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Mitigating Non-Technical Losses and Electricity Theft Through Smart Meters: A Case Study of the Akre District Power Distribution Network

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Abstract: Electricity remains one of the most vital resources for industrial, domestic, and agricultural applications. However, electricity theft has emerged as a significant challenge, contributing to substantial power losses and severe economic repercussions for utility companies. This study examines the role of smart meters (SMs) in minimizing electricity theft and reducing energy losses by transitioning from traditional analogue meters to advanced SMs equipped with automated billing and metering systems. Data collected from the SM system in the Akre energy distribution network reveal that, following the implementation of SMs, overall electrical power losses were reduced by 17.1%, while theft incidents decreased by 96.4%. These results demonstrate that the deployment of SMs significantly contributes to lowering total power losses and yields considerable financial benefits for both utility providers (UPs) and consumers. Moreover, the system enhances the ability to remotely monitor and control customer meters, allowing continuous oversight of meter readings without requiring physical visits. This remote functionality strengthens theft prevention measures, improves grid reliability, and reduces operational costs. The findings highlight the potential of the SM system in advancing power efficiency and promoting a more secure and cost-effective energy distribution network.

Keywords: Electricity theft; Remote monitoring; Advanced metering system; Energy losses; Power efficiency; Distribution grid; Remote billing

1 Introduction

After the three stages of generation, transmission, and distribution, electricity can be used by consumers. In the first stage, electricity is generated in many places with a low voltage of approximately 11 Kv because it is cheaper to generate electricity power at a relatively low voltage. High-voltage transmission lines at 138 Kv, 500 Kv or more are used for power transmission based on the distance and the amount of the transmitted power. Then they are synchronized on a single bus bar. After using step-down transformers, electricity can be utilized by consumers. This electrical energy needs to be payable as well. There are two kinds of commonly used devices for billing: SMs and the traditional electromechanical meters in kilowatt hour (KWh).

In today's world, it can be clearly noticed that the energy resources are under strain. Therefore, it's compulsory to prioritize the utilization efficiency of energy. This confirms the importance of treating electricity with care. While it's known that no password is completely impervious to being cracked, the efficiency of a password is frequently measured by the time needed to crack it. This principle is one of the main reasons for the global change from analogue to digital devices, demonstrated by the change of analogue electromechanical meters to SMs in the electricity field. Digital technology proposals have greater security features and better control choices, enabling more active recognition and management of losses in electrical power systems. This transition is compelled by the necessity to address losses methodically. There are commonly two kinds of energy losses: technical and non-technical power losses. In industrialized states, electrical energy theft is typical, particularly in isolated zones, as they do not purchase electricity from the utility companies. To address this, it is essential for governments to provide financial assistance to resolve this problem.

Utility companies are directly affected by non-technical losses (NTL) and reduce the perception of energy service quality by customers. This type of loss represents 17% of total power generated in South American states, which is considered a big problem for energy distribution companies due to its impact on revenues. Globally, the total estimated losses caused by electricity theft are around $96 billion annually [1]. Ali et al. [2] found that the most prevalent power theft was in rural zones and areas undergoing industrial growth, followed by the residential and commercial districts. In hospitals and universities, the theft cases were rare. This aligns with the previous studies, which show that tampering with the low-voltage power line is the most frequent way of stealing electric energy in developing states. In commercial areas, the losses are estimated at 45-60% of the total stolen electricity, where the distributed voltage is 220V and easy to tamper with.

Electric power utilities are facing two big challenges: electrical power theft and NTL of power. The quantity of these losses is very high in some countries, which accounts for approximately 40% of the total generated power [3]. Otchere-Appiah et al. [4] used a specific program and found that the average reduction of the fundamental data losses of residential consumer types was estimated to be 12.656 kw/month, indicating that the SM system could be the best solution for reducing the total energy losses.

Vlasa et al. [5] explored and proposed a solution to enhance the accuracy of electrical energy readings by reducing and identifying billing errors. The main purpose is to reduce electrical energy losses and required budgets. Therefore, a mathematical model was formed with a suitable algorithm and tested for a power distribution company. The outcomes exhibited an average efficiency enhancement of 4% for the company's technological consumption.

Smart grid (SG) is a progressive advancement to the old distribution networks, which is targeted to simplify and increase reliability in delivering electricity, enhance electrical grid operation, and engage customers [6]. Advanced metering infrastructure (AMI) allows the bidirectional communication system among the SM systems arranged at customer locations and the system operator (SO) for systematic load checking, billing and energy control [7]. Dissimilar to the old power distribution that gathers the readings of monthly energy consumption (EC), the AMI system collects the readings of the power consumption accurately and continually measured and sent by SMs [8].

Electrical power theft is a severe issue in today's energy distribution system that causes heavy economic harm. For example, the electrical losses in the United States are $6 billion yearly because of electrical energy thefts [9]. NTL, caused by any type of irregularity (e.g., meter parametrization error, connection error, energy fraud or faulty meter), is a main problem for the utilities, which cause major income losses and correspondingly affect the distribution system infrastructure as it leads to insecurity of actual power consumption [10]. Decreasing NTL is the main focus of the electrical energy companies as it characterizes an important fragment of the entire power loss [11]. Struggling to identify NTL using a controlled approach can be so stimulating as this is a tremendously unnecessary arrangement problem [12].

SMs enable electricity providers to plan innovative and new approaches to identify NTL. With the SMs, electrical companies have access to regularly measure EC, offering them a good consideration of their clients' consumption behavior [13]. Electrical power theft is similar to the NTL, which is a huge problem for entire service suppliers in the conservative energy distribution networks. NTL is usually correlated to the energy theft and customers' deceitful behavior, which deceive the UPs intentionally in a number of ways [14]. NTL might present chains of extra losses, such as decreasing the trustworthiness of the grid and imposing harmful economic effects on the network substructure. NTL includes bypassing over the meter, meter tampering, meter line swapping, connecting on the low-voltage side, computational mistakes of losses, imperfect meters, delay and error in meter billing and reading, unpaid electric billing, etc. [15, 16].

The execution of SGs and SMs might contribute to a momentous reduction in NTL by reducing some kinds of losses [17]. Nevertheless, the AMI and SG, in particular, increase new hacking hazards and dangers [18–21].

