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Implementation and Performance Assessment of a Nationwide Electricity Prepaid Metering System: Lesson Learned from Sudan

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Abstract:

Electricity distribution utilities in many developing countries continue to face significant operational and financial challenges arising from commercial losses, electricity theft, customer arrears, inefficient billing systems, and high revenue collection costs. Although prepaid electricity metering has become an increasingly adopted solution for addressing these challenges, most published studies emphasize simulation models, economic analysis, customer perception surveys, or smart metering technologies, while comprehensive documentation of large-scale utility implementation remains relatively limited.

This paper presents a comprehensive engineering case study of the nationwide implementation of Sudan's prepaid electricity metering system based on documented operational records from the National Electricity Corporation (NEC). The study describes the planning process, technology selection, pilot implementation, deployment strategy, customer awareness program, organizational transformation, and nationwide rollout of the prepaid metering project. Operational performance is evaluated using utility indicators including customer arrears, revenue collection, commercial loss reduction, prepaid customer penetration, operational efficiency, and customer service improvements.

The documented results indicate substantial improvements following the implementation of prepaid metering. Customer arrears declined significantly, revenue collection became more efficient, commercial losses were considerably reduced, and several labor-intensive administrative activities associated with conventional billing were eliminated. The project also improved customer awareness of electricity consumption while simplifying electricity purchasing and strengthening utility financial sustainability.

Unlike many previous investigations that rely primarily on simulation or theoretical analysis, this study documents practical engineering experience obtained from one of Africa's earliest large-scale prepaid electricity metering implementations. The findings provide valuable technical and managerial lessons for electricity utilities, policymakers, and engineers seeking to modernize electricity distribution systems under resource-constrained conditions.

Keywords: Prepaid Electricity Metering, Electricity Distribution, Commercial Losses, Revenue Collection, Utility Modernization, Smart Metering, Engineering Case Study, Sudan.

I. INTRODUCTION

Electricity distribution utilities throughout the world are under increasing pressure to improve operational efficiency while maintaining financial sustainability and providing reliable electricity services to consumers. Although significant investments have been made in generation and transmission infrastructure, distribution companies in many

developing countries continue to experience severe financial and operational challenges arising from inefficient billing systems, electricity theft, customer payment defaults, inaccurate meter readings, and high administrative costs associated with conventional postpaid electricity billing. These challenges reduce utility revenues, limit investment opportunities, and ultimately affect the quality and reliability of electricity supply.

Among the various approaches introduced to improve utility performance, prepaid electricity metering has emerged as one of the most effective revenue protection mechanisms. By requiring customers to purchase electricity before consumption, prepaid metering fundamentally changes the traditional relationship between electricity suppliers and consumers. The technology reduces credit risk, minimizes customer arrears, eliminates routine meter reading activities, improves cash flow, and provides customers with greater awareness and control over their electricity consumption. Consequently, prepaid metering has been adopted by many electricity utilities worldwide as part of broader distribution network modernization programs.

Despite these recognized advantages, successful implementation of prepaid metering extends well beyond the installation of new electricity meters. Large-scale deployment requires careful planning, appropriate technology selection, customer awareness campaigns, organizational restructuring, staff training, secure vending infrastructure, and continuous operational monitoring. The interaction between these technical, managerial, and organizational factors ultimately determines whether a prepaid metering program achieves its intended objectives.

Sudan experienced many of the operational difficulties commonly reported by electricity utilities in developing countries during the 1990s. The National Electricity Corporation (NEC), responsible for electricity generation, transmission, distribution, and customer services, relied entirely on a conventional postpaid billing system that required periodic meter reading, manual bill preparation, invoice distribution, payment collection, customer disconnection for non-payment, and subsequent reconnection after settlement of outstanding bills. As electricity demand continued to increase, these procedures became increasingly inefficient and expensive to maintain. Historical project records indicate that commercial losses exceeded 45% of generated electricity, customer arrears accumulated to substantial levels, and revenue collection became increasingly difficult, creating significant financial pressure on the utility.

Recognizing the need for comprehensive modernization, NEC initiated an extensive evaluation of alternative metering technologies during the late 1990s. Following technical and economic assessments, a keypad-based prepaid electricity metering system was selected for pilot implementation in Riyadh District, Khartoum, in December 1997. Following the successful completion of the pilot project, the system was progressively deployed throughout Khartoum State before expanding to other regions of Sudan through a carefully planned nationwide implementation strategy. Beyond improving revenue collection, the project represented a fundamental transformation of utility operations involving customer education, staff training, organizational restructuring, and modernization of electricity purchasing services.

