A Technical and Financial Analysis of Smart Prepaid Split Meters on Eskom's Electric Power Distribution Network

by

Iren Sindi Ndaba

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Declaration

I, Iren Sindi Ndaba declare that this dissertation is my original work and that it has not been presented and will not be presented to any other university for a similar or any other degree award.

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I.S. Ndaba Date

Student Number: 21105711

Approved for submission by

__ __15 March 2021________

Supervisor: Professor I. E. Davidson Date

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Abstract

The implementation of a smart metering system in the distribution network does not only promote energy loss reduction, but also improves smart grids. This improvement in smart grids is achieved by the high level information infrastructure, monitoring, accurate measurement and metering operations that provide a widespread communication substructure. The direct effect of smart prepaid split meters is on energy flow management and billing advancing, to aiding the power quality when combined with a smart grid system. The study focused on the technical and financial effectiveness of the smart prepaid split metering system on the Eskom distribution network.

The objectives of the study were, to investigate the severity of non-technical losses in distribution networks before and after smart prepaid split metering roll-out; to investigate the effectiveness of smart prepaid split metering for the utility and customers; to analyze the technical performance on medium voltage (MV) and low voltage (LV) power distribution networks before and after smart prepaid split metering roll-out; and to analyze the effectiveness of smart prepaid split metering for revenue collections. The questionnaire instrumental survey and historical data were used for the analyses. The primary data was obtained from the questionnaire tool. The collected data were analyzed with the Statistical Package for the Social Sciences software (SPSS) version 26.0 and Microsoft Excel 2016 in order to achieve multi-objective decision-making on the effectiveness of smart prepaid split metering in the utility and customer satisfaction. The different inferential statistics techniques used included regressions, correlations, multifactor analysis (MFA), factor analysis (FA) and chi-square test values. These were interpreted using the p-values to identify the change-point, trend and correlated best-fit time series for decision making.

This study concluded that the use of a smart prepaid split metering system faces challenges such as a shortage of experts for new smart meter technology to respond to the faults which led to unfavorable results for power system average interruption duration. The study recommended that South Africa’s power utility (Eskom) should consider educating and train more technical officials concerning smart grids and smart

metering to ensure that this metering technology, which is still in the early stages of development, functions efficiently.

List of abbreviations

AMI	-	Advanced Metering Infrastructure
CC&B	-	Customer Centre and Billing
CDA	-	Conditional Demand Analysis
CIU	-	Customer Interfere Unit
DR	-	Demand Response
DMS	-	Distribution Management System
EDC	-	Econometric Conditional Demand
HV	-	High Voltage
ICT	-	Information & Communication Technology
LAM	-	Linear Additive Model
LCD	-	Liquid Crystal Display
LV	-	Low Voltage
MCDA	-	Multi Criteria Decision Management
MDCA	-	Multi-Criteria Decision Analysis
MV	-	Medium Voltage
NN	-	Neural Network
NTL	-	Non-Technical Loss
OMS	-	Outage Management System
PLC	-	Programmable Logic Controller
PSTN	-	Public Switched Telephone Network
RA	-	Regression Analysis
RAT	-	Remote Access Terminal
SAIDI	-	System Average Interruption Duration Index
SAIFI	-	System Average Interruption Frequency Index
SCADA	-	Supervisory Control Data Acquisition
SPSS	-	Statistical Package for the Social Sciences
SWOT	-	Strength, Weakness, Opportunity and Treats
ToU	-	Time of Use
VIF	-	Variance Inflation Factor

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Chapter One

Study Introduction

1.0 Introduction

Access to a steady and reliable supply of power is of the utmost in advancing the well-being of every society as it encourages economic development and provides job opportunities for both middle-aged and young people. However, amongst the challenges in power utilities is the loss of revenue as a result of energy losses and accurate metering data. The use of a smart split metering system has proven to address such challenges.

Communication between the utility and power consumers is a vital issue of the smart grid [1]. Smart metering involves the installation of an intelligent meter for residential customers and the regular reading, processing and feedback of consumption data to the customer [2]. Smart prepaid split meters are the upgraded metering devices used by developing power utilities for automated measurements, as well as to remotely communicate information for billing customers and operating their electric power system components through control centers [1]. Smart metering contributes to significant improvements in the electrical distribution system by collecting the energy consumption information, monitoring customer power outages and the energy usage characteristics of the load on the grid. A smart split meter is an advanced energy meter that measures the electric energy supplied for consumption and provides information to the utility and customers for better monitoring [3]. These meters benefit the utility with information such as real-time registration of electricity [4]; the ability to read the meter locally and remotely; and the limitation of output through the meter also enables customers to manage energy consumption and reduce their bills [1, 4].

Further to these benefits is the need for a detailed study identifying the factors hindering the effective usage of smart split metering systems. More research could be carried out to minimize energy losses, electric fault indication and power outages, considering the role of power flow management and communication between utilities and power system components. Thus, smart prepaid split metering was introduced on Eskom’s distribution networks in 2013. This study focuses on the technical and financial effectiveness of smart prepaid split meters for electric grid improvements and reliable power flow data on Eskom’s electrical power distribution networks.

1.1 Background to Study

The demand for electricity has grown massively over the past few years and a higher growth rate is anticipated over the coming years. Electricity is essential in everyday life and it is the backbone of the world economy [2, 5]. The utilities need to know how much electrical energy they have generated and supplied to their customers because accurate metering is vital for the measurement of electric power supplied from generating sources to loads, namely industrial, commercial and residential loads [2].

South Africa upgraded the metering system from conventional meters to prepaid meters over the past 20 years [6]. Now there is a challenge of the enormous amount of non-technical losses due to electricity theft and meter tampering [7]. Eskom implemented a smart prepaid split metering system to improve energy efficiency, grid reliability, upfront revenue collection and excellent service to customers. The research analyses the technical and financial effectiveness of smart prepaid split meters as an upgrade to existing prepaid meters, as well as for grid development on Eskom’s electrical power distribution networks. Although the study focuses on technical and financial analyses of smart prepaid meters for distribution power networks, the research findings present opportunities to improve grid security; increase customer choices for power consumption and other developing countries can utilize these improvements.

1.2 Problem Statement

High electrical power loss is of concern in South Africa and it is an issue that many utilities around the world encounter [8]. Eskom faces the challenge of high electric energy losses due to technical and non-technical losses. Energy Loss is defined as the difference between the electricity supplied to customers and the revenue collected [9, 10]. Technical losses are regarded as losses of the electrical system caused by network impedance, current flows and auxiliary supplies [10]. Electricity thefts, measurement system errors and non-payments of bills are the contributing factors to non-technical losses, which resulted in revenue losses worth millions of Rands increasing every year in Eskom [11]. Electricity theft overloads the generation unit and affects the efficiency of the electricity supply, as Eskom has no estimate of the quantity of electricity to be supplied to legitimate customers and illegal consumers.

Non-Technical losses occur due to unidentified, misallocated or inaccurate energy flows. They can be thought of as consumed but not billed energy. It is necessary to distinguish this from the electricity that is billed, but where the bills are not paid [11]. The deployment of smart prepaid split meters is in response to Eskom's high level of non-technical losses and it is implemented to prevent electricity theft and the recovery of revenue collection. Thus the study was carried out to observe how energy is consumed and monitored at the end-user level in the residential sector. The Conditional Demand Analysis (CDA) method was used to model the residential end-use energy consumption in the Diepkloof area. The findings from this study will serve as a basis for the formulation of energy-saving goals and action plans in the electricity supply industry. This can ultimately be used for controlling and monitoring the performance of such energy-saving programs in the power system sectors.

