

# Economic Framework for Maximising Electricity Theft Recovery in Distribution Networks

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## ABSTRACT

Electricity theft, a type of non-technical loss (NTL), reduces utility revenues, distorts feeder loadings, and hampers investments in reliability and clean energy. This study presents an integrated economic framework to maximise recoverable value from theft within distribution networks. The framework combines mechanism design to align customer incentives through pricing, amnesty programmes, and credible penalties with a portfolio approach to detection and remediation strategies. These include advanced metering, feeder/DT balancing, analytics-driven audits, and standardised legal evidence packs, all within budget, legal, and equity constraints. It models recoveries as the discounted net present value of past back-billing and legitimate future consumption, guided by key utility KPIs such as recovered NPV per cost, relapse rates, and alarm accuracy. Implementation follows a three-phase plan: initial pilots, scaling and optimisation, and institutionalisation, supported by governance structures (RACI, due process, independent audits) and measurement & verification. Examples from India and Brazil demonstrate that integrating technology, legal processes, and social measures is vital for shifting incentives away from theft and towards compliance. Ultimately, this approach provides regulators with a justifiable method to reduce NTL while upholding affordability and public trust.

**Keywords:** electricity theft; non-technical losses; mechanism design; advanced metering infrastructure; portfolio optimisation; governance.

## INTRODUCTION

Electricity is a crucial national energy resource, and electricity theft poses a significant obstacle to achieving a stable, reliable supply. Theft of electricity involves unauthorised tampering with meters or bypassing wires, drastically reducing the thief's electricity costs and ultimately leading to substantial economic losses and increased safety risks for everyone involved. In certain regions, such as Uttar Pradesh, India, electricity theft accounts for a remarkably substantial portion of overall power loss, making it a pressing issue for local authorities. The magnitude of electricity theft across multiple countries and the various drivers of theft affecting different segments of society remain poorly understood, complicating efforts to devise effective countermeasures. Addressing this challenge is crucial to enhancing overall energy security and ensuring efficient utilisation of resources (Xia et al., 2022). Non-technical losses (NTL) refer to significant revenue and energy losses an electricity supply system experiences that cannot be attributed to physical losses within the network infrastructure. Hence, revenue-at-risk can arise from various issues, such as billing errors, inaccurately measured demand, misreported consumption data, meter tampering, and even fraudulent activities (Apata et al., 2022). The problem of theft recovery within electricity distribution networks has not been systematically addressed, despite its critical importance across numerous jurisdictions and regions (Adebayo & Aina, 2024). A specific analytical framework based on economic variables can provide a robust method for estimating the value of theft mitigation efforts and evaluating corresponding strategic options to combat these losses effectively. By

implementing this framework, utilities can develop targeted strategies to minimise NTL and enhance their overall operational efficiency. (Guarda et al.2023)

Electricity is a crucial element in fulfilling basic human needs and is essential to everyday life. Ensuring access to a stable electrical supply at reasonable, regulated prices is vital to overall well-being and to meeting fundamental subsistence requirements. Affordability and a dependable, around-the-clock electricity supply are particularly significant in the early phases of development and play a pivotal role in fostering growth and improving quality of life (Maka & Alabid, 2022). Information asymmetry and principal-agent dynamics characterise the interactions of consumers or consumer groups across different segments. Multiple players with heterogeneous bills, physical bypasses, and wire-swap attachments create enforcement impediments that are already challenging in segments such as domestic or commercial. Non-technical losses (NTL) refer to revenue and energy losses experienced by electricity supply systems that are not attributable to physical network losses. (Yuan et al., 2023)

### **Legal and Regulatory Foundations**

Electricity theft is a deeply undesirable activity that involves the consumption of electrical energy without the necessary constraints and regulations, and it is illegal in nearly every nation worldwide. There are primarily two forms of electricity theft that can be distinctly recognised: the first is the act of directly stealing energy from power lines. In contrast, the second involves tampering with the energy meter to falsify consumption. Additionally, electricity theft may occur through various unfair or fraudulent practices, including situations in which providers supply illegal energy sources that bypass the entire transmission system. (Hu et al., 2020). The term non-technical losses (NTL) encompasses lost revenue in the power distribution domain, arising from theft and other issues such as unbilled energy, incorrect customer categorisation, and reductions in billing due to political pressures and interventions. The economic repercussions of power theft are often exacerbated in developing countries, where various factors heighten vulnerability to such illicit practices, primarily due to harsh economic conditions and pronounced income inequalities. To illustrate, in South Africa, electricity theft is reported to cost the industry around R12 billion annually, which amounts to approximately 15% of Eskom's total revenue, highlighting the severity and widespread nature of this issue. (Hu et al., 2020)(Mbanjwa, 2017)