This study aims to investigate the impact of using SMs on decreasing theft cases and reducing NTL. According to the collected data after installing SMs, the results show that the transition from using analogue meters to the SM system led to enhanced power efficiency, reduced losses, and decreased theft, thereby boosting the reliability of the grid and decreasing the total operation cost of the system.

Section 2 shows the related works. Section 3 discusses the technical details and capabilities of SMs. Section 4 describes the ways of electricity theft. Section 5 discusses the risks and consequences of electricity theft. Section 6 shows the actions to stop electricity theft, and explains the measures for controlling the theft. Section 7 discusses the methodology and mathematical techniques of loss calculation. Section 8 discusses the main findings and results. Section 9 shows the conclusion of this study along with the possible future works.

2 Related Words

Meeks and Wang [22] collaborated with an electricity utility in a town within the Kyrgyz Republic and included 20 transformers and 1,500 customers in their research. However, in this study, the data of 759 transformers and 26,571 customers were used, which makes the findings more accurate by decreasing the error ratio, differentiating this study from other studies.

Rausser et al. [23] analyzed EC in European Union (EU) countries, concentrating on the role of SMs in decreasing electricity cost. They used data from 4,232 households surveyed in Ireland. An average of 8.14% power was saved with the use of SMs. However, in this study, 17.1% power was saved, leading to saving electrical energy of 61.506 megawatt hours (MWh) annually, which reduced the total operational cost of the power system, resulting in significant economic benefits for utility companies and the consumers indirectly as the companies can improve the electrical grid and provide better electricity for consumers.

India's power distribution sector faces a big energy crisis due to rising power demand and significant meter tampering and electricity theft. Despite efforts to improve generation capacity by depending on renewable energy, unaccounted energy losses impede economic growth. Chandel et al. [24] focused on challenges of theft and meter tampering, suggesting the SM system as an actual solution due to their remote control and communication capabilities. Energy losses in power distribution systems affect network infrastructure, power quality, and finances, leading to reduced investments in the energy sector and causing damage to both the utility companies and the electricity sector. SMs offer a new method, empowering real-time checking and more precise recognition of abnormalities like illegal users. Techniques for spotting NTL are categorized into network-oriented, data-oriented and hybrid methods, with the hybrid method proving to be the most effective one [24].

Depuru et al. [25, 26] clarified the theft control process clearly by presenting a model. The NTL was calculated. If the NTL is greater than 5%, all legal customs are separated for some time, and harmonic producers are used at that moment, which damages the illicit electrical appliances of all unlawful customers and relinks regular supply for real customs. Nevertheless, this method might be developed to prevent the appliances of illicit customers from working by adopting other techniques or SMs. They also clarified some kinds of electricity theft ways in AMI, and presented communication structure by using the SM system for communication between meters and the control. To enhance data information and signals through receptors and collectors, the backhaul net was used for data transmission to the service providers. Although the energy in SMs might be stolen by a technician, the readings are not sent to the utility if a microcontroller (MC) inside the SM is removed. Depuru et al. [27] and Zheng et al. [28] particularized the methods of communication process, and explained the possible ways of transferring the data to electricity providers. They exposed the operation technique of electromechanical meters, clarifying the superiority of SMs to traditional meters.

A non-hardware technique might be constructed on a specific theory, state approximation, or cataloguing of algorithms [29]. Jokar et al. [30] constructed a model based on the Support Vector Machine (SVM) to differentiate between fraudulent and real consumers. Reasonably, rather than categorizing the consumers directly based on NTL, Ford et al. [31] and Cody et al. [32] predicted the customers' EC by using the neural network (NN) approach and the decision tree (DT), respectively. If the variance between the forecasted and actual consumed power surpasses the boundary, the consumer is measured as fraud.

Aniedu et al. [33] employed the SVM along with the findings from the actual field inspections to identify NTL in Malaysia. Meanwhile, Dangar and Joshi [34] adopted the SVM to uncover instances of energy theft. These algorithms were trained using data gathered from genuine on-site inspections. However, the details on the performance of these methods were not provided. Han et al. [35] came up with a way to catch sneaky moves where people switch their energy contracts to cheaper ones, which causes NTL. A smart computer method called the k-means algorithm was used to group similar electricity usage patterns, aiming to figure out the typical or unusual electricity usage of each customer. Then the SVM was used for analysis.

Costa et al. [36] tackled the problem of fraud detection, especially in the context of a Brazilian electricity company. They gathered data on monthly electricity usage along with other information to train a kind of smart computer system called a NN. This system learned from real inspections conducted by the electricity company in the field.

3 Technical Details and Capabilities of SMs

SMs have the ability to detect theft cases through a combination of cutting-edge technologies and advanced monitoring techniques. The following is detailed information on how this type of meter can prevent and detect theft, explaining their key capabilities suited for this purpose:

3.1 Style Settings

3.1.1 Automated alerts and reporting

a) Notifications and alerts: Energy provider companies receive real-time alerts when the SM detects any tampering attempts or abnormal usage of power.

b) Automated reports: SMs produce automated reports that indicate potential theft cases or abnormalities. These reports can be studied by the utility company's experts for taking actions.

3.1.2 Integration with Other Technologies

a) Geographical information system (GIS): By integration with GIS, SMs can help in mapping out the exact locations of theft incidents and identifying patterns based on geographical location.

b) AMI: SMs are considered a part of a broader (AMI) system that combines data from multiple meters. This integrated system can use and analyze the aggregated data to detect abnormalities and theft patterns more effectively.

3.1.3 Load profiling and demand response

a) Load profiling: By checking and analyzing the regular load profile (the pattern of power usage over time), SMs can detect abnormalities that may indicate theft.

b) Demand response analysis: SMs can monitor and track the demand response programs and evaluate whether the usage patterns align with expected profiles. Significant deviations from these patterns might indicate unauthorized usage or theft.

3.1.4 Secure communication

a) Integrity checks: Regular integrity checks are conducted to verify that the data transmitted from the meters has not been intercepted or altered.

b) Data encryption: To prevent unauthorized access, the data sent from SMs is encrypted. This ensures that any attempts to intercept or alter the data are detected and addressed.