1.3 Research Aim and Objectives

The research aims to evaluate the technical and financial effectiveness of smart prepaid split metering implementation in response to high electric power losses on Eskom's distribution networks.

1.3.1 Research Specific Objectives

The objectives of the study are:

i. To investigate the severity of non-technical losses in distribution networks before and after smart prepaid split metering roll-out;
ii. To investigate the effectiveness of smart prepaid split metering for the utility and customers;

iii. To analyze the technical performance on MV and LV power distribution networks before and after smart prepaid split metering roll-out; and
iv. To analyze the effectiveness of smart prepaid split metering for revenue collections.

1.3.2 Research questions

i. How severe are the non-technical losses in the distribution networks before and after smart prepaid split metering roll-out?
ii. Does the respondent affirm the effectiveness of smart prepaid split metering in the utility and for customers?
iii. What financial impact has the smart metering system had on the utility and customers?
iv. Does the technical performance of MV and LV power distribution networks before and after smart prepaid split metering roll-out improve?
v. How effective is the use of smart prepaid split metering for revenue collections?
vi. What are the technical benefits of smart metering on Eskom's power distribution networks?
vii. What challenges has smart metering transformation created for the utility and customers?
viii. Have smart prepaid split meters enabled the development of a smart grid?

1.4 Rationale and justification for The Research

Prior to 1988, Eskom primarily supplied large customers such as mines and municipalities. At that time, Eskom was one of the largest producers of electricity in the world and there were no prepaid meters, with about 120 000 customers billed on accounts [12]. In 1988, Eskom introduced the electricity-for-all concept to supply the vast masses of domestic residents who did not have access to electricity. During the concept, pre-payment metering was considered as a solution to limit the maintenance of the power supply.

The electrification project for this program started in 1994 and by 2000, over 5.2 million households were connected to the grid. However the prepaid metering system has remained the same over the past 20 years [12, 13]. The growth in the

South African population increased the load in electrical distribution networks which caused the electrical grid to be weaker, hence the smart grid was introduced.

The smart grid is the modernization of the existing grid [14], intended to upgrade the grid with new technology for better control, efficiency and reliability. Smart meters are a fundamental part of smart grid development for data collection and communication on power distribution networks [15, 16]. It allows electric power system operators to disconnect or re-connect the electricity supply to any customer remotely and improves the power flows on the grid [14]. Eskom implemented smart split meters to improve energy efficiency, grid reliability, the payment of bills and to provide excellent service to customers. In the smart grid, smart meters are advanced meters with intelligent capabilities deployed to meet consumer demands and utility objectives [17, 18].

The implementation of smart metering entails the electronic development of grid systems, the starting point of smart grid initiatives and a fundamentally improved energy networks. The smart grid benefits Eskom with opportunities to program the grid, supporting systems and implement a technology that monitors the distribution network performance, reduces electric power outages and improves customer services [19]. Improvements to the electrical grid are needed, and a technical upgrade is the starting point for a reliable power system. Many utilities are uncertain about the possibilities based on the smart meter for techniques and data management development in terms of analytic techniques and energy data management. Hence the availability of information with respect to smart meters for electrical grid improvement will present new opportunities for utilities to gain insight into smart meter’s operation in the distribution network. Different measures have been implemented in several nations and developed countries in an attempt to mitigate the challenge of meter tampering.

Electricity theft has attracted various technological innovations in trying to mitigate the damage and loss it incurs within countries. In this study, the researcher examines two methods for modelling end-use estimation, (engineering and conditional econometric demand models) which can be applied to household data for appliance holdings, demographic and economic variables.

The engineering model has been used to calculate the Diepkloof end-user energy survey from collected documented reports, while the Conditional Econometric Demand (CED) model was applied to data from the same survey. Both models' results were compared to recommendations regarding the choice of end-use approach and which factors are pertinent to effective smart split meter usage, and household surveys designed to disaggregate electricity consumption were postulated. The findings from the study will make Eskom aware of whether they are in the right direction to meet organizational goals for theft prevention of electricity and revenue recovery. Eskom needs to build the sustainability of the electric power system and the satisfaction on customers.

1.5 Scope of The Research

The research is limited to the analysis and discussion of the technical and financial benefits limiting the implementation of smart split meters. It explores the collected medium voltage (MV) information from electrical network performance, actual non-technical energy losses reports and revenue collection to address the smart grid statistics solutions. In addition, it analyses the survey from the questionnaires distributed to customers and Eskom staff to provide a SWOT analysis for the organization (Eskom) in charting a way forward to improve where necessary.

1.6 Research Methodology

The research used a mixed design approach consisting of the theoretical aspects of the topic along with the practical field questionnaire. The collected data from selected stakeholders was used to form a Linear Additive Model (LAM) to evaluate the technical and financial effectiveness of smart split metering usage. Moreover, random customer surveys and field operators were used to gather samples of data on installed smart split meter site operations for network performance and revenue collection. The details procedural research method includes the use of statistical tools namely- (change-point analysis, trend analysis, multi-criteria decision analysis (MDCA) regression, and correction best fit time series with a nonstationary parametric distribution), as the main contribution for capturing the technical and financial viability of smart prepaid split meters usage on Eskom's electric power distribution.

The study attempts to discover the uses of multi-criteria decision analysis (MCDA) to assess abrupt change detection impacts (before and after the roll-out of smart prepaid split meters) on electrical power distribution network performance and revenue collections in the network operations. Different statistical analysis tools were used to reveal the latent understanding of the significant factors responsible for energy loss and the desire to use the smart prepaid split meters as a bridge between the utility user and customer in the study area. The financial effects of smart prepaid split meters on the Eskom distribution network were denoted with hypothesis formulation. The LAM regression analysis of smart prepaid split meter roll-out on the utility and the customers provides opportunities to examine the strengths, weaknesses, opportunities, threats (SWOT) for electrical energy management in controlling smart meter operations.

1.7 Limitations of The Research

This study considered random samples of smart prepaid split meter roll-out effects on the power distribution networks and its cost-effectiveness in reducing energy losses. Quoted values in figures and tables were limited to the accuracy of secondary data and quantitative data gathered from the various source areas. Furthermore, for the models to be useful as decision support, it is crucial to validate the simulation results against either real measurements or expert knowledge, in other words estimating model accuracy.

1.8 Depiction of The Research Area

The study was carried out at the Gauteng Operating unit for the Diepkloof Area. The basis behind this choice was that the implementation of smart split meters is currently 85% and it was the section with a low customer base. There was a high possibility of accurate results as the sampling would be easier and more effective.

Chapter One summarizes the background of smart prepaid split meters and electrical grid improvements; the problem statement; key research questions to be addressed; limitations of the study; the rationale and justification of the study; research contribution; scope and area description of the study.

Chapter Two – Literature Review

Chapter Two focuses on the literature review of electricity, metering technologies used to date, smart meter operation, the technical analysis of electrical grid developments and the benefits of smart metering to power utilities and customers.

Chapter Three – Research Methodology

The third chapter describe the resources and research methodology used to gather information for the thesis.

Chapter Four – Discussion of Findings

Chapter Four provides an analysis and discussion of the research findings.

Chapter Five – Conclusion and Recommendations

The fifth and final chapter provides a summary of the research and answers to the research objectives question, before finally drawing the conclusion and making recommendations.

1.9 Publication

The publications in this section are also materials forming part of this thesis with appearances in peer-reviewed accredited journals and conference proceedings.

1. **Sindi Ndaba** and Innocent E. Davidson. "The implementation of smart meters for electric grid improvements and reliable power flow data on electrical power distribution networks". In Proceedings of the IEEE PES/IAS Power Africa, Nairobi, Kenya, 20–23 August 2020.