### **Economic Principles and Revenue Recovery**

Recovery from electricity theft requires a comprehensive understanding of domicile-level discrepancies among sanctioned supply, recorded consumption, and assumed normal usage. Structural aspects of markets, institutions, rights, residuals, authorities, regulations, mandates, obligations, and penalties inform and constrain both detection and deterrence. Revenue loss is composed of three related components: the price per unit, the fraction of sanctioned supply deemed non-compliant, and the duration of any such non-compliance. Regulation-disciplined utilities face the challenge of recovering the extra-market supply loss they capture under the threat of additional sanctions, inducing only corrective changes in supply, billing, and service; these, in turn, affect broader economic, social, and welfare objectives. Analysis of the corresponding stage game, involving non-consented alternative recovery of sanctioned utility supply under detection uncertainty, reveals driver-player incentive rents arising from the utility's supply distortion (Hu et al., 2020). Given that the requisite detection features are generally unavailable without widespread deployments, the price drop-deterrent opportunity cost is optimally maximised via metering regularity and coverage; at a second stage, the detection-target differential continues to dominate the recovery-profit opportunity assessment.

### **Measurement, Detection, and Valuation of Losses**

Electricity theft is the illegal acquisition of electricity from the electricity supply network. Non-technical losses include not only theft but also consumption resulting from errors in billing procedures and measurement errors; consequently, the measurement and valuation of such losses are of great economic significance (Joaquim et al., 2017). Losses in the energy supply sector are categorised into technical and non-technical losses (Hu et al., 2020). Technical losses result from factors such as resistance and transmission losses, while non-technical losses refer to energy distributed but not billed to customers. Non-technical losses are often caused by meter tampering,

fraud, and similar actions. Customer parameters can categorise measurements and loss detection across the electricity distribution network. These parameters include the level of metering accuracy, the quality of consumption or customer data, the presence of tampering indicators, and the estimation of the total volume of non-technical losses. Metering data is fundamental for quantifying and measuring losses. Some companies collect metering readings from smart devices installed on customers' premises; however, data from smart meters is often collected at very low frequency. The management of metering data, therefore, depends on the governance of the underlying data framework. Alternatively, companies utilise direct injection data from distribution transformers to estimate the overall volume of distribution to customers. (Ghori et al.2023)

### **Cost-Benefit Analysis of Recovery Strategies**

Cost-benefit analysis aids decision-making for substantial investments, competing alternatives, and uncertain outcomes. A detailed analysis quantifies capital expenses, operating costs, social costs, and expected benefits, enabling prioritisation of theft recovery initiatives. Completed projects and deployments of advanced measurement and metering technologies across regions inform estimations of theft reduction and remain the primary analytical focus. Assessment of specific components remains speculative, although valuable insights are provided. Analysis encompasses the initial deployment and subsequent expansions of detection and recovery programmes, along with periodic updates to metering capability (Pretorius & Gaunt, 2015). Competing policy options, absent formalised revenue assurance practices, undergo evaluation. Opportunity costs of misallocated resources, impacts of theft-induced changes to the customer base, and scenario-specific variations in time-to-detection and recovery rates exert significant influences over break-even thresholds and expected net gains. Identification of capital and operating investments associated with detection, deterrence, and recovery initiatives constitutes a preliminary stage in cost-benefit analysis.

The implementation of fully developed detection programmes demands a substantial financial commitment, while ancillary information gathered during the initial deployment can subsequently lower the cost of detecting residual theft. Moreover, specific enhanced programmes require only incremental resource allocation and may achieve cost recovery more rapidly. The expansion of detection frameworks, when circumstances permit the use of previously acquired information on tampered customers, prioritises this and thus qualifies as a project timing modification. Established estimates of expected reductions in annual theft from the initial implementation of detection programmes provide a basis for anticipated benefits. Available experience further guides the enumeration of anticipated total theft reduction attributable to each policy alternative under consideration (ESTEBASARI et al., 2016). The principal finding indicates that the expected net gain from pursuing enhanced employee- or customer-level deterrence and recovery initiatives ranks below that attainable through the maturation of the initial detection programme. Competing scenarios are thus further compared on the premise that the first programme is completed before engagement with supplementary options. (Zhang, 2024)