Although prepaid electricity metering has been widely investigated in the scientific literature, the majority of published studies focus on simulation models, customer behavior, economic evaluations, smart metering technologies, or theoretical analyses. Comparatively few publications document the practical implementation of nationwide prepaid metering systems using operational utility records collected throughout actual deployment. Consequently, there remains limited published evidence describing the engineering decisions, implementation strategies, organizational changes,

and operational lessons associated with large-scale prepaid metering projects, particularly within developing countries.

This paper addresses that gap by presenting a comprehensive engineering case study based on documented operational records from Sudan's nationwide prepaid electricity metering project. Unlike simulation-based investigations, the study evaluates an actual utility modernization program from technology selection and pilot implementation through nationwide deployment and operational performance assessment. The work documents measurable improvements in revenue collection, customer arrears, commercial loss reduction, operational efficiency, and customer service while highlighting the engineering and managerial practices that contributed to successful implementation under challenging operating conditions.

The principal contributions of this paper are fourfold. First, it documents one of Africa's earliest large-scale prepaid electricity metering implementation projects using actual utility operational records. Second, it presents the complete implementation methodology, including technology selection, pilot deployment, customer awareness, organizational transformation, and nationwide rollout strategy. Third, it evaluates the operational performance of the project using documented indicators related to revenue collection, customer arrears, commercial losses, and utility efficiency. Finally, it identifies practical engineering and managerial lessons that may assist electricity utilities and policymakers planning similar modernization programs in developing countries.

The remainder of this paper is organized as follows. Section II reviews previous research related to prepaid electricity metering systems. Section III describes the Sudanese electricity distribution system and the operational challenges that motivated the modernization program. Section IV presents the research methodology, while the subsequent sections describe the implementation process, deployment strategy, system architecture, and operational performance evaluation. The final sections discuss the principal findings, study limitations, conclusions, and recommendations for future research.

II. RELATED WORK

The modernization of electricity distribution networks has attracted considerable research attention over the past three decades, particularly with the emergence of digital metering technologies, advanced customer management systems, and smart grid infrastructures. Among these developments, prepaid electricity metering has become one of the most widely adopted approaches for improving revenue collection, reducing commercial losses, and enhancing customer participation in electricity consumption management.

Early prepaid electricity systems were primarily introduced to address persistent challenges associated with conventional postpaid billing, including customer arrears, electricity theft, delayed payments, inaccurate meter reading, and high administrative costs. By requiring customers to purchase electricity before consumption, prepaid metering fundamentally shifts financial risk from the utility to the consumer while improving cash flow and reducing outstanding debts. Consequently, many electricity utilities in Africa, Asia, and other developing regions have adopted prepaid metering as an important component of broader utility modernization programs.

Recent advances in smart metering technology have significantly expanded the capabilities of prepaid electricity systems. Modern prepaid meters are increasingly integrated with Advanced Metering Infrastructure (AMI), Internet of Things (IoT)

platforms, mobile payment services, cloud-based customer information systems, and real-time communication networks. These technologies enable remote monitoring, automatic meter reading, demand-side management, dynamic tariff implementation, and enhanced customer engagement while supporting the long-term evolution of smart electricity grids. Numerous studies have reported positive operational impacts following the implementation of prepaid metering. Previous research has demonstrated improvements in revenue recovery, reductions in customer arrears, decreased commercial losses, lower operating costs, elimination of manual meter reading activities, improved billing accuracy, and increased customer awareness of electricity consumption. Several investigations have also shown that prepaid customers tend to modify their electricity consumption behavior because they receive immediate feedback regarding available credit and energy usage, thereby encouraging more efficient electricity utilization.

Within Africa, prepaid metering has been implemented in several countries as part of national electricity sector reform programs. Reported experiences generally indicate that prepaid metering contributes to improved financial sustainability through enhanced revenue protection and reduced non-technical losses. However, implementation outcomes vary considerably depending on technology selection, regulatory frameworks, customer acceptance, vending infrastructure, staff training, and organizational readiness. These findings demonstrate that prepaid metering should be considered not merely as a metering technology but as a comprehensive utility transformation program involving technical, operational, and managerial dimensions.

Although the existing literature clearly demonstrates the potential benefits of prepaid electricity metering, several important limitations remain. Most published studies focus on simulation models, economic assessments, optimization techniques, customer satisfaction surveys, or smart meter communication technologies. Others investigate specific technical components such as token encryption, meter security, communication protocols, or demand forecasting. While these studies provide valuable theoretical insights, relatively few publications document the complete engineering implementation of large-scale prepaid metering projects using actual operational records collected during deployment.

Furthermore, limited literature is available describing the organizational challenges associated with nationwide implementation, including project planning, pilot deployment, customer awareness campaigns, staff training, phased expansion strategies, and operational management. These practical engineering aspects often determine the long-term success of prepaid metering programs but receive comparatively less attention in academic publications.