Chapter Two
Literature Review

2.0 Introduction

The electric power system serves to generate, transmit and distribute electrical energy to consumers in an efficient, economical and reliable manner. It comprises generating stations, transmission lines and distribution networks. The electrical power system is considered to be a complex system as it has many components and systems, namely: mechanical, civil, electrical, and communication systems [3]. Electrical energy is generated from generating stations, transmitted through transmission lines to substations and distributed through high voltage (HV), medium voltage (MV) and low voltage (LV) distribution networks to individual customers. In an electrical power system, the electricity distribution system is the final stage in the delivery of electric power to customers [1, 5].

Electricity distribution networks are an essential part of the power delivery system, smart control, and management of distribution networks are vital in order to satisfy technical, economic, and customer requirements [20]. The management philosophy, techniques, and methods are essential to handle security and stability associated with the power flow management, demand forecasting and customer needs in power networks [6].

2.1 Smart Grid for Electrical Power Distribution System

The distribution of electrical energy involves many operational losses as the majority of power events mostly happen at this level [2]. In recent years, Eskom has undergone a reformation process of smart grid enhancement aimed at improving the ageing power grid. These include improvements in power quality, the reliability of power supply, customer satisfaction, and the rationalization of electricity tariffs. The smart grid is the improved power network for electricity delivery systems so that it monitors, protects, and automatically optimizes the operation of its interconnected elements from the central and distributed generators through the high-voltage network, distribution system, and consumers [16]. Grid modernization (smart grid) aims to upgrade the grid with new technology for better control, efficiency, and reliability.

Smart meters are a fundamental part of smart grid development for data collection and communication systems on power distribution networks [8, 20], as they give network visibility to the distribution system operator and provide real-time load data for planning [21]. In the smart grid, smart meters are advanced meters with intelligent capabilities deployed to meet consumer demands and utility objectives [12]. A smart split meter is an advanced energy meter that monitors the electricity supplied for consumption and provides the utilities and consumers with information for better monitoring [22].

In power distribution networks, smart prepaid split meter implementation is the electronic development of grid systems, additionally, it is the starting point of smart grid initiatives and fundamental to improved energy networks [1, 11, 23]. In recent years, smart grids in general terms have emerged as a plausible approach to addressing the problems above [24]. Mainly, the smart grid involves an increased usage of Information & Communication Technology (ICT) in power systems. Advances in ICT offer the possibility to extend the observability and controllability, by using and exchanging information between components and actors in the system, thus, allowing these entities to be more active in their operation.

The smart grid concept is about optimizing grid and market operations by utilizing information for decision-making in real-time to provide balancing power and storage solutions to the power systems. Demand response (DR) is a proposed component within the smart grid framework. Demand-response refers to changing the net-consumption of end-users, e.g. industries and households by either moving it in time (load shifting), reducing it at specific points in time (load reduction), or using standby generated electricity [25, 26]. The incentive for end-users to alter their consumption could be an economical or environmental benefit. Demand-response involves the potential of influencing end-user consumption profiles to increase the efficiency and utilization rates in the electricity market.

The coordination of numerous end-users is needed to deliver the flexibility that can make a real impact on the system [27]. These smart meters benefit the utility with information such as the real-time registration of electricity [28], the opportunity to read the meter both locally and remotely, providing customers with feedback to manage energy consumption, monitoring and optimizing their budgeting [17].

2.2 Review of Previous Works on Smart Meters

The focus of the smart grid with smart meters is to provide choices to every customer for deciding the timing and amount of power consumption based upon the price of the power at a particular moment [29]. The two-way communication technology used in smart prepaid split meters enables the utility to remotely read information off the meter, detect technical alarms [30], and to send the commands to the meter remotely. Smart meters can be integrated with advanced metering infrastructure (AMI) [18], which is an integrated system of smart meters, communications networks and data management systems for better control of the metering system [28].

Smart grid technologies advanced metering infrastructure with an intelligent electricity device to address the challenge of electricity theft using smart split metering [31]. This explains that solutions to electricity theft across literature have been increasingly identified as technical. Smart grid technologies are increasingly being pushed into place to address the challenge of electricity theft using intelligent electricity devices [32]. The research has highlighted that the new challenges of a power blackout and electricity theft could be tackled by engaging smart grid technologies that modify traditional ways of distributing electricity. This allows for the implementation of straight-forward algorithms which have better reliability, give quick protection and are immune from the power system disturbances [3, 32].

The use of smart metering has been introduced in India, where it is inserted into the distribution system to detect and avoid the theft of electricity. This also confirms how in India, Hyderabad the Genetic Algorithm was put in place as a measure to ensure a Non-Technical Loss (NTL) through a hybrid approach to reduce electricity theft, avoid billing errors and the decrease of faulty meters [2, 10]. Therefore, the use of these smart split meters is argued to provide an automatic feature extraction method for load profiles with a combination of support vector machines which is used to identify fraudulent customers [33]. However, despite the measures and controls to address the problem, electricity theft remains and persists in India [34].

With the advent of smart metering technologies, real-time energy consumption data will be available at the utilities which can be used to detect illegal consumers [16]. In the US the implementation of advanced metering infrastructure (AMI) is one of the key technologies in smart grids which promises to mitigate the risk of energy theft through its monitoring capabilities and fine-grained usage measurements [35]. These technologies measure the data that is being consumed on smart meters to detect and find fraudulent customers. Moreover, one of the strategies that has previously attracted researchers in traditional power systems is to monitor the loaded customers' profiles to detect signs of energy theft [5, 22].

Mathematical modeling is an approach to addressing the complex questions related to end-user flexibility and demand response. The top-down forecast approach uses huge historical data and the most forecasting methods, such as regression, time series, fuzzy logic, neural network and expert systems [33]. On the other hand, the bottom-up approach involves developing engineering modules and using these to capture data at the appliance level [36]. The dependency of the top-down forecast approach on past data means that it does not detect incremental changes that may occur slowly, but is radical in forecasting behavioral changes.

Most electricity market sectors lack the necessary information and models to assess the feasibility of these investment options, amongst the several studies pointing to diverse factors influencing household electricity consumption and the measurement of electricity consumption [37, 38]. Three important and well-documented methods that have been used over the years by different researchers, these methods namely regression analysis (RA), conditional demand analysis (CDA) and neural networks (NN) [39]. Tobit, Probit and quantile regression are different approaches used for different purposes. However, regression is used for evaluating linear or nonlinear data distribution changes in any quantile [40]. Quantile regression is regarded as an extension of the traditional least squares method (OLS). It also includes the logistic Regression Models, the goal of which is to correctly predict the category of output for individual cases using the most parsimonious model.

Logistic regression calculates the probability of success over the probability of failure and the result of the analysis is in the form of odds ratios [41]. The method has effectively been used in the studies of multi-faceted problems, such as in public works management and policy [42], veterinary and human epidemiology [43], healthcare policy and economy [44-48], clinical investigation and environmental resources [49, 50]. Conditional demand analysis (CDA) is a regression-based econometric technique and relies on survey data on total household energy consumption and appliance ownership. At the same time, Artificial Neural Networks (ANN) is an adaptive and self-learning data-driven approach which can capture complex non-linear processes in measured data [42].

The stochastic frontier approach used on rural households in China employs the stochastic energy demand frontier for cross-sectional data analysis [51]. Given a generalized demand function;

$$Q_i = f\left(Y_i + P_i + X_i\right) + E_i \tag{1}$$

Where Q_i is the quantity of energy demanded expressed as a function of a household's inputs, income Y_i, energy price P_i, and other household determinants of energy consumption X_i. A Cobb Douglas functional form consisting of many empirical studies using an energy demand frontier that is flexible, without the imposition of strict restrictions on the input parameters provides an easy interpretation of the coefficients estimated [52].