Table 1. Comparison between electromechanical meters and SMs

#	Electromechanical Meters	Smart Meters (SMs)
1	Relies mainly on meter readers	No need for readers (automated billing system)
2	Manual reading is vulnerable to human errors	100% accurate
3	No cross-checking of human readers	Continual real-time checking
4	High risk of theft and bribery	Rare theft due to theft-detecting techniques
5	Possible to alter readings when taking photos	Impossible to alter meter readings
6	Higher company expenses (salaries, travel)	No need for employees for reading
7	Meters not checked regularly if inside homes	Continual sending of readings to control room
8	Customers do not receive regular updates	Instant updates on power consumption
9	Irregular receipt of energy bills	Regular and timely bill receipt

Table 2. Stakeholders' benefits by using SMs

#	Stakeholders	Benefits
1	Consumers	• More precise and timely billing • Better access to and data management of energy • Enhanced power quality and data accuracy
2	Field operations and general customer service	• Eliminating handheld metering devices • Reduced metering costs • Fewer call-center transactions
3	Utility companies	• Enhanced employee safety • Improved risk profile and safety for customer premises and reduced operation cost
4	Billing services and security systems	• Decreasing the need for back-office rebilling • Identification of energy theft and interruptions • Enhanced billing accuracy and more secured data
5	General stakeholders	• Support for the SG initiative • Enhanced environmental benefits
6	Load forecasting and data cost	• Improving data collection and quality • Reducing data collection costs
7	Transmission lines and distribution networks	• Enhanced data quality regarding load, losses, and efficiency • Facilitating the use of capacitor banks • Enhanced load management

3.1.5 Remote communication and sensing

a) Tamper detection: SMs contain sensors that can distinguish manipulation or physical tampering. For example, if someone attempts to tamper or open the meter, a tamper alert can activate.

b) Remote diagnostics: The status of the meter can be checked remotely by utility companies to execute diagnostics to recognize and detect tampering signs or malfunction.

3.1.6 Data analysis

a) Historical comparison: The SM system can compare the existing data with historical energy usage to recognize abnormalities that may propose to be theft.

b) Pattern recognition: SMs save usage patterns and analyze them over time. Uncommon consumption patterns, such as a major drop or a sudden spike in power usage, can indicate potential tampering or theft.

3.1.7 Real-time monitoring

a) Immediate alerts: When the meter detects unexpected changes or abnormalities in the usage data, it can send alerts to energy provider companies for additional investigation.

b) Continuous data collection: Electricity usage can be continuously recorded by SMs in real-time. This kind of monitoring helps in identifying any abnormal power consumption or contradictions from expected power usage.

Table 1 shows more details and concise explanations of key capabilities that make SMs suited for this purpose through a comparison with electromechanical meters.

SMs have benefits for different stakeholders. Table 2 shows more details about this.

4 Ways of Electricity Theft

People use different ways to steal electricity, such as taping directly into the main electric line, and bypassing the electric meter in industrial, commercial, and residential contexts.

The several types of electrical energy theft are as follows:

a) Tapping into the power line/hooking directly, which is the most common way of electricity theft.

b) Messing with the electric meter, including interfering with its connections, blocking it physically or adding foreign objects. This stops the meter from accurately recording the energy being used [37].

c) Irregular billings by the meter readers.

d) Grounding the neutral cable.

e) Manipulating the energy meter remotely by installing a circuit inside, which leads to slowing down the meter. This type of alteration can avoid detection from outside inquiries since the meter remains accurate as long as the remote is activated.

f) Placing a magnet on the electromechanical meter [25].

g) Sliding in the disc to halt the coil's rotation.

h) Causing damage to the revolving coil by hitting the meter [38].

i) Swapping connections for input and output.

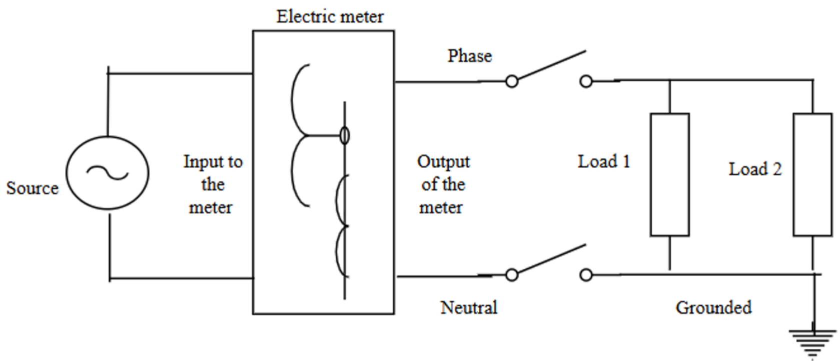


Figure 1. Power theft by connecting the neutral to the ground

In certain sophisticated methods, electrical energy can be stolen through the secondary-side tampering of the current transformer (CT) where the meter is joined. When a CT is alleviated, the measurement readings of current decrease and are not precisely similar to the normal working case of the current flowing. The calibration of coils used in electromechanical meters is not accurate. Therefore, in three-phase meters, if one phase is used and the neutral remains open, as shown in Figure 1, the meter cannot sense any current flow to the consumer. However, this type of theft can be detected by SMs and give an alarm whenever there is any leakage or missmatch between the neutral and the phase. In addition, unbalanced load on the transformer can cause losses [39]. Renewable energy resources could also be the best way for electricity saving in the power grid and lead to producing sustainable energy with economic benefits for the electricity providers and consumers at the same time [40–44].

5 Risks and Consequences of Power Theft

5.1 Risks of Power Theft

5.1.1 Risks to people's lives

Illegal power connections are not safe, as they are not conducted by professionals. It is dangerous for anyone who might work on that line in the future as it cannot be turned off through regular board breakers and the electricity remains, especially in emergency cases.

5.1.2 Risks to the components

Power surges because of electricity theft which may damage the cables inside the home and can cause a fire. The overloads can also harm the electrical equipment and appliances.

5.1.3 Risks to the power distribution system

Power theft causes overload of transformers, feeders and even substations, which lead to power surges and failures in the whole electrical system, consequently harming the transmission line equipment and the whole power system and collapsing it.

5.1.4 Risks to the economy

With the electricity theft, the total incomes of the utility companies decrease with insufficient profits, making them incapable of continuing delivering electricity to the consumers, which affects the economy of the whole country.