### **Revenue Assurance and Risk Management**

To maximise recovery from electricity theft, an economic actions framework considers the institutional, regulatory, and operational environment of electric distribution networks. The study assesses financial losses at risk from theft, the expected value of additional revenue recovered if such losses are reduced, and the efficiency of recovery strategies. To further assist operators in actively recovering revenue lost to theft, attention shifts to high-level revenue assurance and risk management. A comprehensive revenue assurance framework guides the utility in implementing end-to-end controls that reduce non-compliance risks. The framework identifies the risk of revenue loss as a system-level variable that is universally applicable and of concern to the organisation at the governance level. Appropriate procedures, governance structures, and performance metrics outline compliance obligations, opportunities for recovery, and risks associated with additional investment. A technical perspective briefly examines considerations for measurement technology choices, including upfront costs, ongoing monitoring and detection capabilities, and operational implications. The additional monitoring capacity offered by automated distribution networks and the effect of extended time between theft occurrence and detection on overall loss are also discussed (Lateefat & Bankole, 2023). Risk-sharing arrangements include insurance contracts to safeguard against high-impact, low-probability events, external contingency-response capabilities

to aid in re-establishing normal operations, and mitigation measures for the regulatory, product, and brand-reputation component of income at risk.

### **Technical Considerations in Distribution Networks**

Utilities deliver electricity to consumers through a vast distribution network, making massive investments in the grid with no ability to monitor its use once it leaves substations. Despite extensive efforts to detect electricity theft, technical and non-technical losses remain endemic globally (Hu et al., 2020). The casing of tracking devices, concurrent load studies, and the installation of a theft-detection system on the electricity meter are the most common approaches for detection. Utilities face the challenge of selecting appropriate technologies to detect electricity theft while balancing the magnitude of theft and operational costs. Different technologies can yield different results in detecting electricity theft. Automatic Meter Reading is widely used equipment for detecting electricity theft in many countries. Lack of attention to the recovery of expenditure in the development and exploitation of intelligent metering systems for detecting electricity theft manifested in diverse influences in several regions (Joaquim et al., 2017). The technologies for detecting electricity theft in these two developments can be categorised into two main groups: direct and indirect detection methods, which differ in their detection capabilities.

### **Policy Instruments and Incentive Alignment**

Reliable electricity is a foundational input for modern growth, trade, and digital services. As technological progress accelerates and systems incorporate more variable renewable energy, efficient distribution and credible billing become even more critical. However, theft via bypassing, tampering, illegal connections, or meter damage remains a global disruptor (Cavraro et al., 2024). Non-technical losses (NTL) are material: estimates attribute roughly a quarter of global energy output, about twelve per cent in electricity supply, and roughly US\$35 billion in annual utility losses to NTL (Brocks et al., 2016). Exposure spans residential through industrial customers, reflecting heterogeneous ability to pay, perceived detection risk, and the availability of recovery pathways. NTL erodes value through three channels: direct revenue loss (unbilled energy), upkeep investment loss (deferred maintenance and asset stress from hidden loading), and overhead loss (higher operating and legal costs). International reviews indicate that at least 15 countries have theft-recovery programs, five of which have nationwide coverage, underscoring both the prevalence of the problem and the diversity of responses (Hu et al., 2020).

A coherent policy toolkit aligns incentives so that lawful consumption dominates rational alternatives. First, pricing and tariff instruments should match willingness-to-pay at the margin: lifeline blocks or social tariffs for basic needs; demand-reflective or time-of-use rates for small commercial users; and hybrid credit-prepay options that stabilise bills and reduce arrears. Second, advanced metering infrastructure (AMI) instruments, distribution-transformer and feeder metering, and tamper-evident enclosures increase the probability and speed of detection while supporting accurate back-billing. Third, enforcement and legal instruments must deliver swift certainty within due process: standardised evidence packs, dedicated prosecutor partnerships, and transparent penalties. Fourth, social and equity instruments, such as amnesty-to-regularisation offers, structured arrears repayment (e.g., PAYS), and safety upgrades for hazardous wiring, provide viable compliance paths, lowering relapse. Fifth, contracting and procurement instruments should bundle meter upgrades with communications, analytics, and service-level agreements to ensure performance rather than one-off hardware drops. Finally, governance and transparency roles and RACI, KPI dashboards, and independent audits sustain legitimacy. Effective programs combine these instruments as a portfolio. Pricing moderates incentives; AMI and audits raise perceived detection; legal process makes outcomes predictable; and regularisation preserves future revenue. The result is maximised recoverable value both past back-billing and future lawful consumption while protecting affordability and public trust (Cavraro et al., 2024; Brocks et al., 2016; Hu et al., 2020).