The logarithmic form of the equation is presented as follows:

$$q_i = \alpha_0 + \beta_1 p_i + \beta_3 y_i + nx_i + E \qquad (2)$$

The set of variables comprises a series of household characteristics and control variables such as house size and ownership of various appliances. Furthermore, these variables can contain continuous variables, dummy variables, and categorical variables. Regarding this, the dummy variables and categorical variables are not affected by the natural log X_i. The residential energy consumption per capita for the country *i* in a year *t*, *cit*, can be mainly described as a function of the demography, age, gender, ethnic group, level of service, familiarity and smart split meter installation energy price, *pit*, per capita income, *yit*, annual heating and cooling degree-days as measures of the annual climatological demand for heating and cooling, *hddit*, *cddit*, average demographic characteristics, *dit*, and the energy efficiency level of the residential sector, *eeit*:

$$C_{it} = f\left(p_{it}, y_{it}, hdd_{it}, cddy_{it}, d_{it}, ee_{it}\right) \qquad (3)$$

The literature exposition explains two main categories of time series models known to represent two different cultures in statistical modelling. These are the data modelling culture and the algorithmic modelling culture [36]. An analytically formulated stochastic model is behind the generation of the data. Simultaneously the latter behind this process is something complex and unknown, which does not have to be analytically formulated, as long as a purely algorithmic model can offer high forecast accuracy. In other words, profoundly understanding and accurately modelling the future behavior of a process is strongly connected within the data modelling culture, but completely irrelevant within the algorithmic modelling culture [37]. Time series analysis and forecasting have been a powerful tool useful in reducing the uncertainty in predicting many phenomena and has helped the various researchers to project and plan for upcoming event periods. The approach involved the development of models that can capture key properties of a system - in this case, the technical and financial viability of smart meters usage.

2.2.1 Change-Point and Trend Analyses

Abrupt shifts in a time series reflect a transition from one regime to another and the system remains in this state until a new shift takes place. In most cases, the change-point analysis is carried out to detect sudden changes in the mean of the variable of interest distribution [38]. However, sudden changes in distribution variance (indicating an increase or decrease in the data scatter) can have a significant impact on the extremes [39, 40].

For this reason, the researcher tested the data for abrupt changes not only in the mean but also in the variance by applying the Pettit test to the time series of the squared residuals computed concerning a line obtained using local polynomial regression. When a series is cyclical for period *T*, differencing can also be performed by removing the value corresponding to time *t-T,* which breaks it into seasonal, cyclical and trend [41]. A time series is referred to as stationary if the distribution is invariant under temporal translations and there are not periodic, sudden, and slowly varying changes [41, 42].

2.2.2 Stationarity and Differencing

A stationary time series is one whose properties do not depend on the time at which the series is observed. Thus, time series with trends, or with seasonality, are not stationary, hence the trend and seasonality will affect the value of the time series at different times. On the other hand, a white noise series is stationary, hence it does not matter when it was observed, implying that it should look much the same at any point in time. Differencing shows one way to make a non-stationary time series stationary, computing the differences between consecutive observations. This is known as differencing. Transformations such as logarithms can help to stabilize the variance of a time series. Differencing can help stabilize the mean of a time series by removing changes in the level of a time series, and therefore eliminating (or reducing) trend and seasonality.

An analysis of the presence of monotonically increasing or decreasing trends can be carried out by means of two widely-used nonparametric tests the Mann-Kendall and Spearman [43, 44]. Similar to the Pettitt test, both of these tests are nonparametric and have similar power [45]. The approach by first performing change-point analysis was adopted in splitting the time series into two sub-series (before and after the change) and evaluating each of the two time series separately for potential monotonic patterns. Even though the focus on monotonic trends was the main aim of this study, the researcher acknowledges that the data could exhibit non-monotonic patterns [46, 47].

2.2.3 Smart Split Meter SWOT Capabilities

Smart meters are capable of the following:

i. Real-time consumption of electricity use;
ii. Reading the meter locally and remotely on demand;
iii. Remote power disconnection or re-connection for customers; and
iv. Minimizing manual energy meter reading, measurement errors and improving power flow data accuracy management [32, 35, 48].

2.2.4 The Strengths of Smart Split Metering Systems

Smart meters provide power consumption profile data from individual and groups of meters to enable energy management, load analysis, and tariff advancement. The benefits are:

i. Offering a monitoring framework for the low voltage network to quickly detect outages of supply, resulting in better reliability and improved power service levels [49];
ii. Providing a sophisticated method for the identification of energy losses to individual LV feeder levels [50];
iii. Using a PSTN / GSM, the individual meter reading can be channeled directly to the local substation, thereby removing the need for a site visit to read the meter minimizing human labor. [27];
iv. Any tempering of the meter is recorded to the central control system immediately, which increases energy efficiency by properly detecting energy losses [51];
v. The system provides fast billing through automated software enabled for easy billing [52];

vi. The meter can be configured to disconnect at a pre-determined load or total energy usage for the purposes of credit control or load management and which will eliminate grid failure by overload [53];
vii. Day-to-day billing is available, resulting in effective load management for the customers as they can use appliances at off-peak hours with less energy consumption [54];
viii. Due to remote data reading, there are fewer site visits for technical officials, this reduces field trips and vehicle emissions;
ix. The LCD on the meter can be programmed to display various facilities including the amount of credit left on the meter; and
x. The smart metering system increases the safety in power utilities, has less injuries, and fewer fatalities.

2.2.5 Challenges Brought by the Smart Split Metering System in Power Utilities

Despite the many benefits that smart metering offers, smart meters have not always been met with approval and acceptance. There are fears about the loss of the jobs of meter readers when implementing the smart meter programme [7]. While smart meters achieve the goal of smart grid development, they also pose extant challenges to electric utilities as well as customers. The challenges are as follows:

i. The smart metering system is costly in terms of personnel training, equipment development, transition to new technology and the implementation of new sets of processes;
ii. Managing public skepticism and acquiring customer acceptance of the new smart meters;
iii. Making a long-term financial commitment to the new smart metering technology and the related software involved;
iv. Managing and storing immense quantities of collected metering information;
v. Ensuring metering and consumer data protection and privacy;
vi. It is hard to verify that the new meter is accurate after installation; and
vii. There is an additional fee for the installation of the new meter.

2.2.6 Smart Split Metering Opportunity for Smart Grid Development

Challenges amongst the power industries resulted in the utilities upgrading the existing power grids with a smart grid [19] aimed at improving the reliability and quality of electricity supply to customers. Smart grid development is a global initiative in power engineering [55, 56], a modernization of the existing electrical network to provide visibility, automatic control, and intelligent systems monitoring to control the entire spectrum of electrical system components from generation to the end-user. The purpose of smart grids is to ensure that utilities begin to provide future systems architecture that will integrate all of the processes and systems required for a highly intelligent electricity network [57]. Figure 2.1 illustrates the smart metering system architecture.