5.2 Consequences of Power Theft

Electric theft has a harmful effect on many aspects of any power system in the world and even people's lives as follows:

a) Poor power system quality.
b) Challenges with funds and unemployment.
c) Tariff issues and insufficient revenue.
d) Power system instability.
e) Grid troubles such as overload of the transformers, electrical feeders, and transmission lines.
f) Load shedding.
g) Irregular power supply.
h) Death cases.
i) Equipment damages, failure and increased feeder faults.

6 Actions and Measures to Stop and Control Electricity Theft

6.1 AMI

A new technology such as SMs can be implemented to detect any abnormal usage of the power or theft. This system can afford the real-time information and assist the utilities in recognizing and finding theft quickly.

6.2 Underground System

Underground cables can be used for power distribution in the grid, making electricity theft more difficult than the overhead electricity lines.

6.3 Data Analysis

With data analysis, it is possible to recognize abnormalities among consumption patterns that might indicate theft. These usage data analyses help electricity companies locate zones with high rates of electricity theft.

6.4 Tamper-Proof Equipment

A tamper-proof meter can be used to prohibit any tampering and illegal access in the power distribution system.

6.5 Community Engagement

Organizations and leaders can raise consumers' awareness of no electricity theft and enhance the sense of responsibility to prevent it.

6.6 Legal Penalties

Strict penalties can be applied to electricity theft, including service disconnection, legal actions, and fines. Some examples of prosecuted cases can be announced to prevent and deter others from electricity theft attempts.

6.7 Awareness Campaigns

The consciousness of electricity consumers about the harmful consequences of power theft on communities can be increased, including safety risks, high costs, and possible service interruptions. Reporting and whistleblowing of doubtful activities can be encouraged.

6.8 Rules and Regulations

Legislation of new rules and regulations prohibits electricity theft, emphasizing the role of combating electricity theft crime and changing the entitlement mindset that leads to electricity theft.

Entitlement mentality is a mindset where people believe they inherently deserve specific resources, rights, or benefits without certainly earning them or meeting specific conditions. This perception might lead to a sense of justification for taking or receiving what they want, even if it includes illegal or unethical actions such as electricity theft. People with this mindset may feel that social rules or personal achievements are unrelated to their alleged rights, resulting in some behaviors that disregard fairness and respect for other people. This type of attitude can be affected by numerous economic, cultural and social factors, and contributes to broader issues such as social discord and dishonesty.

The change in entitlement mindset includes a combination of societal and individual methods as follows:

a) Accountability stimulation: People can be encouraged to take responsibility for their actions and understand the consequences of their behaviors. The teaching of personal accountability can help change their focus from entitlement to deserving and earning.

b) Gratitude and empathy: Practices that form gratitude and empathy can be boosted, such as reflecting on what a person has and appreciating the contributions of others, understanding others to decrease the entitlement feelings.

c) Awareness and education: Educational courses and programs, which emphasize the fairness, value of hard work, and respect for others' rights and property, can be implemented.

d) Clear boundaries and prospects: Clear expectations and boundaries in several settings (e.g., community and workplace) can be communicated and established to strengthen the idea that resources and privileges are earned instead of being inevitably granted.

7 Methodology

7.1 Data Collection and Loss Calculation

The essential purpose of the methodology defined in this research is to study the impact of using the SM system in tackling electricity theft in the power distribution network of the Akre District, and minimize the rate of other NTL to increase the efficiency of the power grid.

A quantitative observational method was used in this study. Real-time SM data for the four main types of customers were used, i.e., residential, commercial, agricultural and industrial customers. To be more clear, this study provides detailed information on the data collection, the models of SMs used and all other steps in the procedure.

By collaborating with the power distribution network of the Akre District, the customer data was collected from the energy department with a duration of 24 months, ranging from July 2020 to June 2022. Four customer types were included in this research, i.e., residential, industrial, commercial and agricultural customers. The SM models used include three-phase SM_MK10M (Model 212), single-phase SM_MK32H (Model 212), and Gateway_GW30_GSM 850/900/1800/1900 MHz. This study uses the data of 26,571 customers with SMs installed, 759 distribution transformers, and 31 feeders. The load data was taken from several substations, i.e., Akre_132KV substation, Akre_33KV substation, Dinarta_33KV substation, Bijil_33KV substation, and Bakerman_33KV substation. The data on customers was collected for 12 months from July 2020 to June 2021 before SMs were installed, as shown in Table 3. The power loss rate of each month before SM installation was calculated by using Eq. (4). The post-SM installation data was collected for the other 12 months, ranging from July 2021 to June 2022, as shown in Table 3. The power loss rate of each month and the total decreased power loss rate after SM installation were calculated by Eqs. (4) and (5), respectively.

Furthermore, some real load samples of feeders were also taken in Akre_132Kv substation and Dinarta_33Kv substation. All these data used in those substations were used to study the impact of the SM system installation on decreasing theft ratio and minimizing electricity losses. Power theft is the illegal way to obtain electricity for their daily requirements, causing huge economic losses for electricity providers. The world annual losses are approximately $25 billion [19]. Power losses can essentially be calculated using the supplied energy, subtracting the quantity of billed electricity divided by the paid amount [20].

The following two equations can be used to calculate NTL:

$$\text{Total power losses} = \text{Supplied power} - \text{Paid bills} \tag{1}$$

$$\text{Total power losses} = \text{NTL} + \text{TL} \tag{2}$$

where, TL means technical losses.

The following equation can be derived:

$$\text{NTL} = \text{Supplied power} - \text{Paid bills} - \text{TL} \tag{3}$$

The total power losses can be calculated using the following equations:

$$\text{Percentage losses} = \left(\frac{\text{Recieved value} - \text{Sold value}}{\text{Recieved value}}\right) * 100\% \tag{4}$$

$$\text{Total decreased losses} = \text{pre-SM installation losses} - \text{post-SM installation losses} \tag{5}$$

In Table 3, the data shows that the average monthly power loss ratio is 21.5 from July 2020 to June 2021. When the old, traditional, analogue metering system was used to count the total energy used by consumers, the loss ratio was very high compared to the standard allowed losses in any normal power system in the world. Whereas in July 2021 until June 2022 after the SM system was installed, it can be clearly noticed that the average monthly power loss rate decreased to 4.4, which is considered a successful way to be adopted for combating the electricity theft and keeping the total power losses inside the normal allowed range in any power system.

