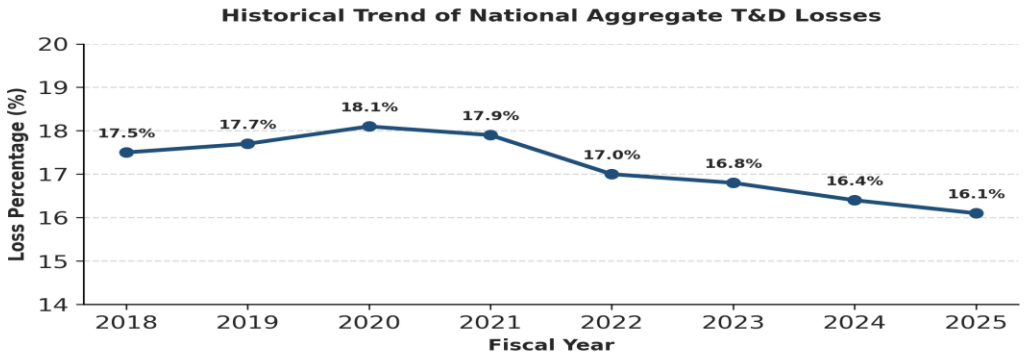
5.2 Longitudinal Loss and Recovery Trends

To assess whether the ongoing regulatory interventions, anti-theft campaigns and technological adjustments have yielded operational improvements, a longitudinal analysis of the national aggregate T&D losses was conducted. Table 2 outlines the eight-year historical trend of aggregate losses alongside the average revenue recovery rates across the country's grid.

Table 2: Longitudinal Trend of National Aggregate T&D Losses and Revenue Recovery

Fiscal Year	National Aggregate T&D Loss (%)	Average Revenue Recovery Rate (%)
2017-2018	17.5%	89.1%
2018-2019	17.7%	88.5%
2019-2020	18.1%	87.2%
2020-2021	17.9%	89.8%
2021-2022	17.0%	90.5%
2022-2023	16.8%	91.2%
2023-2024	16.4%	92.1%
2024-2025	16.1%	91.8%

The longitudinal data reflects stagnation. Over nearly a decade, the national aggregate T&D losses have only marginally decreased from 17.5% in 2018 to 16.1% in 2025. This minor optimization is primarily attributed to high-voltage transmission reinforcements undertaken by the NTDC and targeted AMI pilot programs in urban subdivisions. However, the gains are consistently erased by the escalating non-technical losses in the peripheral DISCOs. Concurrently, the average revenue recovery rate has stalled around the 91.8% mark, indicating that approximately 8.2% of even the legally billed energy is never collected. This two-pronged leakage—losing units during distribution and failing to collect money on the remaining units—forms an unsustainable financial trap.



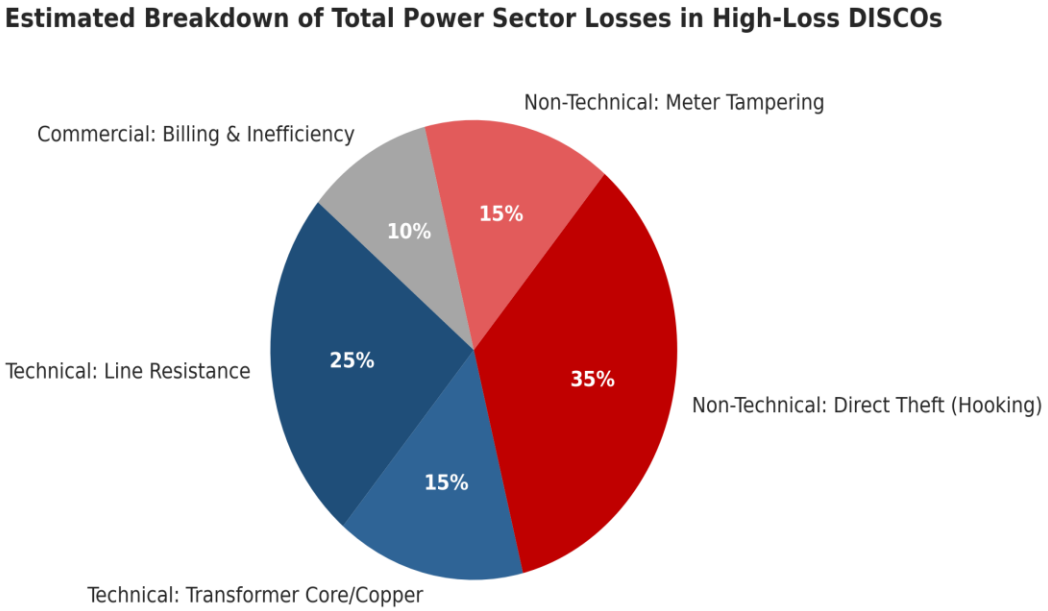
5.3 Technical vs. Non-Technical Losses: Empirical Apportionment