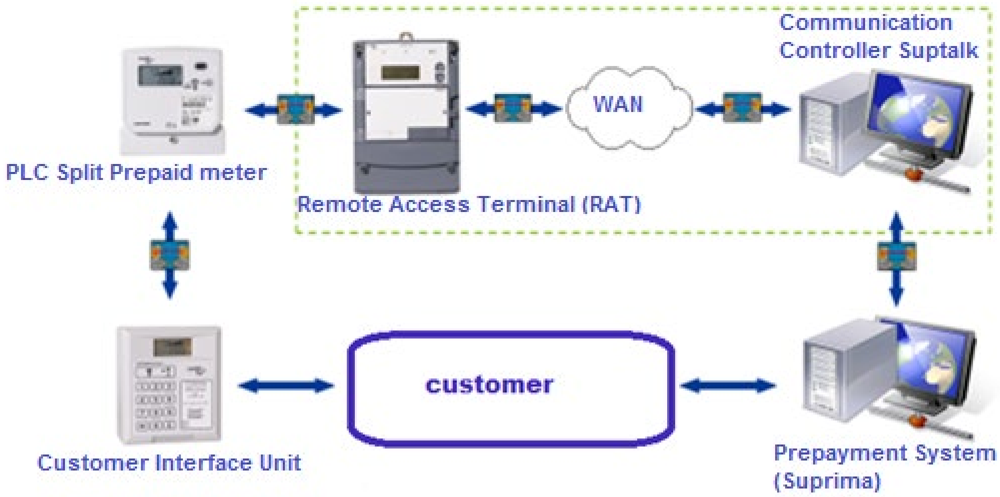


Figure 2. 1 Architecture of Smart Metering System

With the deployment of the smart grid, consumers are empowered with a demand response to regulate their real-time consumption, thereby facilitating consumers' ready access to, which will influence their behavior and encourage initializing the wiser use of energy [22]. A consumption-based pricing model relies on the fundamental philosophy that customers pay according to the amounts of service that they use or consume as smart meters record and send energy consumption [58]. The aim of energy pricing with a smart split meter is to increase the participation of the customer in electricity demand providing the price signals that display energy costs more accurately.

This enables power utilities to follow a more systematic procedure in controlling the energy produced from generating sources according to the existing demand, which is visible through the data provided by theses smart meters. Smart energy meters generate a digital response to the fluctuations in demand [59]. Through the smart metering system, the consumers obtains more organized data regarding their electricity consumption [15]. This information reaches the consumer at regular intervals as programmed and is also accurate and error-free, unlike the data obtained through manual meter reading [4, 35].

Smart metering systems offers the utility several functionalities and the utility can choose to have meters implemented for the following functions:

i. Time of use - In this rate plan, the customer's bill is determined by how much energy is used and when the customer uses it. The rates apply different per-unit prices for usage at separate blocks of time, which is important to utilize as the cost of energy generation is not fixed throughout the day. The definition of Time Of Use (TOU) phases varies from utility to utility, based on the periods in which their peak demands are scheduled over the day of the week [60, 61].
ii. Critical Peak Pricing - In this function, rates are applied for certain hours on previously appointed days and the pricing is usually combined with a TOU rate [61].
iii. Real-time pricing - Rates constantly fluctuate over time, following the fluctuation of the wholesale prices. Most often, the rates separate prices for the hour of the day and the customers are being notified about these prices in advanced [18].
iv. Pick time rebates - Tariffs offer credits for load reduction, but do not react when the load grows. This benefits consumers in cutting down the electricity bill. In addition, this makes the load duration curve almost flat. It does not require more power plants to be built to meet an excessively high peak, thereby reducing carbon dioxide emissions. Moreover, it reduces the stress on the transformer [62].

2.3 Smart Split Metering Opportunities

Smart meters are equipped with intelligent energy management facilities and advanced communication features that enable users to track any small aspect of consumption through records from the meter. Through the use of smart meters, electricity consumption can be precisely monitored and controlled [34]. When smart meters are coupled with smart grids, they monitor the flow of electricity from the grid based on the identified energy consumption patterns. As the global population is moves towards a green energy initiative, smart meters and grids can support the citizens of today to minimize the wastage of valuable resources [51].

2.4 Smart Solution for Smart Cities

Smart meters are the most adequate solution to smart cities, as they help people to control their energy consumption and reduce energy wastage. The advantage of smart meters is the increase in energy literacy which educates customers about the concept of energy consumption and resource conservation. Most customers were not aware of the importance of energy consumption monitoring, but with the introduction of smart meters, it is easy to read load patterns through the user-friendly interface which helps users to understand their consumption easily. Figure 2.2 depicts the smart meter operation centre distribution.

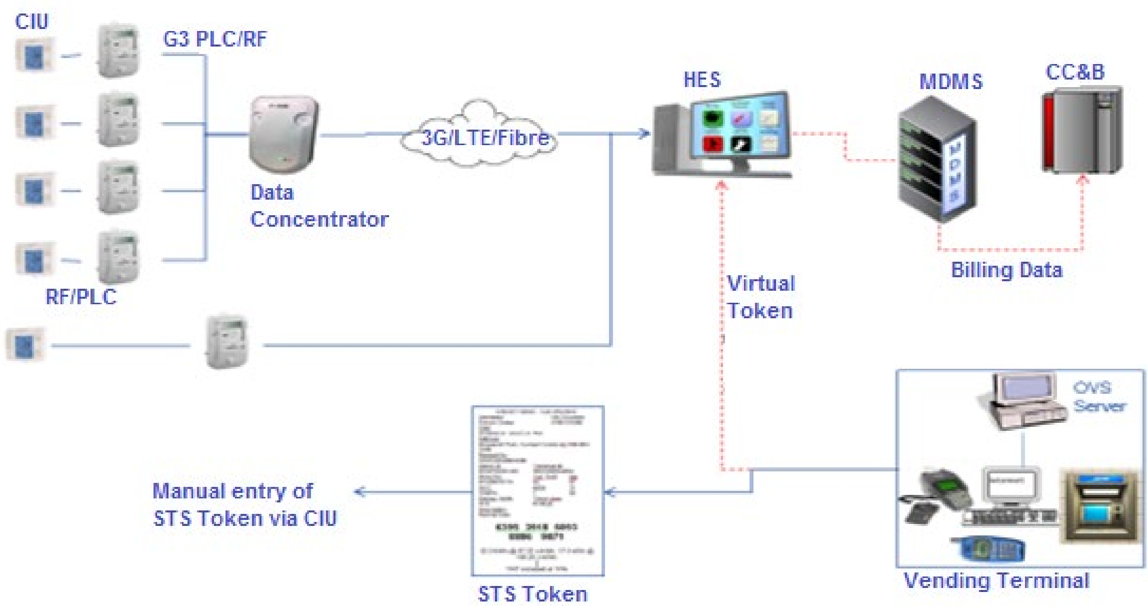


Figure 2. 2 Smart Split Meter Distribution Operating Centre

The implementation of smart meters entails new technologies and new processes in the entire revenue chain of utilities. Managing the public's view of smart meters and understanding why these meters are implemented significantly reduces negative customer feedback [49]. These applications deployed in the smart metering framework are sufficiently advanced to deliver data in real time. With such advanced technology smart grids and smart meters are considered as the baseline for any city to be smart. With the automation of these recording processes, the quality of analytics and the way forward for strategic planning has improved to a great level. Previously, the utility had to allocate operators to monitor the readings on energy meters, but there was a massive chance of data and tracking error. These human errors in recording mostly led to tremendous amount of energy losses and the illegal use of electricity. This automation metering system not only helps the power utilities to plan efficient management, but also it helps the end-user to save a good amount on their electricity bills [63].

2.5 Electricity Usage-Controlled with the Smart Meter

Despite certain similarities, AMR and smart meters use different technologies and have their own benefits. AMR meters only communicate between the customer and the energy supplier, whereas smart meters have two-way communication between the energy supplier and the business customer. Recently, in the year 2017, research conducted showed that the domestic electricity market consumes 23% of the total energy and the commercial market consumes 32% of the total energy generated. The reasons for the high price of electricity are the scarcity of good quality fossil fuel and the increasing demand for energy.

Reducing energy losses and using resources effectively aid power utilities to fulfill the power demand quickly, whilst it automatically decreasing the price of electricity [64]. It is claimed that smart meters with effective grid management in place reduce energy consumption and non-technical losses. If the energy management process is not right, then a scarcity of energy may occur shortly, which will affect the generation of electricity, thus leading to increasing electricity units [25].