**Table 1:** Policy Instruments and Incentive Alignment

Incentive Effect	Pricing / Tariffs	Metering & Tech	Enforcement / Legal	Amnesty (Social)	PAYS (Equity)	Contracting / Procurement	Governance & Transparency	KPIs (examples)
Affordability	Lifeline blocks; TOU where beneficial; hybrid credit-prepay options	AMI; DT/feeder metering; tamper-evident enclosures	Proportionate penalties; clear back-billing rules	Time-bound waiver of penalties for self-reporters; safety fixes for hazardous wiring	Meter-attached repayment plans; capped instalments; hardship protections	Performance-based SLAs for meters, comms, analytics	KPI dashboards, independent audits, and RACI ownership	Share on lifeline/social tariffs; average arrears days; disconnection rate; customer complaints per 1k
Deterrence & Predictability	Bill stability signals; transparent pricing	Tamper alarms, anomaly analytics, and feeder balancing	Swift-certainty via prosecutor MoUs; standardised evidence packs	Clear re-entry rules after self-report; outreach campaigns	Grace periods; on-time payment incentives	Data-quality SLAs; uptime guarantees	Due-process KPIs; service timelines published	Audit hit-rate; alarm precision/recall; median days detection to adjudication
Sustained Compliance	Tariff glide paths to prevent step-change shocks	Continuous monitoring; remote disconnect/reconnect governance	Predictable adjudication; appeal routes	Post-amnesty follow-ups; community partners	Retention tracking; default management playbooks	Lifecycle support & upgrades; vendor penalty/bonus	Annual external verification; stakeholder forum feedback loop	Relapse rate at 6/12/24 months; regularisation on retention; NPV recovered per \$ spent

**Notes:** Social & Equity is split into separate Amnesty and PAYS columns. KPIs are illustrative and should be adapted to your regulator and data availability.

**Case Studies and Comparative Perspectives.**

Electricity theft persists across diverse regulatory settings, but its economic and operational impacts are most acute in developing contexts where distribution utilities already face tight margins and service-quality constraints. As summarised in the attachment, non-technical losses (NTL) depress billable energy, destabilise feeder loading, and erode investment capacity, with global evidence indicating substantial and recurrent losses to utilities and economies (Jindal et al., 2020). The problem’s salience is amplified where affordability pressures, data scarcity, and uneven enforcement raise the perceived gains from illicit consumption relative to the expected costs of detection and sanction (Hu et al., 2020). India illustrates the scale and persistence of the challenge. In high-loss states and dense urban pockets, widespread tampering, bypass connections, and billing leakages make periodic raids or blanket inspections insufficient on their own. The attachment notes the prominence of localised hotspots where theft accounts for a large share of overall losses and undermines reliability improvements. Utilities, therefore, pair targeted audits with modernisation of metering (AMI/MDM), distribution-transformer and feeder metering for energy balancing, and pathway-to-compliance programs that replace punitive back-billing alone with durable regularisation (e.g., prepayment migration and structured repayment). These measures aim to raise perceived detection probability while reducing relapse. Complementary policy instruments stress segmentation by feeder and customer class, so scarce inspection capacity is directed to value-at-risk clusters rather than spread thinly.