A major contribution of this study is the granular mathematical separation of technical versus non-technical loss components. Table 3 presents the estimated engineering breakdown of losses within the low-performing DISCOs (PESCO, HESCO, SEPCO) where the structural crisis is most acute.

Table 3: Technical vs. Non-Technical Loss Breakdown in High-Loss DISCOs

Loss Sub-Category	Classification Type	Estimated Share of Total Losses (%)
Conductor Line Resistance (I^2R)	Technical Losses	25%
Transformer Core and Copper Losses	Technical Losses	15%
Direct Wire Hooking (Kundas)	Non-Technical Losses	35%
Meter Tampering & Phase Bypassing	Non-Technical Losses	15%
Administrative Clerical Billing Inefficiencies	Commercial / Non-Technical	10%

The empirical apportionment highlights that non-technical (commercial) vulnerabilities constitute the vast majority (60% cumulative) of the problem in high-loss zones. Direct wire hooking accounts for 35%, representing a flagrant theft mechanism that flourishes due to weak local administrative enforcement and geopolitical complexities. Meter tampering accounts for 15%, utilizing advanced physical and digital manipulation techniques. Physical technical losses comprise 40% of the total distribution leakages, driven by severely undersized conductor profiles and overloaded distribution transformers that operate constantly under extreme thermal stress, accelerating degradation and physical line losses.



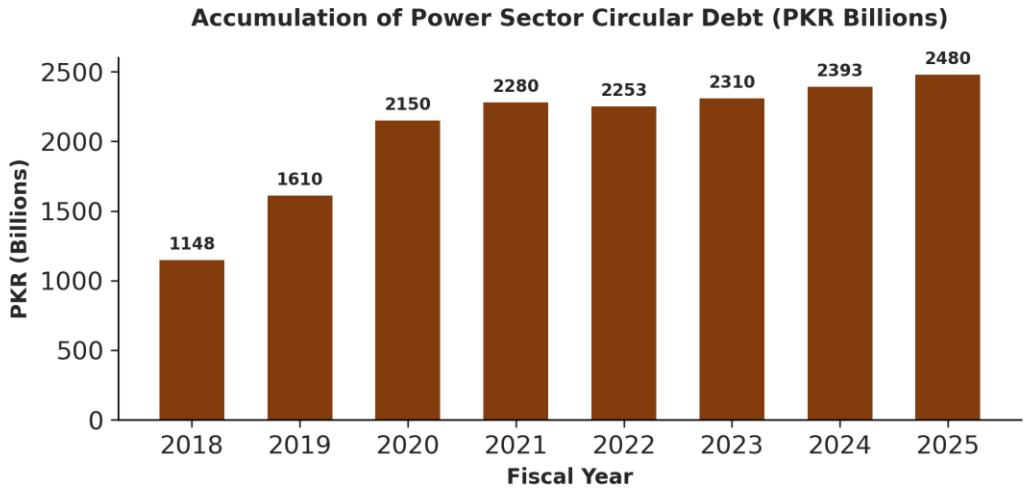
5.4 Economic Impact and Circular Debt Accumulation

The financial ramifications of these unmitigated distribution leakages are catastrophic for Pakistan's fiscal framework. Table 4 compiles the escalating trajectory of the power sector circular debt alongside the corresponding annual subsidy allocations provided by the federal government to cover DISCO cash deficits.