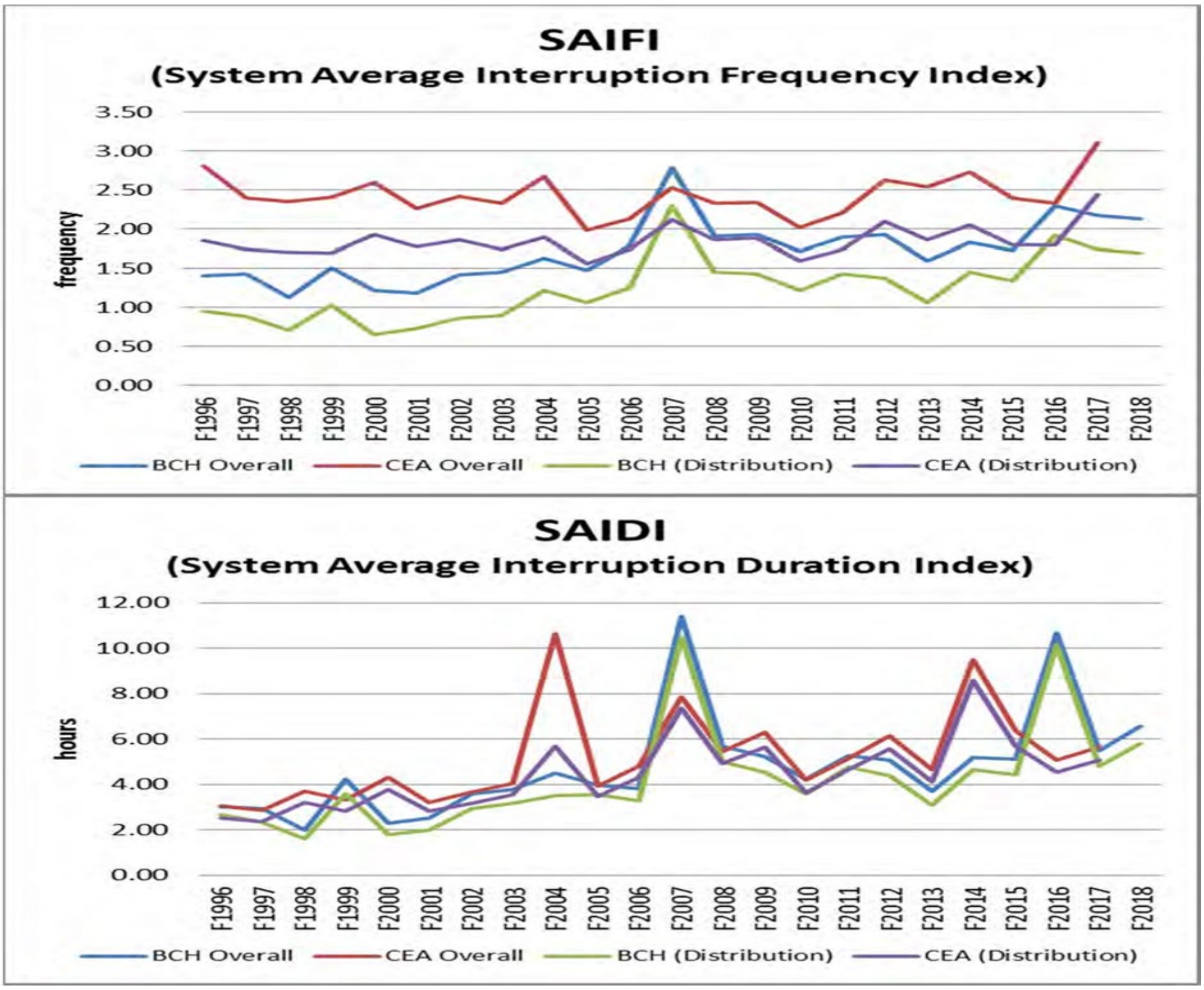
2.6 Network Performance and Smart Meter Technical Design Operations

A smart metering system employs several control devices; various sensors to identify parameters, and devices to transfer the data and command signals. Proper selection of the communication network and design of the communication devices are essential and must satisfy multiple complex requirements [65, 66]. The first purpose of smart meter installation is the improvement of metering business efficiency by automated, remote meter reading and tamper prevention. However, despite new services utilizing such accurate and frequent smart metering data, outage location has been considered [67]. Outage management is one of the most crucial processes in the operation of a distribution network and using smart metering for the user management system (UMS) has been a hot trend in the utility industry over the last few years [68]. The benefits of integrating smart metering and outage management are derived from the reduction of average outage duration, the technical official's dispatcher, reductions in restoration and massive call centre costs. The outage management system uses information from smart meters to identify the outage area and this function provides the outage extent information [69].

2.7 Distribution System Reliability Measures

Power utilities use various control and information systems such as supervisory control data acquisition (SCADA), distribution management systems (DMS) and outage management systems (OMS) for efficient distribution systems management, including the prevention of power outages and rapid power restoration in the case of outages. The OMS plays an essential role in the operation of distribution networks and it is one of the critical applications in distribution network control centers [67]. An outage area identification method is combined with the smart metering communication models in order to evaluate the impact of the communication performance of smart metering infrastructure on outage management [70].

Smart metering infrastructure provides the improved opportunity of checking the outage and determining on how to deal with it. The technologies implemented in smart metering are also used for the validation of restoration from the outage, as well as enabling the power utility to check customers who require restoration in advance [71]. Figure 2.3 shows the annual reporting interruption frequency index and the duration index graph for reliability indices distribution. The determination of whether a low voltage interruption event counts against reliability metrics such as the system average interruption duration index (SAIDI) and the system average interruption frequency index (SAIFI), depends on the duration and severity of the event [72]. The smart metering system is linked to MV/LV transformers such that if an outage occurred the boundary branches would be identified and updated by the algorithm based on the available smart meter information [73]. Automated restoration from smart meters offers the potential of improved reliability over manually restored systems. It is possible to reduce average customer outage times, annual unavailability and expectations of unserved energy by automating distribution systems [62].



[73]

Figure 2. 3 Annual Reporting of Reliability Indices Distribution

Enhancing system performance in terms of reliability, speed of restoration and the incorporation of distributed resources through the use of smart metering data has considerable potential. However, these reforms encounter challenges [74], including high cost, reduction of losses due to electronic switching, improvement of the reliability of electronic converters and innovative solutions to insulation coordination matrix [75]. Automated restoration offers the potential of improved reliability over manually restored systems. It is possible to reduce average customer outage times, annual unavailability and expectations of unserved energy by automating distribution systems. The analysis of when, and how to restore service has been proposed using an off-line calculated table and properties of the binary bus connection matrix. A suggestion has been offered for the calculation of the cost-to-benefit ratio of distribution automation. The ideas indicated are in line with the smart grid concept, which is the use of sensory information to enhance the system [76].

2.8 Smart meter for Non-Technical Losses Reduction

Non-technical loss (NTL) during the transmission of electrical energy is a major problem in developing countries, and it has been very difficult for utility companies to detect and fight the people responsible for the theft. Electricity theft forms a major chunk of NTL. These losses affect the quality of supply, increase the load on the generating station and affect tariffs imposed on genuine customers [16]. A combination of technical and non-technical energy loss is of concern and it is very high, despite recent reforms and measures taken by Eskom across South Africa. Improvement in managing energy losses is significant for the financial and technical viability of the distribution system at the economic level [77].