Brazil, as framed in the attachment’s comparative discussion, faces similarly entrenched NTL concentrated in specific urban and peri-urban zones. The response emphasises technical hardening (tamper-resistant metering, remote monitoring), analytics-guided field operations, and standardised legal evidence packs to shorten time-to-resolution, an approach that seeks “swift-certainty” within due-process limits rather than relying solely on extreme fines. Social-policy levers (targeted affordability mechanisms and clear regularisation offers) are deployed to depress incentives for subsistence theft while preserving prosecutorial focus on organised commercial fraud. Although the precise program mix differs by concession area, the common thread is the integration of AMI/MDM data with legal process design to raise the expected penalty of theft and improve collectability. Across both countries, the attachment’s core insight is that technology alone is insufficient: the most effective portfolios combine (i) data-driven detection (AMI, feeder/DT metering, anomaly analytics), (ii) credible enforcement with faster adjudication, and (iii) customer-centric compliance pathways (prepayment, structured arrears repayment, and limited-time amnesties). This triad maximises recoverable value both past back-billing and future lawful consumption while reducing relapse and political resistance, aligning with the broader economic framework advanced in the document (Jindal et al., 2020; Hu et al., 2020). The table below lists one example country from each inhabited continent. Antarctica has no sovereign countries and is governed by the Antarctic Treaty System.

**Table 2:** Example country from each inhabited continent.

Continent	Example Country	Notes / Reference
Africa	Nigeria	The United Nations geographic scheme lists Nigeria as an African state (UN Geoscheme; UN Member States list).
Asia	India	Recognised in Asia under the UN Geoscheme; UN Member States list.
Europe	France	Classified in Europe (UN Geoscheme; UN Member States list).
North America	Canada	Part of North America per the UN Geoscheme and the UN Member States list.
South America	Brazil	Listed in South America (UN Geoscheme; UN Member States list).
Oceania	Australia	In Oceania, per the UN Geoscheme (UN Member States list).
Antarctica	—	No sovereign countries; governed by the Antarctic Treaty System (ATS).

- United Nations Statistics Division – Standard country or area codes for statistical use (M49) / UN Geoscheme.
- United Nations – Member States.
- Antarctic Treaty Secretariat – Antarctic Treaty System.

### Implementation Roadmap and Governance

Electricity theft diminishes the economic efficiency of distribution utilities and compromises reliability. An effective response should therefore go beyond ad hoc inspections to a well-structured roadmap with transparent governance. Based on the attached framework, the roadmap combines analytics, technology, legal processes, and community engagement to maximise recoverable value while maintaining fairness and legitimacy.

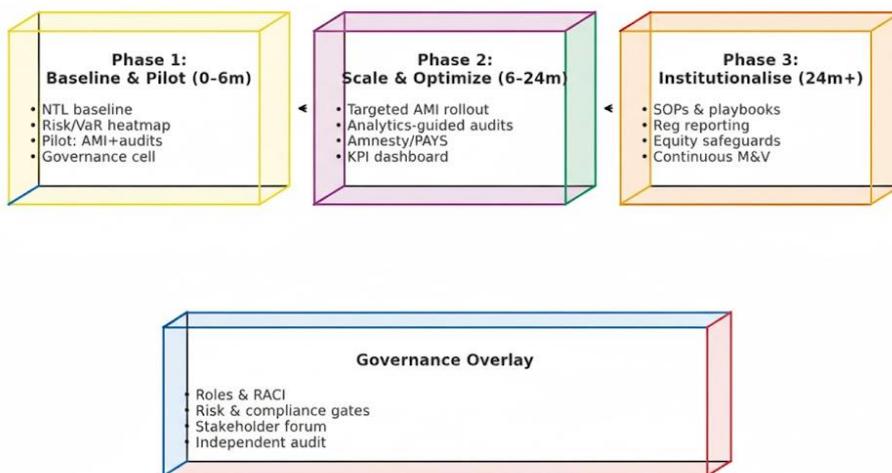
Phase 1 (0–6 months): Establish baselines and run learning pilots. Utilities quantify non-technical losses (NTL) at substation, feeder, and distribution-transformer levels; build a value-at-risk heatmap; and launch pilots that combine AMI/MDM reads, feeder/DT metering for energy balancing, and analytics-guided field audits. A small

governance cell coordinates legal, field, customer, and data functions, sets initial KPIs (e.g., recovered NPV per unit cost, relapse rate at 6–12 months), and defines due-process standards and equity safeguards. This phase also designs the evidence pack for back-billing and prosecution to shorten time-to-resolution.