To address this gap, the present study documents the implementation experience of Sudan's nationwide prepaid electricity metering project using operational records obtained from the National Electricity Corporation (NEC). Unlike previous studies that primarily rely on simulation or theoretical analysis, this paper evaluates a real utility modernization program from technology selection and pilot implementation through nationwide deployment and operational performance assessment. The study therefore contributes practical engineering evidence concerning the implementation of prepaid electricity metering under real operating conditions and provides transferable lessons for electricity utilities undertaking similar modernization initiatives in developing countries.

III. SUDAN ELECTRICITY DISTRIBUTION SYSTEM

A. Overview of the Electricity Sector

During the period preceding the implementation of the prepaid metering project, Sudan possessed one of the largest geographical territories in Africa, covering approximately one million square miles with a population exceeding 35 million people. The National Electricity Corporation (NEC) was responsible for electricity generation, transmission, distribution, customer services, and revenue collection across the country. The utility served nearly one million electricity customers, while the national installed generation capacity was approximately 1,400 MW. To satisfy the increasing demand for electricity, NEC planned substantial expansion of generation facilities, targeting approximately 5,650 MW during the 2005–2010 planning period.

The rapid growth of electricity demand placed considerable pressure on the distribution network and highlighted the need for more efficient operational and financial management. Although generation capacity was gradually expanding, improvements in distribution efficiency and revenue collection became equally important for ensuring the long-term sustainability of the electricity sector.

Sudan's climatic conditions also introduced operational challenges. Ambient temperatures frequently exceeded 45 °C during the summer months, and dust storms created harsh operating conditions for electrical equipment, including metering devices. These environmental conditions required electricity meters with high reliability and durability while minimizing maintenance requirements.

B. Conventional Billing Infrastructure

Before adopting prepaid metering, NEC relied entirely on a conventional postpaid billing system. Since 1968, customer billing operations had been computerized using an offline mainframe system. Subsequent technological upgrades introduced an online NCR mainframe during 1986–1987. In 1995, NEC decentralized its customer management operations by establishing approximately thirty billing offices connected through local area networks to improve customer service and administrative efficiency.

Although these developments represented significant improvements in information management, the overall revenue collection process remained dependent on conventional billing procedures. Meter readers periodically visited customer premises to record electricity consumption manually, after which invoices were prepared and distributed. Customers were required to settle outstanding bills before the utility initiated disconnection procedures for non-payment. Restoration of service required additional administrative processing and reconnection activities.

While technically functional, this process demanded substantial human resources and generated considerable operational expenses. Furthermore, inaccuracies associated with manual meter reading, delayed bill delivery, customer payment defaults, and repeated service disconnections reduced the overall efficiency of the electricity distribution business.

As customer numbers increased annually, maintaining the conventional billing system became progressively more difficult. NEC therefore recognized that improvements in customer information systems alone would not solve the broader operational and financial challenges affecting revenue collection.

IV. CHALLENGES OF THE CONVENTIONAL BILLING SYSTEM

The decision to replace conventional electricity billing was driven by several operational, technical, and financial challenges that had accumulated over many years. These challenges significantly affected the utility's financial performance and its ability to expand electricity services throughout Sudan.

One of the most serious concerns was the high level of commercial losses. Historical project records indicate that total energy losses exceeded 45% of generated electricity before implementation of prepaid metering. These losses were attributed primarily to electricity theft, meter tampering, inaccurate billing, and ineffective revenue collection procedures.

Another major issue involved the accumulation of customer arrears. By 2001, unpaid customer debts had reached approximately 17,900 million Sudanese Dinars (approximately USD 70 million at that time), placing considerable financial pressure on NEC. Because electricity consumption occurred before payment, utilities assumed substantial credit risk whenever customers delayed or failed to settle their accounts.

Operational costs also continued to increase. Conventional billing required routine meter reading, invoice preparation, bill distribution, payment processing, customer complaint management, disconnection for non-payment, and subsequent reconnection after payment. These activities demanded significant labor resources while extending the revenue collection cycle.

Mechanical electricity meters introduced additional technical problems. Meter accuracy gradually deteriorated with age, increasing measurement uncertainty and reducing billing reliability. Since conventional meters were physically accessible, opportunities for unauthorized tampering further increased commercial losses.

Utilities also encountered considerable difficulties serving customers located in rural and remote regions where frequent field visits were costly and time-consuming. Collecting outstanding payments from geographically dispersed consumers became increasingly difficult, thereby reducing collection efficiency.