The accurate metering and billing of the actual energy consumed by users are fundamental to the commercial management of an electric utility [13]. Smart prepaid split meters offer a better alternative to traditional meters when it comes to managing electricity usage [1, 17]. Non-technical losses in distribution networks are widely acknowledged by electricity distribution utilities worldwide as electrical losses but, these losses cannot be calculated at present from first principles because, these losses are due to human intervention in the network. Some distribution network companies estimate the loss of revenue as high as 30% of the total electricity supplied to the distribution network [49]. Therefore, the total electrical energy supplied to the distribution network includes non-technical losses as a parameter and can be calculated as:

$$\sum P_g = \sum P_{used} + \sum P_{Technical} + \sum P_{Non-technical} \qquad (4)$$

Where

P_g, is the power generated;

P_{used}, is the power used by the network;

$P_{Technical}$, is the technical losses in the network; and

$P_{Non-Technical}$, is the non-technical losses in the network.

Therefore, such a situation calls for the implementation of the smart grid. Smart meters have been the tool of choice to tackle the problem of non-technical losses often caused by the theft of electricity. A smart grid helps utilities get to information about the electricity usage of consumers and allows the utilities to potentially adapt their distribution processed concerning the time and quantum of power demand. The smart grid, which uses smart meters, could potentially be used for detecting power theft. In addition, the info that the consumers would have access to through the smart meters would possibly help them manage their energy usage in a better and more efficient way [34, 61].

By using the smart meter and basic software for monitoring the low voltage grid, energy suppliers can monitor their grid easily and find the place of illegal energy usage in their grid if this problem existed. A focus area of power flow management research is the reduction of electrical energy losses occurring in the electricity distribution network. These losses are the technical and non-technical losses, thus reducing these losses ensures that the cost of electricity to customers will be reduced and the efficiency of the distribution network will be improved.

2.9 Demand Response and Smart Meters

In recent years, the demand for electricity has increased in households due to the use of various appliances. This raises a concern for many developed and developing nations, with the demand for an immediate increase in electricity. There is a need for consumers or people to track their daily power usage in households

[78]. Most of this increase in demand has occurred during peak periods. Peak periods are the times when the demand for electricity is high – usually when several customers use electricity at the same time, e.g. from 7 am to 10 am and 6 pm to 8 pm. Due to the way in which residential consumers use electricity throughout the day, the residential customer base contributes significantly to the electricity used during peak periods [34, 78]. Electricity consumptions are high during peak hours when the demand is high. This encourages consumers to connect heavy loads during the non-peak hours.

Using demand responses from flexible loads in the building stock is a promising solution to overcome these challenges for electricity market actors. However, as demand response is not used on a large scale today, there are validity concerns regarding its cost-benefit and reliability when compared to traditional investment options in the power sector, e.g. network refurbishment. To analyze the potential in demand response solutions, bottom-up simulation models which capture consumption processes in buildings are an alternative. These models must be simple enough to allow aggregations of buildings to be instantiated and, at the same time, intricate enough to include variations in individual behaviors of end-users. This is done so that the electricity market sector can analyze how large volumes of flexibility acts in various market and power system operation contexts, but can appreciate how individual end-users are affected by demand response actions in terms of cost and comfort.

2.10 A Threat to Sustainable Smart Meter Usage

Several concerns about smart meters still remain and not all will be resolved by technology evolution. Many of the doubts are centered on uncertainty and the lack of emerging technology know-how or knowledge. The public's perception of smart meters is a key factor that could well determine the future of smart meters. If the public does not accept smart meters, their implementation will be slow and their benefits will be reduced. Despite these concerns, smart meters form an integral part of a smart grid and are being widely deployed around the world. Moreover they are likely to improve as the technology continues maturing. These points are explored below for elaboration and diagnostic purposes. It is imperative in this study to incorporate the solution strategies for the long-term sustainability of smart meter usage.

2.10.1 Customer Acceptance

Customer engagement is a crucial factor for a smart metering project to succeed. The project is unlikely to be successful if the public is not well prepared for the implementation. In terms of peak loads, smart metering relies on customers adjusting their consumption patterns in order to reduce peak loads. This is unlikely to happen if customers do not understand the new system [66].

2.10.2 Privacy and Data Protection

A key issue on which Government and commentators have focused is data privacy. The creation and storage of such extensive data on household energy consumption patterns will generate a plethora of data security challenges and these will need to be met in a market that is increasingly less tolerant of mis-handled data privacy issues. These require that systems must:

i. Feature privacy principles in their overall project governance framework and proactively embed privacy requirements into their designs;
ii. Make privacy a core functionality in their design and architecture. They should build in privacy end-to-end, throughout the entire life cycle of any personal information collected; and
iii. Be visible and transparent to consumers to ensure that new smart grid systems operate according to stated objectives.

The prospectus makes it clear that the Government's position on this matter is that the customer should have control over how their consumption data is used and by whom. With the sole exception of data required to fulfill any regulatory duties, this is in line with the position taken by the European Regulator's Group for Electricity and Gas [63]. As it develops its position, the Government will use its powers under the Energy Act 2008 to amend existing electricity supply licences and industry codes and to create a new licence, code and regulations governing smart metering. [8].

2.11 Chapter Overview

The smart metering system is referred to as the next-generation power measurement system and, it is considered as an evolutionary regime of existing power grids. One of the ways to fight the energy losses concerns in power utilities is by optimizing the use of resources such as smart meters. A smart grid offers substantial opportunities for utilities and consumers to manage energy consumption by the usage of smart metering infrastructure with dual-way and real-time communication. It also provides opportunities to integrate renewable and non-renewable generation sources into grid operations, reducing outages and cascading problems, and enabling consumers to manage their energy consumption better.

Chapter Three

Methodology

3.0 Introduction

This chapter explains the various methods employed to gather information used in analyzing the research questions/hypotheses. The tested hypotheses for the present study are: (1) Respondent responses affirmed the severity of non-technical losses in distribution networks after smart prepaid split metering roll-out to be significant; (2) irrespective of the time period, respondent responses affirmed that smart metering implementation has a positive/significant level of effectiveness in the utility and customers' usage; (3) respondents affirmed the technical performance of both the MV and LV power distribution networks to be more significant after smart prepaid split metering was implemented and (4) respondent responses affirmed that the effectiveness of smart prepaid split metering for revenue collections improved after smart prepaid split meter introduction. The detailed methodologies are enumerated as follows after the review of literature work and the development of data collection techniques and instruments.

3.1 Research Design

A historical research design was used, where the information collected was verified from records to establish the facts that defend the hypotheses. Primary and secondary sources of data such as questionnaires, records, and reports were used. The research focuses on the technical and financial effectiveness of smart prepaid split meters after the roll-out. Therefore the historical approach was well suited for trend analysis and added important contextual background required to understand, interpret and answer the research problem. The data was collected from Diepkloof customers in the Gauteng operating unit, while Eskom staff members provided reports and documents for verification.

3.2 Research Location

Diepkloof is a section of the Soweto Township in the south-west of Johannesburg in the Gauteng province of South Africa. It is located between latitude -26.195246, and longitude 28.034088 of Johannesburg. The township is Soweto’s eastern suburb, located approximately 15km from the south-west of the city of Johannesburg.

3.3 Research Approach

The research was approached using the triangular concept of qualitative and quantitative data collection techniques. The triangular technique uses multiple methods of data collection intending to increase the reliability of observations. It was used due to some findings that require a personal assessment of the provincial information collected from smart split meter users and the utility operators, while some outcomes were reached after conducting a few mathematical computation. The administered questionnaire was used to obtain relevant data about the subject matter. A quantitative approach technique uses data that are numerical and that can be quantified, this data help to affirm and to bring clarity to the quantitative collected data. It consists of the reports and records of smart split meters and the grid operation in MV and LV distribution networks.