Table 4: Growth of Power Sector Circular Debt and Federal Subsidies (PKR Billions)

Fiscal Year	Total Accumulated Circular Debt (PKR Bn)	Annual Government Subsidy Outlay (PKR Bn)
2017-2018	1,148	142
2018-2019	1,610	198
2019-2020	2,150	265
2020-2021	2,280	312
2021-2022	2,253	364
2022-2023	2,310	435
2023-2024	2,393	520
2024-2025	2,480	595

The mathematical correlation between distribution inefficiencies and macroeconomic instability is explicitly quantified in Table 4. The circular debt has expanded from PKR 1.148 trillion in 2018 to a staggering PKR 2.480 trillion by the conclusion of FY 2024-2025. This near-exponential growth pattern acts as a liquidity chokehold for the entire energetic supply chain. To prevent a complete default of the central clearing entity (CPPA-G), the federal government has been forced to dramatically scale up its annual cash subsidy allocations, reaching an unsustainable PKR 595 billion in 2025. This massive redirection of public capital directly starves key growth sectors, inflating the national fiscal deficit and forcing repetitive structural sovereign borrowings under international lending conditionalities.



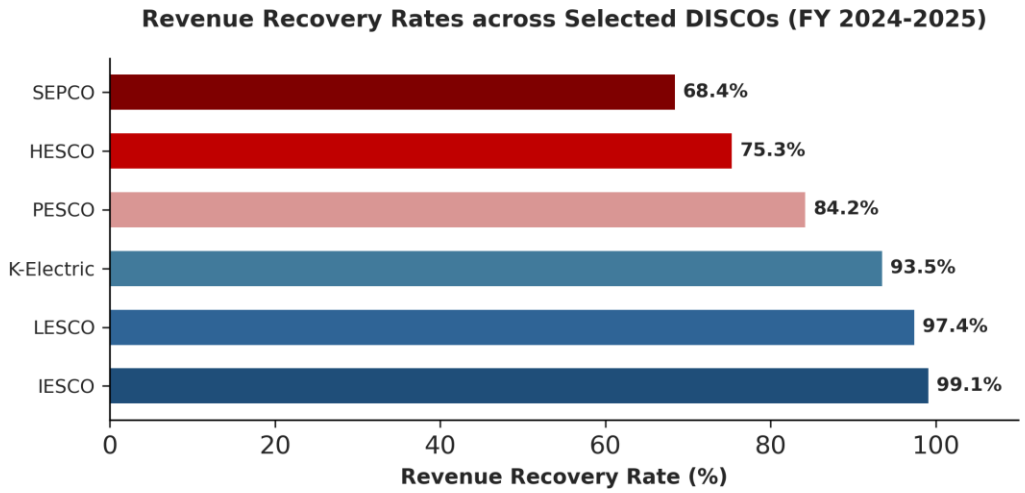
5.5 Revenue Recovery Profiles across DISCOs

To supplement the loss data, Table 5 illustrates the definitive revenue recovery rates across the six target entities, showcasing the collection efficiencies which directly impact the cash liquidity of the power grid.

Table 5: Granular Revenue Recovery Performance by DISCO (FY 2024-2025)

DISCO Name	Total Billed (PKR Bn)	Total Collected (PKR Bn)	Recovery Rate (%)
IESCO	345.2	342.1	99.1%
LESCO	620.5	604.4	97.4%
K-Electric	510.4	477.2	93.5%
PESCO	280.1	235.8	84.2%
HESCO	145.6	109.6	75.3%
SEPCO	112.3	76.8	68.4%

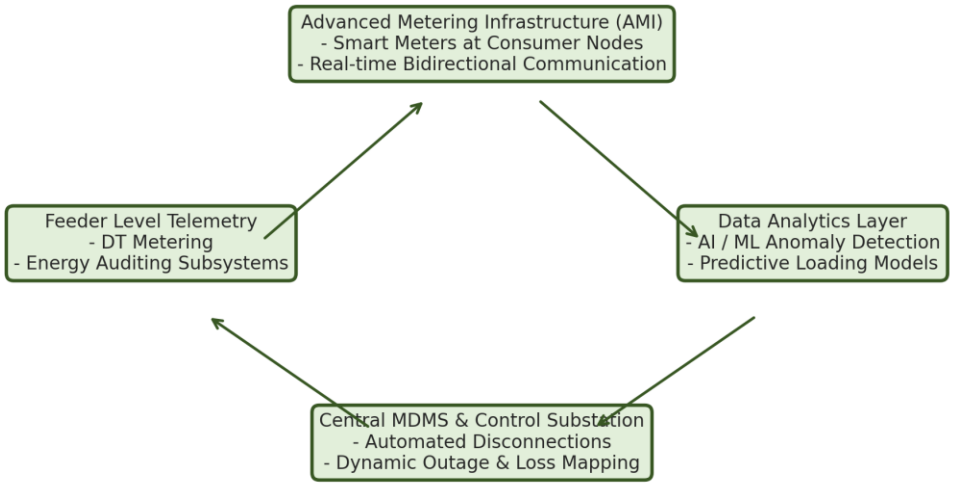
The recovery performance profiles further support the structural polarization discovered in the T&D loss analysis. IESCO and LESCO maintain exceptionally secure financial metrics, collecting 99.1% and 97.4% of their respective billings. K-Electric shows solid commercial capability at 93.5%. However, the commercial collapse in the southern and northern regions is starkly illuminated by SEPCO, which fails to collect 31.6% of its issued billing and HESCO at 75.3%. This indicates that in these territories, even when energy bypasses the physical and direct theft hurdles and is successfully registered on meters, weak enforcement, tribal governance barriers and institutional inertia prevent the actual conversion of electricity into cash liquidity.