Table 3. Energy losses before and after installing the SM system

Months	**2020-2021**			**2021-2022**			**Decrease**
	Energy (MWh)		**Pre-SM Loss Ratio**	**Energy (MWh)**		**Post-SM Loss Ratio**	
	Received	**Sold**		**Received**	**Sold**		
Jul.	30.4	25.7	18.3	25	24	4	14.3
Aug.	25.2	20	26	37.5	36	3.73	22.3
Sep.	26.9	21	28.1	26.2	25	4.2	23.9
Oct.	22.9	18.5	23.8	33	32	3.94	19.8
Nov.	23.3	20	16.5	28	27	4.29	12.2
Dec.	24.2	20	21	27	26	4.07	16.9
Jan.	31.6	24.7	21.8	21	20	4.29	17.5
Feb.	41.1	32.6	20.7	25	24	4.8	15.9
Mar.	40.8	33	19.1	33.8	32	4.73	14.4
Apr.	30	24.3	19	30.6	29	4.9	14.1
May	32.6	25.6	21.5	26.3	25	5.32	16.1
Jun.	32.8	25.5	22.3	24.5	23	4.9	17.4
Av.	30.2	24.2	21.5	28.2	26.9	4.4	17.1

The difference or the decrease ratio between the two cases was calculated by subtracting the percentage of monthly losses in 2021/2022 from the 2020/2021 loss ratios. When the analogue system was used, the total average monthly power loss was 21.5. After installing the SMs, the number was 4.4. It is noticeable that the total average losses decreased by 17.1%, which has significant economic benefits. Therefore, it is considered a very important step toward improving the total power system, increasing the reliability of the UP, increasing the efficiency and decreasing the total costs of the operation system.

Table 4 illustrates the total theft cases and tampering in the power lines before and after SM installation. From July 2020 to June 2021, the total number of pre-SM theft cases in the grid is 431 per year, with 35.9 monthly cases on average, which is a very high rate and causes major losses of energy. Whereas post-SM installation, the number of theft cases from July 2021 to June 2022 is only 14 per year, with the average monthly theft cases decreasing from 35.9 to 1.2, a reduction of 96.4%.

This reduction in theft cases is mainly attributed to the use of SMs, where the meters are inside a closed enclosure and installed in the top of the electricity poles, as shown in Figure 2, making electric theft impossible. Furthermore, the government legislated some rules to deter any attempts at electricity theft. All these factors contribute to that reduction.

Table 4. Energy losses before and after installing the SM system

Year	2020-2021 pre-SM Installation Theft Cases	2021-2022 post-SM Installation Theft Cases	Decreased Percentage (%)
Jul.	34	1	97
Aug.	39	2	94
Sep.	30	0	100
Oct.	38	1	97
Nov.	29	1	96
Dec.	37	0	100
Jan.	35	2	94
Feb.	40	0	100
Mar.	31	1	96
Apr.	38	2	94
May	41	1	97
Jun.	39	3	92
Total	431	14	96
Av.	35.9	1.2	96.4

Table 5 shows the impact of the SM system installation on decreasing the total energy demand by consumers. The Dinarta 11KV feeder in the Dinarta_33KV substation was chosen as a sample to study the behavior of the real load demand by customers in pre-SM installation. The data clearly shows that after installing SMs, the average feeder load per year decreases by 23.97% due to prevention of electricity theft cases. The consumers realized that they have to pay for each KWh that they consume. Therefore, they were obliged to use energy wisely, thereby decreasing the total load demand and the total energy losses.

Table 5. Energy losses before and after installing the SM system

Maximum Monthly Load of the Dinarta Feeder Before and After SM Installation					
Before SM Installation		After SM Installation			
Time	Maximum Load Without SMs (MW)	Time	Maximum Load with SMs (MW)	Decreased Load (MW)	Decreased Percentage (%)
July _2020	143	July_2021	121	22	18.18181818
August_2020	139	August_2021	118	21	17.79661017
September_2020	142	September_2021	116	26	22.4137931
October_2020	169	October_2021	131	38	29.00763359
November_2020	221	November_2021	194	27	13.91752577
December_2021	304	December_2021	248	56	22.58064516
January_2021	316	January_2022	241	75	31.12033195
February_2021	248	February_2022	191	57	29.84293194
March_2021	199	March_2022	162	37	22.83950617
April_2021	160	April_2022	129	31	24.03100775
May_2021	145	May_2022	109	36	33.02752294
June_2021	177	June_2022	144	33	22.91666667

7.2 Configuration and Implementation of SMs

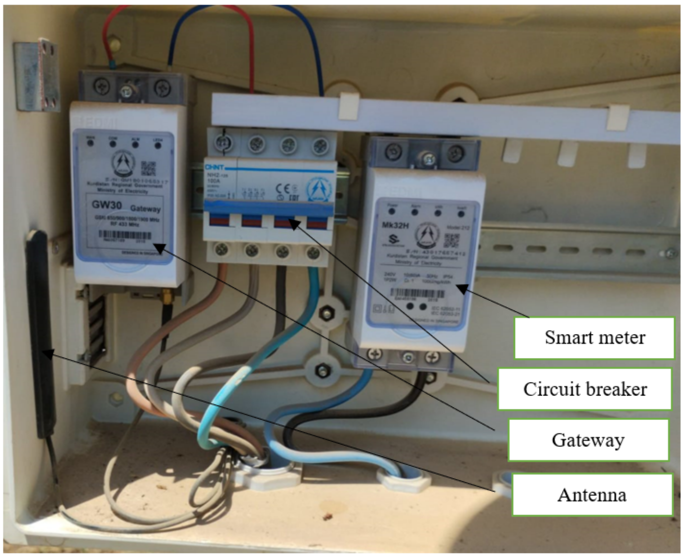
The configuration and implementation of the presented SM system in the power grid are essential for replicability. Understanding its impact involves the following crucial aspects:

a) Hardware setup

• The SMs were installed inside an enclosure on the top of the electricity poles, as shown in the subgraph (a) of Figure 2. This installation technique prevents any attempts at electricity theft as the SMs are inside the closed enclosure. Any attempts at opening the enclosure lead to a notification sent to the utility companies to take actions directly.

• These SMs are connected with each other through gateways and antennas inside the enclosure, as shown in the subgraph (b) of Figure 2, which collect the data of all customers and send it to the control room of the utility company.