Customer dissatisfaction represented another important challenge. Billing disputes resulting from incorrect meter readings, delayed invoices, and service disconnections often damaged the relationship between customers and the utility. Consequently, NEC sought a solution capable of improving both operational performance and customer satisfaction simultaneously.

Based on these challenges, NEC identified the following principal objectives for modernization:

- Reduce commercial and non-technical losses.
- Improve revenue collection efficiency.
- Eliminate the accumulation of customer arrears.
- Reduce operational and maintenance costs.
- Improve billing accuracy.
- Simplify customer payment procedures.
- Enhance customer satisfaction.
- Improve financial sustainability.

These objectives ultimately became the foundation for introducing prepaid electricity metering throughout Sudan.

V. RESEARCH METHODOLOGY

This study adopts a descriptive engineering case study methodology based on documented implementation records of Sudan's prepaid electricity metering project. Unlike analytical studies based on mathematical modeling or laboratory experiments, the present work evaluates a real-world utility modernization project by examining the planning process, deployment strategy, and operational outcomes reported during implementation.

The primary source of information is the official project presentation prepared by NEC, which documents the motivations for system modernization, project implementation procedures, pilot deployment activities, and operational performance indicators observed during the nationwide rollout.

The research methodology consists of four stages:

Stage 1 – Problem Identification

Historical operating conditions were reviewed to identify the major technical and financial limitations associated with conventional postpaid electricity billing.

Stage 2 – Technology Assessment

Available metering technologies were evaluated according to operational requirements, implementation complexity, customer usability, maintenance requirements, and expected revenue protection.

Stage 3 – Pilot Implementation Evaluation

The planning and execution of the pilot project were analyzed, including customer selection criteria, staff training, customer awareness campaigns, installation procedures, and operational monitoring.

Stage 4 – Performance Assessment

Project outcomes were evaluated using operational indicators reported by NEC, including:

- Customer arrears.
- Revenue collection.
- Commercial losses.
- Customer migration to prepaid metering.
- Operational efficiency.
- Customer service improvements.

Because this study is based on documented operational records rather than controlled experimentation, its conclusions are limited to the observed implementation experience and should be interpreted as evidence from an industrial case study rather than a statistical investigation.

VI. PREPAID METER TECHNOLOGY SELECTION AND PILOT PROJECT DESIGN

Selecting an appropriate prepaid metering technology represented one of the most critical stages of the modernization program. NEC evaluated several commercially available prepaid metering solutions before choosing the system that best satisfied Sudan's operational requirements.

The evaluation considered several technical criteria, including system reliability, meter security, ease of customer use, maintenance requirements, implementation cost, scalability, and compatibility with existing utility operations. After reviewing different technologies, including magnetic-card and smart-card solutions

figure (2), NEC selected a keypad-based prepaid metering system. The keypad technology allowed customers to purchase electricity credit in the form of encrypted numerical tokens that could be entered directly into the electricity meter. This approach simplified the purchasing process while reducing dependence on physical cards that could be damaged or lost.

Before commencing large-scale deployment, NEC conducted a comprehensive feasibility study to assess the expected technical and financial benefits of prepaid metering. The study indicated that a pilot implementation should be undertaken before expanding the system across the national electricity network.

Following completion of the feasibility study, NEC established a multidisciplinary implementation team responsible for project planning, technical design, installation procedures, customer communication, and operational monitoring. Project personnel received specialized technical training to ensure that installation, maintenance, and customer support activities could be performed effectively throughout the pilot phase.

To maximize the effectiveness of the pilot project, Riyadh District in eastern Khartoum was selected as the demonstration area. Approximately 3,000 electricity meters were installed in this district. The selection was based on several engineering and operational criteria:

- High electricity consumption levels.
- Significant commercial losses.
- Manageable customer population.
- High levels of accumulated arrears.
- Well-developed distribution infrastructure.
- Relatively high customer education levels.

These characteristics provided an appropriate environment for evaluating both the technical performance of the prepaid metering system and customer acceptance before expanding the project to additional regions.

VII. PILOT PROJECT IMPLEMENTATION

A. Customer Survey and Preparatory Activities

Following the selection of Riyadh District as the pilot area, NEC initiated a comprehensive preparation phase before installing prepaid meters. The objective was to minimize operational risks while ensuring that customers understood the purpose and expected benefits of the new billing system.

The implementation team conducted a detailed field survey to collect customer information, verify service connections, and assess the condition of the existing distribution network. This survey established the technical baseline required for planning installations and monitoring project performance.