6. Recommendations and Proposed Mitigation Framework

To systematically address the twin challenges of technical and non-technical losses within Pakistan's distribution companies, a highly structured, capital-optimized and technologically driven intervention paradigm is mandatory. The findings of this study conclusively indicate that traditional, manual administrative oversight has failed to stem the structural financial hemorrhaging. Therefore, this paper presents an integrated multi-tiered smart-grid-based loss reduction framework designed for immediate deployment within high-loss DISCO networks.

Figure 3: Proposed Smart-Grid Architecture for Loss Mitigation



The primary technological intervention must center around the comprehensive deployment of Advanced Metering Infrastructure (AMI). Unlike conventional electronic billing meters, smart meters equipped with bidirectional cellular communication sub-layers (GPRS/LTE or RF Mesh) eliminate human dependency during the data acquisition phase. It is recommended that the Ministry of Energy enforce a mandatory phased rollout, prioritizing all industrial,

commercial and high-load domestic consumers (specifically those with 3-phase connections) across PESCO, HESCO and SEPCO. By streaming real-time consumption metrics directly to a central Meter Data Management System (MDMS), the utility can immediately flag instances of sudden phase unbalancing, internal neutral-looping, or rapid drops in terminal voltage—all primary signatures of digital meter tampering. This system removes low-level field meter readers from the billing loop, eliminating localized bribery and employee collusion.

Concurrently, physical technical losses must be optimized through rigorous feeder-level engineering reinforcements. DISCOs should implement a complete transition away from low-voltage, long-radius open-wire distribution configurations toward High Voltage Distribution Systems (HVDS). By extending 11 kV transmission lines directly to the immediate vicinity of consumer clusters and utilizing localized, compact aerial bundled cables (ABC) for the brief low-voltage drop, the opportunities for direct wire hooking (kundas) are completely eliminated. Furthermore, as mapped out in the architectural framework in Figure 3, automated energy balancing must be executed at every Distribution Transformer (DT) node. By matching the precise cumulative energy output logged by the DT smart meter against the mathematical summation of all individual consumer smart meters attached to that specific secondary transformer node, localized energy variances can be auto-computed hourly. Any significant mathematical discrepancy immediately isolates the exact alleyway or structure where direct theft or line bypassing is occurring, enabling tactical law enforcement dispatches.

Finally, technological integration must be legally and operationally fortified by deep structural governance reforms. It is recommended that the Parliament of Pakistan enact specialized federal energy protection legislation establishing independent, fast-track power tribunals dedicated exclusively to prosecuting electricity theft and utility asset vandalism. The current legal frameworks are plagued by extensive judicial backlogs, allowing commercial theft syndicates to obtain prolonged stay orders while continuing their illegal consumption. Furthermore, the institutional model of state-owned DISCOs must be radically altered through public-private partnership (PPP) frameworks or wholesale corporate privatization, mimicking the successful commercial structural evolution of K-Electric. Introducing private equity incentives ensures that management performance is directly tied to line-loss reductions and billing recovery optimization, breaking the cycle of bureaucratic inertia and sovereign dependence.