Phase 2 (6–24 months): Scale winning portfolios and optimise. AMI rollout is targeted to high-VaR feeders; anomaly engines guide audit routing; and customer-centric compliance pathways (prepayment migration, structured arrears repayment, and limited-time amnesties) reduce relapse. Operational playbooks specify responsibilities (RACI), escalation paths, and safety protocols. A live KPI dashboard tracks financial recovery, technical loss reduction, customer outcomes, and the timeliness of legal actions. Feedback loops tune inspection intensity, meter hardening, and outreach based on measured elasticities and collectability. Phase 3 (24+ months): Institutionalise and assure. Standard operating procedures, training, and regulator-facing reports make results durable. Independent audits validate NTL metrics and case handling; stakeholder forums surface equity concerns; and continuous M&V maintains model fidelity. At this stage, deterrence is stochastic and continuous (via AMI alarms and randomised audits), not cyclical.

Governance overlay: Across all phases, a formal governance structure aligns incentives and protects legitimacy. Key elements include a multi-disciplinary steering group; a RACI matrix for field, legal, customer, and analytics teams; risk/compliance gates before mass actions; and transparent routes for customer redress. Mathematical models inform prioritisation (inspection routing, tariff and settlement design, CVaR-bounded recovery planning) and ensure that deterrence, capacity upgrades, monitoring, and targeted detection are chosen on expected value rather than intuition (Kasumba et al., 2025).

**Fig. 1: Implementation Roadmap and Governance Overview**



## Ethical and SocFinal Implications

Conversations surrounding the ethics of energy theft, especially in an unequal world where access to energy is tied to income, raise questions about redistribution and the boundaries between public and private property. The South African case demonstrates that electricity theft comprises a combination of non-technical and technical losses, with the former characterised as a wide-scale, unmeasured load that can be engineered by the utility or the consumer to go undetected (Mbanjwa, 2017). Societal costs underpin the economics of energy theft. In the absence of theft, the average cost per kilowatt-hour, paid on a nominal basis, does not vary across different locations. The cost of theft can be recovered from both overall electricity sales and the eventual limit on theft, which also supports system security. When Parliament passed a bill into a drought-disaster area, low-income and low-payment prospects increased, exacerbating the crisis of widespread unlawful connections, electrical fires, and transformer explosions, prompting intervention on the distribution network itself. A case study of KwaXimba in eThekweni, KwaZulu-Natal, illustrates how Eskom’s financial burden leads to a cycle of infrastructure dampening, storage reduction, and ultimately translates into load shedding. Educating communities about the detrimental cascade of theft to system viability is an indirect yet crucial way to address

theft through various metrics. The approach advocates refraining from quantifying the social costs of electricity theft, often deemed insurmountable, in favour of stress-testing estimated recovery gains against perceived costs of improvement to business metrics. Public transport, accessible routes to education, and township residents indicate that awareness of faulty infrastructure significantly reduces the perceived need for theft. Each municipal region is expected to experience theft as a function of the consumer's relationship to the utility, warranting diligence in evaluating the theft dynamics for electricity recovery. (Hole, 2022)

Unmonitored “free” energy fuels additional societal ramifications: system unsustainability ultimately aligns back to public sustenance. Structures capable of estimating public accountability enable stakeholders beyond currency-printing institutions to intervene and recapture sustenance. Such processes quantifiably bolster the trajectory from non-technical and systemic, unmeasured losses to gains recovery towards urban, sector-positioned, and corporate welfare. However, the contestable framing of electricity as an inalienable right invariably arises. Never does the question originate from a value standpoint; rather, it concerns how theft adjusts business lifelines to continue funding incumbent and emergent businesses (Jindal et al., 2020).

## CONCLUSION

Electricity theft is fundamentally an incentives and optimisation problem, not merely an enforcement challenge. Treating NTL reduction as recoverable-value maximisation clarifies priorities: segment customers and feeders by value-at-risk; invest in information (AMI/MDM, feeder/DT metering, analytics) to raise credible detection; pair swift-certainty legal pathways with amnesty-to-regularisation and PAYS-style arrears management to reduce relapse; and institutionalise governance that balances deterrence with equity. The staged roadmap proposes baseline & pilots, scale & optimise, and institutionalise, providing a practical sequence for building durable capability, while KPI-driven M&V and independent audit sustain legitimacy. Comparative evidence underscores that technology alone is insufficient; enduring results come from aligning tariffs, detection, legal process, and social supports so that lawful consumption is the rational choice. Utilities that adopt this framework can boost recovered NPV, improve reliability, and create a transparent, regulator-friendly program that persists beyond one-off raids or meter swaps, ultimately funding the transition to a cleaner and more resilient distribution system.

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