Customer engagement formed a critical component of the implementation strategy. Residents were informed about the proposed changes through direct communication during field visits. Customers who did not initially respond received official letters explaining the objectives of the project and inviting them to participate in the transition process. Public awareness was further enhanced through television and radio campaigns, which explained the operation of prepaid meters and addressed common customer concerns. To improve service accessibility during the transition period, NEC extended office operating hours until 9:00 PM to accommodate electricity purchases and respond to customer inquiries.

These activities demonstrated that successful implementation depended not only on technical deployment but also on effective communication and customer support.

B. Meter Installation and Commissioning

The first prepaid electricity meter was installed in December 1997, marking the beginning of Sudan's prepaid metering program. Rather than immediately replacing all conventional meters, NEC adopted a phased implementation strategy that allowed engineers to monitor system performance and resolve operational issues before expanding deployment.

New technical procedures were developed to support meter installation, commissioning, maintenance, and customer service. These procedures standardized installation practices across implementation teams while improving quality assurance.

During the initial deployment phase, prepaid meters were installed for selected customer groups, including government officials, senior NEC personnel, and other influential customers. This strategy demonstrated confidence in the new technology and helped increase public acceptance before extending installation to the wider customer base.

The pilot project remained in operation for approximately two years. Throughout this period, engineers continuously monitored system performance, customer feedback, operational reliability, and revenue collection. At the end of the pilot phase, NEC concluded that the observed operational benefits exceeded those predicted during the feasibility study. Consequently, the project advanced to large-scale deployment across Khartoum State beginning in March 1999.

VIII. CUSTOMER AWARENESS AND CHANGE MANAGEMENT

The introduction of prepaid metering represented a significant change in the relationship between customers and the electricity utility. Unlike the conventional billing system, customers were now responsible for purchasing electricity credit before consumption and monitoring their remaining balance. Consequently, effective change management became essential for successful implementation.

NEC developed a comprehensive customer awareness strategy based on three principal objectives:

1. Explain the operating principles of prepaid metering.
2. Demonstrate the purchasing process.
3. Build public confidence in the new technology.

Communication activities included direct customer visits, printed information, television broadcasts, and radio programs. Technical staff were trained to answer customer questions regarding token entry, credit balance, electricity consumption, and troubleshooting.

This customer-centered approach reduced resistance to the new billing system and encouraged widespread participation in the pilot project. It also helped customers recognize several practical benefits, including:

- Immediate access to electricity after purchasing credit.
- Elimination of monthly bills.
- No estimated meter readings.
- Better control of household electricity expenditure.
- Greater awareness of energy consumption.

From an organizational perspective, customer education significantly reduced the number of service complaints after deployment and contributed to the project's overall success.

The Sudan experience demonstrates that customer engagement should be considered an integral component of prepaid metering implementation rather than an optional activity.

IX. NATIONWIDE DEPLOYMENT STRATEGY

A. Expansion Beyond the Pilot Area

Following the successful evaluation of the Riyadh pilot project, NEC initiated a phased expansion throughout Khartoum State. Deployment began in Khartoum East before extending to Amarat and subsequently to the remaining districts of the capital.

A phased rollout strategy provided several operational advantages. Engineering teams were able to apply lessons learned during the pilot project while maintaining continuous technical support for newly installed customers. Staff training programs were expanded simultaneously to ensure that installation capacity increased in proportion to customer demand.

As deployment progressed, prepaid metering gradually became the standard electricity billing system across Khartoum.

B. National Rollout

The long-term objective of the modernization program was nationwide implementation. According to project planning documents, NEC targeted complete replacement of conventional electricity meters throughout Khartoum by 2006, followed by expansion to seventeen additional towns outside the capital. The remaining conventional meters across Sudan were scheduled for replacement during the following implementation phase.

Project records indicate that by the end of 2005, approximately 79,651 customers outside Khartoum had already been incorporated into the prepaid metering program, demonstrating steady progress toward nationwide deployment.

The gradual rollout minimized operational disruptions while allowing the utility to allocate technical and financial resources efficiently. It also enabled continuous refinement of installation procedures as deployment expanded into different geographical regions.

X. SYSTEM ARCHITECTURE AND VENDING INFRASTRUCTURE

A. Overview of the Prepaid Metering System

The prepaid metering system implemented by NEC consisted of four principal components:

1. Customer prepaid electricity meter.
2. Central vending and customer management system.
3. Point-of-sale network.
4. Secure token generation mechanism.

Unlike conventional billing systems, electricity consumption was authorized only after customers purchased prepaid electricity credit. Each purchase generated a secure numerical token that was entered through the keypad installed on the electricity meter.

The meter automatically deducted energy consumption from the available balance until the purchased credit was exhausted.

This architecture eliminated monthly billing cycles while providing immediate revenue collection for the utility.