(a)



(b)

Figure 2. SM implementation (a) SM enclosure; (b) SM inside the enclosure

• The SM is a telecommunicated and developed device. It contains a MC, which is the brain of the meter. Therefore, it processes the data, has the ability to measure EC, voltage, current and power, and connects with each other and the control room through Global System for Mobile Communication (GSM) protocols.

b) Linking process: After the old electromechanical meters were replaced with SMs and the hardware installation process was completed, all installed SMs were linked and connected to the system through the network communication setup.

c) SM definition: All SMs were defined inside the system with their serial numbers, and the detailed information of the consumers was entered, such as name and location, to avoid billing errors.

d) Data management: The collected data was stored such as data base or cloud storage. A specific software was used for managing and analyzing usage patterns, producing reports and identifying irregularities.

e) Network structure: SMs were connected with each other and the control room through radio frequencies using the microwave communication system for data transmitting. Through these links, the data of all consumers, such as the power usage, can be sent to the control room in real-time.

f) Integration with systems and bill management: System management was incorporated to enhance energy distribution and discourse disputes in real-time. Compatibility with existing billing schemes was confirmed for correct and precise invoicing based on SM data.

g) Implementation of security measures: Users' interfaces were managed to view their consumed energy and their accounts, making sure only authorized persons can access to specific data or perform actions.

h) User interface: Interfaces were offered for all SM users to have access to their energy usages and manage their accounts. By creating dashboards for users to analyze and monitor the overall performance, the SM system provides valuable data for both utility companies and consumers.

8 Results and Discussions

8.1 Zones with Installed SMs

This study illustrates that the SM system offers significant benefits for both utility companies and customers in the electric power grid. For utilities, it leads to major economic benefits and cost savings by automating the whole process, such as meter readings and decreasing manual checks. For consumers, it provides accurate billing and minimizes errors. It is noteworthy that the findings of this study are applicable. The results clearly illustrate that after the SM installation, 61.506 MWh of electrical energy was saved annually due to the loss reduction of 17.1% and the reduction of theft cases of 96.4%. These findings could encourage other global energy companies to apply the SM system as a solution for reducing losses and minimizing electricity thefts, thereby bringing major economic benefits to utility companies and enhancing the reliability of the power system. Furthermore, the following potential economic and reliability benefits can be achieved for both utility companies and consumers:

a) Economic benefits

• Cost reductions: The total operational costs for utility companies decreased due to the automatic system of meter reading with fewer manual checks.

• Precise billing: Disputes and billing errors were minimized, leading to higher revenue and more accurate consumer bills.

• Power efficiency: Enhanced data improved energy management and led to potential cost reductions for both customers and utilities.

• Demand response: The ability to implement demand response plans, reduce associated costs and peak demand was enhanced.

b) Reliability benefits

• Earlier outage detection: Faster response and detection of power outages led to downtime reduction.

• Improved grid management: Enhanced monitoring of the grid's performance led to more effective maintenance and management.

• Enhanced service quality: Real-time data led to faster and more responsive and reliable service provision.

Moreover, the results can be applied to other regions and electricity markets. However, generally, like any other project, the implementation of SMs involves some challenges, including high initial costs for integrating and installing the technology infrastructure. Additionally, managing huge amounts of detailed usage data might raise concerns about cybersecurity risks and data privacy. Further research on this technology is crucial to increasing the effectiveness of SMs, reducing losses and increasing the safety of the data and the whole system.

Figure 3 illustrates the difference between the received and the sold energy. The huge gap between them shows the high amount of energy losses in the power system before installing the SM system.

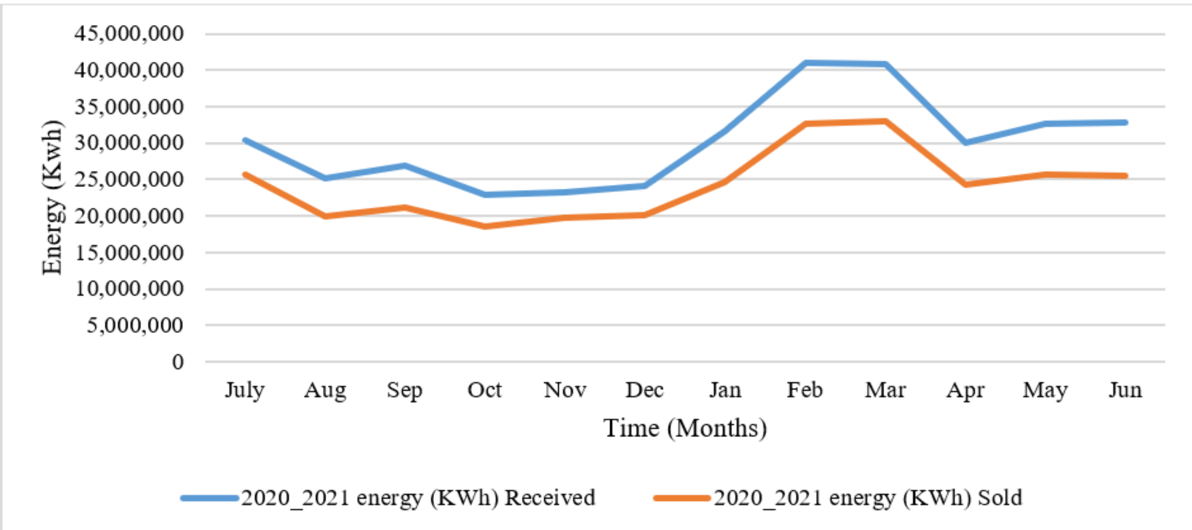


Figure 3. Difference between the received and the sold energy before installing SMs

As shown in Figure 4, the big gap between the received and sold energy decreases to the minimum, which means that installing the SM system leads to the reduction of losses and electricity theft.