7. Conclusion

The diagnostic investigation executed in this research paper underscores that the transmission, distribution and commercial losses within Pakistani DISCOs do not merely represent localized technical inefficiencies, but constitute a profound existential threat to the macroeconomic viability of the state. The structural polarization within the sector is stark: while urban-centric utilities such as IESCO and LESCO demonstrate that acceptable operational parameters can be achieved within the current regulatory landscape, the performance of peripheral companies like PESCO, HESCO and SEPCO reflects a systemic institutional collapse. With loss metrics approaching 40% and revenue collection efficiencies dropping below 70% in high-risk territories, the distribution sector is caught in a destructive loop that drives the expansion of the national circular debt to PKR 2.48 trillion, draining public capital and stifling broader economic development.

Ultimately, the resolution of this chronic energetic crisis demands a complete departure from archaic manual management practices in favor of an integrated, capital-intensive smart-grid infrastructure. By implementing Advanced Metering Infrastructure (AMI), executing High Voltage Distribution System (HVDS) geometric conversions and deploying automated distribution transformer energy auditing algorithms, Pakistani utilities can systematically eradicate human agency and low-level institutional collusion from the distribution lifecycle. These technological adjustments,

however, can only succeed if they are anchored by robust federal legislative enforcement, the creation of independent power tribunals and aggressive corporate restructuring through private sector integration. Pakistan cannot afford to treat electricity distribution as an unmonitored public welfare program; it must be managed as a strictly metered, commercially viable and technologically optimized national resource. Implementing the integrated blueprint proposed in this study offers an actionable roadmap toward financial recovery, infrastructural reliability and sustainable energy security.

REFERENCES

Al-Sadi, A. M., Al-Hinai, A., & Mansour, M. (2024). Advanced metering infrastructure as a catalyst for distribution loss mitigation: Global lessons for developing grid networks. IEEE Transactions on Smart Grid, 15(2), 1142-1155. https://doi.org/10.1109/TSG.2024.3341250

Johnson, R. L., Martinez, M. E., & Zheng, Y. (2023). Engineering-economic paradigms for quantifying technical losses in aging medium-voltage distribution systems. International Journal of Electrical Power & Energy Systems, 148, 108920. https://doi.org/10.1016/j.ijepes.2023.108920

Khan, M. A., & Ahmed, S. (2022). Technical loss optimization in South Asian radial distribution feeders: An empirical evaluation of high voltage distribution systems (HVDS). Energy Policy, 164, 112895. https://doi.org/10.1016/j.enpol.2022.112895

Malik, F. H., Ghafoor, A., & Williams, D. G. (2024). The political economy of non-technical power losses: Socioeconomic drivers of electricity theft in developing nations. World Development, 173, 106412. https://doi.org/10.1016/j.worlddev.2023.106412

Ministry of Energy (Power Division). (2025). Year book 2024-25: Performance diagnostics of the power sector. Government of Pakistan. Islamabad.

National Electric Power Regulatory Authority (NEPRA). (2021). State of industry report 2021. Government of Pakistan. Islamabad.

National Electric Power Regulatory Authority (NEPRA). (2022). State of industry report 2022. Government of Pakistan. Islamabad.

National Electric Power Regulatory Authority (NEPRA). (2023). State of industry report 2023. Government of Pakistan. Islamabad.

National Electric Power Regulatory Authority (NEPRA). (2024). State of industry report 2024. Government of Pakistan. Islamabad.

National Electric Power Regulatory Authority (NEPRA). (2025). Performance evaluation report of distribution companies (DISCOs) for the fiscal year 2024-25. Government of Pakistan. Islamabad.

National Transmission & Despatch Company (NTDC). (2024). Power system statistics of Pakistan (49th ed.). WAPDA House, Lahore.

Rehman, A. U., Ali, Z., & Taylor, P. J. (2025). Detecting sophisticated firmware-based meter tampering using machine learning anomaly detection vectors. IEEE Transactions on Power Delivery, 40(1), 321-334. https://doi.org/10.1109/TPWRD.2024.3411090

Smith, T. J. (2021). Power systems analysis and distribution design constraints (3rd ed.). McGraw-Hill Education.

Water and Power Development Authority (WAPDA). (2024). Annual report 2023-24: Historical evolution of transmission infrastructure. Lahore, Pakistan.

Zaidi, S. M., & Husain, A. (2023). Macroeconomic choking and circular debt: The multi-layered financial crisis of Pakistan's power network. Pakistan Development Review, 62(3), 405-428. https://doi.org/10.30541/v62i3pp.405-428