B. Electricity Purchase Methods

To improve customer convenience, NEC introduced multiple methods for purchasing electricity credit. According to the project documentation, customers could obtain prepaid electricity through several channels:

- Direct purchases at NEC customer service offices.
- Scratch-card systems using encrypted numerical codes.
- SMS-based purchasing services.
- Interactive Voice Response (IVR) purchasing systems.
- Remote vending terminals distributed across service areas.

Providing multiple purchasing options increased accessibility while reducing congestion at customer service offices. The strategy also supported future expansion toward electronic payment services.

C. Operational Advantages

Compared with the previous postpaid billing system, the prepaid architecture simplified utility operations by eliminating numerous manual processes, including:

- Periodic meter reading.
- Invoice preparation.
- Bill distribution.
- Payment collection.
- Service disconnection due to unpaid bills.
- Reconnection after payment processing.

Instead, the prepaid system established an automated revenue collection process in which electricity credit was purchased before consumption. This significantly reduced administrative costs while improving cash flow and operational efficiency.

Moreover, customers gained greater control over electricity expenditure by monitoring remaining credit directly on the meter. This encouraged more efficient energy use and strengthened the relationship between the utility and its customers.

D. Engineering Lessons Learned

The Sudan prepaid metering project illustrates several engineering principles that are broadly applicable to utility modernization initiatives:

1. Technology selection should consider environmental conditions, customer usability, and long-term maintainability.
2. Pilot implementations provide valuable operational experience before nationwide deployment.
3. Customer education is essential for successful adoption of new utility technologies.
4. Organizational restructuring and staff training are as important as technical system design.
5. Multiple electricity purchasing channels improve accessibility and customer satisfaction.
6. Continuous performance monitoring enables refinement of operational procedures throughout deployment.

These lessons contributed significantly to the success of Sudan's prepaid metering program and may provide useful guidance for utilities undertaking similar modernization efforts in developing countries.

XI. RESULTS AND PERFORMANCE EVALUATION

The performance of the prepaid electricity metering project was evaluated using operational indicators reported by the National Electricity Corporation (NEC) during the pilot phase and the subsequent rollout across Khartoum State. The assessment focuses on revenue collection, customer arrears, prepaid meter deployment, commercial loss reduction, operational efficiency, and customer service improvements. Since this study is based on an engineering case study rather than a controlled experiment, the results presented reflect the documented implementation experience.

A. Expansion of Prepaid Meter Deployment

Following the successful completion of the pilot project, prepaid metering was progressively deployed throughout Khartoum State before expanding to other regions of Sudan.

Project records indicate that a substantial proportion of customers had already migrated from conventional billing to prepaid metering. Adoption levels varied across different service areas, with urban districts achieving the highest implementation rates. By the time of project reporting, Khartoum, Khartoum North, and Omdurman had each achieved prepaid penetration levels approaching 90%, while areas outside the capital continued to expand steadily.

The high adoption rate demonstrates that the phased implementation strategy successfully balanced technical deployment with customer acceptance. It also indicates that prepaid metering was capable of supporting large-scale utility operations without major disruption to electricity services. as shown in table (1) the total customers at Khartoum capital of Sudan till April 2006.

Table (1) total number of customers for all NEC at April 2006

City	Total customers	Prepaid	Traditional	% of prepaid
Khartoum	183,405	157,198	26,207	86%
Khartoum North	110,919	98,926	11,993	89%
Omdurman	124,353	111,585	12,768	90%
Outside Khartoum	432,646	173,741	258,905	40%
Total	851,323	541,450	309,873	64%

B. Reduction in Customer Arrears

One of the principal objectives of the modernization program was the elimination of accumulated customer debt.

According to NEC operational records, total customer arrears before large-scale implementation amounted to approximately 4,436 million Sudanese Dinars in January 2001. Following the widespread deployment of prepaid metering, arrears had declined to approximately 1,707 million Sudanese Dinars by March 2003, representing an overall reduction of approximately 62% as shown in table (2).

This reduction can be attributed to the prepaid billing principle, whereby customers purchase electricity before consumption rather than receiving monthly invoices after energy has been used. Consequently, new debt accumulation is substantially reduced because payment precedes electricity delivery.

From a financial perspective, this transition significantly improved the utility's working capital and reduced the administrative effort required for debt collection and customer disconnection.

Table (2) Customers Areas

Total arrears before PPM January 2001	4436 MSD
Total arrears after 76 % PPM March 2003	1707 MSD
Percentage of collection from total arrears	62%

C. Improvement in Revenue Collection

Revenue collection constitutes one of the most important performance indicators for electricity distribution utilities.

Under the conventional billing system, revenue collection depended upon several sequential activities including meter reading, bill preparation, invoice distribution, payment processing, customer follow-up, disconnection for non-payment, and reconnection after settlement.