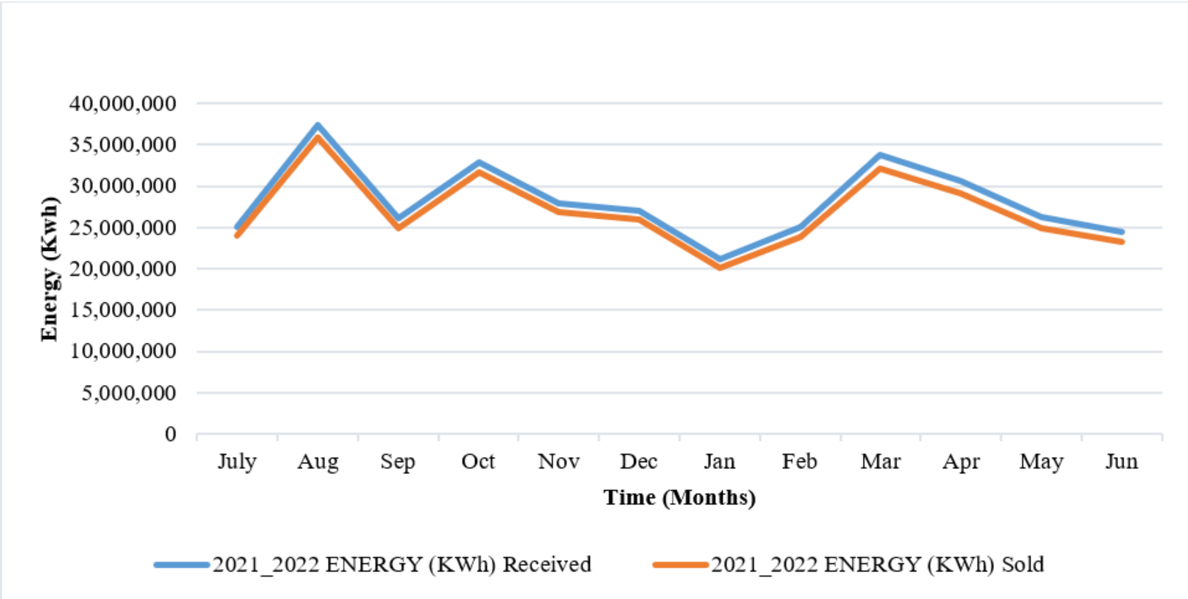


Figure 4. Difference between the received and the sold energy after installing SMs

In Figure 5, it is clearly noticeable that installing the SM system decreases the total losses from 21.5% to 4.4%, with a reduction of 17.1%. The reduction has significant economic benefits for utility companies and consumers as well as fair distribution of energy. In addition, it increases the efficiency and boosts the reliability and trustworthiness of the system.

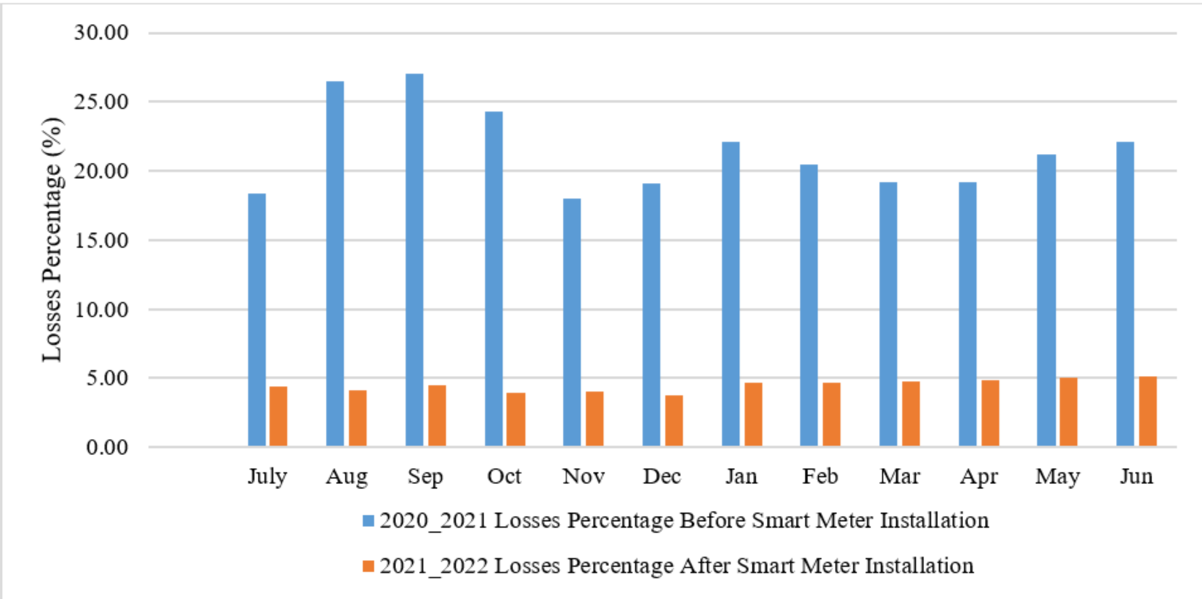


Figure 5. Power losses before and after the SM installation

Figure 6 shows the effect of digitalizing the energy meters on enhancing the efficiency of the grid by decreasing the gap between the total electricity produced and used by consumers. The total load of the feeder decreases as the losses ratio and theft cases decrease, which decreases the operation cost of utility companies and increases the reliability of the power system with economic benefits for electricity providers and consumers.

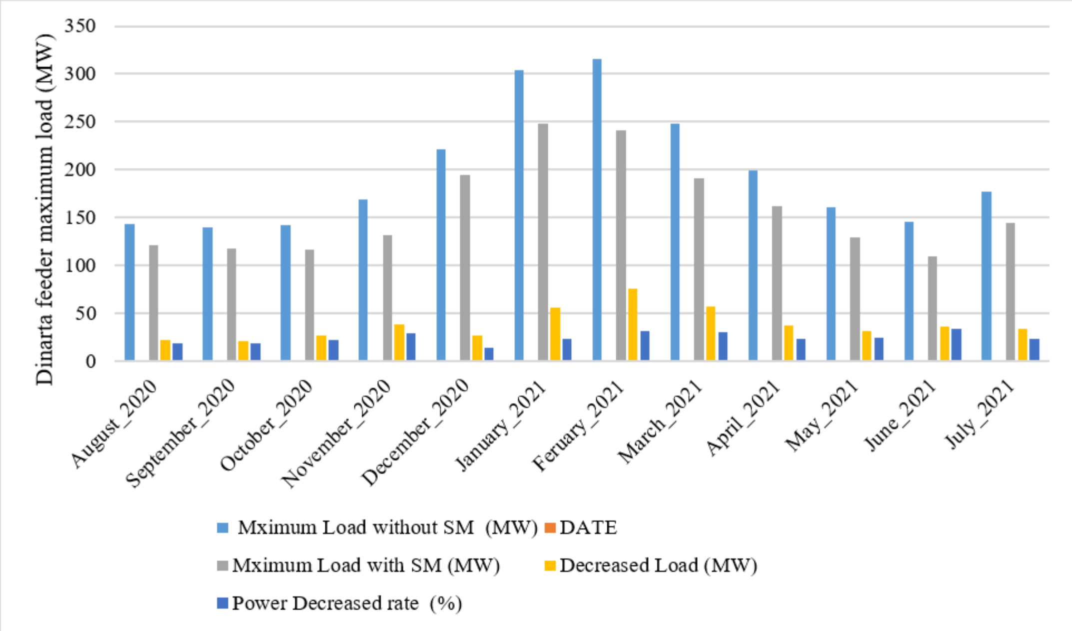


Figure 6. The maximum load of the Dinarta feeder before and after the SM installation