The prepaid metering system fundamentally changed this process by collecting revenue before electricity consumption occurred. Consequently, cash flow became more predictable while collection efficiency increased substantially.

Project documentation reports measurable improvements in revenue recovery following prepaid implementation, together with significant reductions in outstanding customer balances. The elimination of delayed payments reduced financial uncertainty and strengthened the economic sustainability of the electricity distribution business.

D. Reduction of Commercial Losses

Commercial losses represent electricity supplied but not paid for because of theft, meter tampering, billing inaccuracies, or collection failures.

Prior to implementation, NEC estimated that total energy losses exceeded 45% of generated electricity. Following widespread deployment of prepaid metering, annual loss reports demonstrated a continuous downward trend between 2001 and 2005 as shown in figure (1).

Several engineering factors contributed to this improvement:

- Reduced opportunities for electricity theft.
- Elimination of estimated billing.
- Improved meter accuracy.
- Secure token-based electricity purchasing.
- Better customer accountability.
- Simplified revenue management.

Although additional network modernization initiatives may also have contributed to improved performance, prepaid metering clearly formed one of the principal components of NEC's loss-reduction strategy.

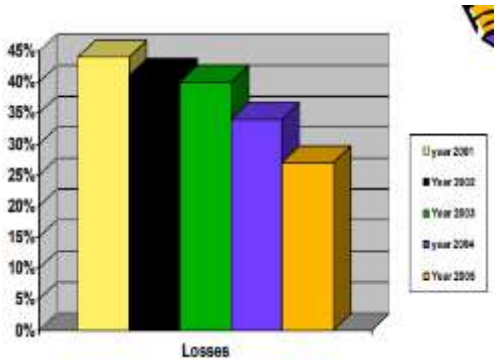

Figure (1) Losses improvement

E. Operational Efficiency

Beyond financial improvements, prepaid metering significantly simplified utility operations.

Under the conventional billing system, customer management required numerous manual activities, including:

- Monthly meter reading.
- Invoice generation.
- Bill delivery.
- Payment collection.
- Service disconnection.
- Service reconnection.
- Customer complaint investigation.

Following prepaid implementation, many of these activities were eliminated or substantially reduced.

Project records identify several operational improvements:

- Elimination of routine meter reading.
- Reduced maintenance requirements.
- No monthly bill preparation.
- Elimination of disconnection and reconnection procedures for unpaid bills.
- Improved meter installation quality.
- Reduced administrative workload.
- Faster customer service.

These operational efficiencies enabled NEC to redirect technical resources toward network expansion and service improvement rather than routine billing activities.

F. Customer Benefits

The project also produced measurable improvements from the customer's perspective.

Customers gained the ability to monitor their electricity consumption continuously and purchase electricity according to their financial circumstances. Instead of receiving unexpected monthly bills, customers could manage their household energy expenditure through advance purchasing.

The project documentation identifies several customer benefits:

- Elimination of incorrect meter readings.
- No accumulated monthly debt.
- No reconnection fees after payment.
- Immediate electricity availability following credit purchase.
- Greater transparency in electricity billing.
- Improved relationship between customers and NEC.
- Increased awareness of electricity consumption.

These findings indicate that prepaid metering can improve customer satisfaction while simultaneously strengthening utility financial performance.

XII. DISCUSSION

The Sudan prepaid metering project represents one of the earliest documented large-scale implementations of prepaid electricity technology in Africa. Unlike many academic investigations based primarily on simulation or theoretical modelling, this study documents practical engineering experience obtained during real utility operations.

The results demonstrate that prepaid metering should be viewed not merely as a replacement for conventional electricity meters but as a comprehensive transformation of utility business processes. The project required coordinated changes in technology, organizational structure, customer communication, staff training, and revenue management.

From an engineering perspective, several factors contributed to the project's success.

First, NEC adopted a pilot-first implementation strategy. Rather than immediately replacing all conventional meters, engineers conducted a controlled pilot deployment that allowed operational procedures to be refined before nationwide expansion. This approach reduced implementation risks while providing valuable technical experience.

Second, technology selection emphasized simplicity and reliability. The keypad-based prepaid meter proved well suited to Sudan's operating environment because it minimized dependence on physical smart cards while providing a secure token-entry mechanism as shown in figure (2).

Figure (2) Smart card

Third, customer education received considerable attention throughout implementation. Public communication through television, radio, direct customer visits, and extended office hours helped build confidence in the new billing system and encouraged rapid customer acceptance.

The operational results further indicate that prepaid metering directly supports several strategic objectives of electricity utilities:

- Improved financial sustainability.
- Enhanced operational efficiency.
- Reduction of commercial losses.
- Better customer engagement.
- Improved revenue predictability.
- Simplified administrative procedures.