8.2 Zones Without Installed SMs (with Electromechanical Meters)

Areas with old electromechanical meters face numerous obstacles and disadvantages compared with the SM-installed zones. Furthermore, the high rate of theft cases, more power losses, and billing problems due to manual readings lead to many disputes and errors. Unavailability of real-time energy monitoring causes inefficient energy management. Outage finding and recovering are slower, causing longer downtime. Additionally, total operational costs are higher because of manual meter readings and increased administrative tasks. Finally, these areas without SMs have limited capacity for real demand response. Peak demand management is more challenging, and there are many obstacles to distributing energy efficiently.

Table 6 and Figure 7 show that in zones with no SM installation, the number of average theft cases is 9.75 per month from July 2020 to June 2021 and is 10.83 per month from July 2021 to June 2022. This illustrates that the average theft cases increase by 11% during one year. Whereas in zones with SMs installed, the average theft cases decrease by 96.4%. It can be clearly noticed that the SM has a significant role in reducing losses, saving energy and enhancing the reliability of the power grid.

Table 6. Total theft cases from 2020 to 2022 in zones without the SM installation

Year	2020-2021	2021-2022	Increased Percentage (%)
Jul.	7	8	14
Aug.	10	10	0
Sep.	6	7	17
Oct.	8	9	13
Nov.	10	12	20
Dec.	13	14	8
Jan.	14	14	0
Feb.	12	13	8
Mar.	10	11	10
Apr.	9	11	22
May	8	9	13
Jun.	10	12	20
Total	117	130	11
Av.	9.75	10.83	11

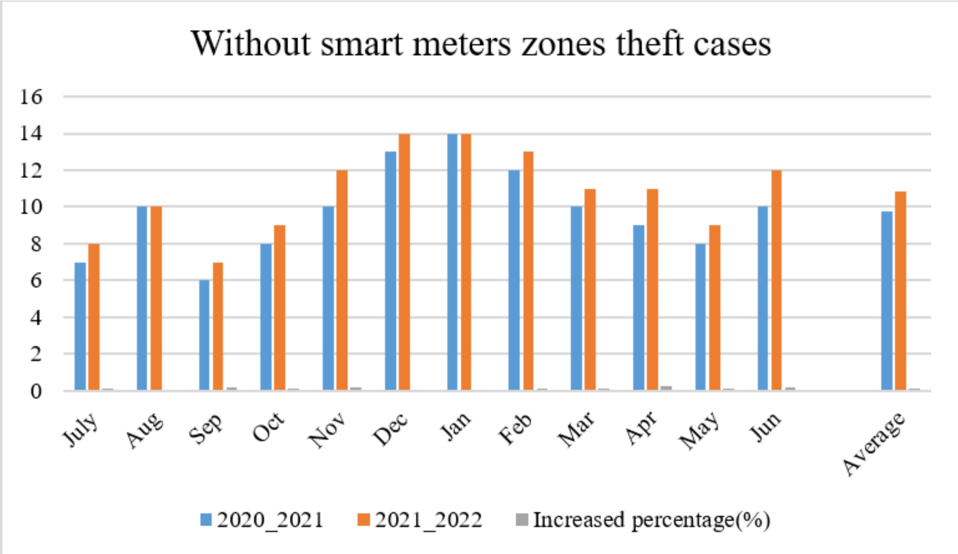


Figure 7. Theft cases of zones without the SM installation

9 Conclusion

In conclusion, the implementation of the SM system is an exceptional solution to reducing NTL and minimizing electricity theft in the power system. Through forward-thinking monitoring abilities and analytics of data in real-time, the SMs offer extraordinary visions into EC designs, enable utilities to identify misdeeds in energy usage, and locate possible tampering or theft with better accuracy. The adoption of SMs increases the power efficiency, enables consumers to have detailed information on their power usage, reduces EC and contributes to a sustainable environment and a reliable grid. In this study, it can be clearly noticed that the SMs can significantly decrease NTL and the average monthly percentage losses reduce by 17.1%. Considering these benefits, this approach enhances the usage of electricity resources equitably, guarantees fair practice of consumers' billings, improves service delivery, and boosts the resilience of the power system infrastructure, thereby facilitating more efficient, sustainable, and secure energy usage for the future generation.

The findings have significant implications for utilities, policymakers, and regulators. For utilities, it facilitates real-time advanced analytics and data collection, leading to better grid management and increasing operational efficiency and consumer service. Through the enhanced data, policymakers can formulate more informed and precise energy policies that are sustainable and environmentally friendly and support initiatives like energy conservation and programs of demand response based on accurate load data. Furthermore, regulators can benefit from the increased transparency to enforce compliance more efficiently, guaranteeing accurate billing and fair pricing.

With a long period of data collection, which is 24 months of 26,571 consumers, this study makes the findings more accurate compared with other studies. Installing the SMs in the top of electricity poles makes the theft attempt impossible as it can be detected directly by the utility, which reduced theft cases by 96.4%, a high reduction compared with other studies. All these actions and procedures led to energy savings of 61.506 MWh annually, which contributes to major economic benefits for utility companies. In addition, they also bring environmental benefits because pollution decreases with less power demand, decrease operation costs, and increase the reliability of the power system, thus providing better energy quality for consumers.

Although the SM technology has many advantages, the integration of artificial intelligence (AI) with SMs can obtain more detailed information and the EC might offer better analyses of the total load demand by the consumers in the power system, which helps to predict the required expansion of the grid and leads to better and more resilient and robust plans for the future designs of the modernized power system.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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