Nevertheless, several limitations should be acknowledged. This paper relies on operational records collected during project implementation rather than controlled experimental measurements. Furthermore, some reported improvements may have been influenced by concurrent organizational reforms and network modernization activities. Consequently, the results should be interpreted as evidence from an engineering case study rather than proof of direct causal relationships.

Despite these limitations, the Sudan experience provides valuable guidance for utilities in developing countries considering prepaid metering as part of broader electricity sector modernization programs. The project demonstrates that careful planning, phased deployment, and sustained customer engagement can enable successful large-scale implementation while delivering significant operational and financial benefits.

XIII. STUDY LIMITATIONS

Although the Sudan prepaid metering project demonstrated significant operational and financial improvements, several limitations should be recognized when interpreting the findings presented in this paper.

First, this study is based on documented implementation records and project reports produced during the deployment of the prepaid metering system. The analysis therefore reflects practical engineering experience rather than a controlled experimental investigation. Consequently, statistical hypothesis testing and confidence interval estimation were beyond the scope of the available data.

Second, the operational indicators reported in the project documentation were collected primarily for utility management rather than academic research. Therefore, some performance measures, including customer satisfaction indices, detailed energy consumption profiles, and cost-benefit analyses, were unavailable for inclusion in this study.

Third, the project was implemented over several years during a period of continuous organizational development within the National Electricity Corporation (NEC). Improvements in operational performance may therefore have been influenced not only by prepaid metering but also by complementary initiatives such as staff training, organizational restructuring, network maintenance, and improvements in customer service.

Finally, the case study focuses on the Sudanese electricity distribution system. Although many of the engineering principles are applicable to other developing countries, differences in regulatory frameworks, electricity tariffs, customer behavior, and

distribution infrastructure may influence the outcomes of prepaid metering implementation elsewhere.

Despite these limitations, the study provides valuable evidence from one of Africa's earliest large-scale prepaid metering deployments and offers practical lessons for utilities considering similar modernization programs.

XIV. CONCLUSION

This paper presented an engineering case study of the implementation and performance assessment of Sudan's nationwide prepaid electricity metering project. The study documented the motivations for replacing the conventional postpaid billing system, the methodology adopted during pilot implementation, the nationwide deployment strategy, and the operational improvements observed following large-scale implementation.

Before introducing prepaid metering, the Sudanese electricity distribution system experienced substantial commercial losses, increasing customer arrears, inefficient billing procedures, and high operating costs associated with manual meter reading and revenue collection. To address these challenges, NEC adopted a phased implementation strategy beginning with a pilot project in Riyadh District, Khartoum, before expanding throughout the capital and subsequently to other regions of Sudan.

The documented project outcomes indicate that prepaid metering significantly improved utility performance. Customer arrears were substantially reduced, revenue collection became more efficient, commercial losses decreased, and administrative processes were simplified. Customers also benefited from greater control over electricity consumption, elimination of monthly billing disputes, and improved transparency in electricity purchasing.

One of the most significant findings of this study is that the success of prepaid metering depended not only on the selection of appropriate technology but also on effective project management, staff training, customer education, phased deployment, and continuous operational monitoring. The Sudan experience demonstrates that organizational readiness and stakeholder engagement are essential components of successful utility modernization.

From an engineering perspective, the project illustrates how prepaid metering can serve as a strategic tool for improving the financial sustainability of electricity utilities while simultaneously enhancing customer service. Although newer technologies such as Advanced Metering Infrastructure (AMI) and smart grids continue to evolve, the principles demonstrated by the Sudan project remain relevant for utilities operating in resource-constrained environments.

The experience documented in this paper contributes to the growing body of knowledge on prepaid electricity systems and provides practical guidance for engineers, policymakers, and utility managers planning similar projects in developing countries.

XV. FUTURE WORK

Future research should investigate the integration of prepaid metering with modern smart grid technologies to further improve utility performance. Several research directions are recommended:

- Integration of prepaid meters with Advanced Metering Infrastructure (AMI).
- Deployment of Internet of Things (IoT)-enabled smart electricity meters.

- Artificial intelligence for electricity demand forecasting and customer consumption analysis.
- Mobile payment platforms integrated with digital electricity vending.
- Cybersecurity frameworks for secure prepaid token generation and communication.
- Machine learning techniques for electricity theft detection.
- Real-time distribution network monitoring.
- Renewable energy integration with prepaid customer management systems.

These developments would enable utilities to transition from conventional prepaid metering toward intelligent digital electricity management systems capable of supporting future smart cities and sustainable energy infrastructures.

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