3.4 Population of Study

A population is the entire set of cases in which a study is interested. It is the full set of individuals or objects having some common characteristics. In this study, the population was customers based at Diepkloof, where smart split meters were successfully installed and are currently operating. Eskom staff members who operate and monitor the smart split meters for daily operations assisted with information.

3.5 Sampling and Data Analysis

The sample is a fraction of the population where the study took place, a fraction of the whole, selected to participate in the research study. The population for this study covers a considerable number of customers. Therefore, getting all of them to participate in data collection was not possible. As a result, sampling was used through the Eskom customers and staff who assisted in filling the distributed questionnaire.

3.5.1 Sampling Size

In total, 365 questionnaires were dispatched, and 334 were returned, which gave a 92 % response rate, of which 280 were customers and 54 were Eskom staff from the Diepkloof area in Soweto Gauteng's operating unit. At this rate, 7 respondents from the customer sample were not aware of the new meter system and were eliminated from the technical analysis, but not the biographical.

3.5.2 Sampling Technique

The sampling technique defines selecting the part of the population to represent the whole population. The employed sampling technique was a probability sampling technique, which ensures that all the members of the population have an equal chance of being selected. Descriptive statistics such as frequency distribution tables, mean, the confidence interval and standard deviation were used to analyze the socio-economic characteristics of the respondents.

3.6 Data Collection

Data collection is the process of gathering and measuring information on the variables of interest, in an established systematic manner that enables one to answer stated research questions, test hypotheses, and evaluate outcomes. In this study, both the primary and secondary data collection which combines qualitative and quantitative research data was used.

3.6.1 Primary Data Collection

Primary data was obtained from Eskom staff and customers residing in the Diepkloof area using a set of questionnaires as an instrument to gather information for the analytical part of the study. The questionnaire includes a set of questions in a predetermined order. This helped to gain a deeper understanding of the real extent of the smart split metering technical and financial effectiveness on distribution networks. The questionnaire had two sections, namely:

i. Section A was on the demography information of the respondent's while

ii. Section B was on smart prepaid split meter system operations in Distribution Networks.

The content of the questionnaire instrument was structured in the modified Likert fashion on a 5- point scale ranging from Strongly Agree (SA) to Agree (A), Neutral (N), Disagree (D) or Strongly Disagree (SD). Participants were then instructed to respond with their degree of agreement with the statements contained in the instrument.

3.6.2 Secondary Data Collection

Secondary data refers to data that have already been collected for some other purpose. For this study, the statistical data from Eskom revenue collection; distribution network performance reports; and energy trading management reports were used for quantitative data collection.

3.7 Validity of Data

Validity is described as a measure of the truth or falsity of the data obtained through the instrument of research. It was classified as the internal and external validity of the measuring instrument. In this study, an Eskom feeder balancing expert was consulted to check the questionnaires before distributing them to the relevant participants. Modifications where necessary were made before actual data collection to assess theoretical meaning, concepts and accuracy of the language used to describe concepts. A validity test pre-test of the questionnaire was carried out to identify irrelevant, unclear and redundant questions.

3.8 Pre-Data Analysis

In all, a descriptive statistics summary consisting of the (mean, standard deviation, and skewness kurtosis) of all the different historical data collected, was presented. This was followed by a preliminary analysis to test the data reliability, stationarity, consistency and trend. This includes the Kolmogorov-Smirnov normality test to show if the data is uniformly distributed. Both Excel and SPSS 2.6.0 computer software were employed for the analyses. The data analysis carried out includes; tables, and figures for regression, correlation, multivariate, principal component analysis (PCA), factor analysis (FA), Multivariate analysis of Variance (MANOVA), and t-significant tests. These analyses were carried out to show whether the implementation of smart split metering was effective in revenue collection, energy loss reduction, and for power grid performance improvement.

3.8.1 Reliability Test

Reliability is the degree to which an instrument evaluates the same way each time it is used under the same conditions with the same subjects. In this study, the reliability of qualitative data was tested using Cronbach's Alpha. The responses obtained through the questionnaire schedule were split into two halves and then scored independently to check correlation using the test-retest method.

3.8.2 Stationary Test

A time series is stationary if it meets the following conditions: The series mean is constant over time; the series variance is constant over time; the covariance between a measurement at a time *(t)* and measurement at a time *(t + m)* does not depend on time. There are several types of stationarity tests. This study uses the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test, for which the null hypothesis is stationarity and the alternative hypothesis is non-stationarity.

3.8.3 Consistency/Homogeneity Test

A homogeneity test is used to verify if two samples belong to the same population. Non-homogeneity in data often arises from human-made developments [79]. The homogeneity test helps to understand the prevailing underlying physical mechanism in the data given from different sources. The nonparametric tests: Mann-Kendall, Sen slope and Spearman were used in this study.

3.8.4 Correlation

A correlation was used as part of the inferential statistics analyses to test the relationship between factors that influence the use of smart split meters and the cost-effectiveness of its usage. In contrast, regression analyses were used to determine if there is any relationship between the determining factor and other independent variables that explain the effectiveness of smart split metering in the utility and customer service. The model predicts the impact of smart prepaid split metering on each determinant variable. The correlation regression analysis describes the effect of one or more independent variables on a single dependent variable. Two empirical methods of regression analysis were used in the analysis of the data obtained from the structured questionnaires in order to estimate the effectiveness of smart split meters. The two methods are Tobit and Probit regression models.

The actual objective of using the Probit model is to determine the mean estimate of the effectiveness and regress other technical and financial factors of the respondents to estimate the effectiveness functions. This helped in discovering the reliability of the contingent valuation results and increase confidence in preventing energy loss and ensuring satisfactory billing valuation [80]. Furthermore, Tobit is an alternative method that can be used when the dependent variable is zero for a significant fraction of the data. MANOVA was used to test if there were statistically significant differences amongst the determinant variables. It entails the traditional cross-tabulations approach to report a statistical statement of significance. A p-value is generated from a test statistic.

A significant result is indicated with $p\text{-value}<0.05$, while a second Chi-square test was performed to determine whether there was a statistically significant relationship between the variables (rows vs columns). The null hypothesis states that there is no association between the two however, the alternate hypothesis indicates that there is an association.

3.8.5 Wilcoxon Signed-Rank Test

This test was designed to test the significance of the difference between two populations using random samples drawn from the same population. It is a non-parametric equivalent of the parametric t-test and chi-square test, which are interpreted using the p-values.

3.8.6 The Multifactor Analysis (MFA)

MFA is useful to uncover latent structure (dimensions) of an asset of variables. It reduces attribute space from a more significant number of variables to a smaller number of factors through its principal component analysis. The PCA, as a choice of MFA, explains the contribution of the unobserved standard features in a target event from observed ones. Purposely, it reduces the variety of the collected data matrix to form a few selected derived component variables, which form a true representation of the original sets.

3.8.7 Factor Analysis (FA)

FA was used to represent a number of questions with a small number of hypothetical factors, which can be combined to create a new variable. A factor score variable contains a score for each respondent on the factor. In this study, Kaiser Meyer Olkin (KMO) and Bartlett's test were used to extract the factor analysis for the primary data collected. This test measures the strength of the relationship amongst the variables. The KMO determines whether or the responses given with the sample are adequate or not; the result from this test should be 0.5 or more for satisfactory factor analysis to proceed. Bartlett's Test is another indication of the strength of the relationship between the subject variables. This tests the null hypothesis that the correlation matrix is an identity matrix. The result from this test should be 0.05 or less for satisfactory factor analysis to proceed.

The section below details the Research Objectives Breakdown on how each objective was accomplished. To investigates the severity of non-technical losses in distribution networks before and after smart split metering roll-out.

This objective was achieved through statistical tools on both the collected energy losses data and responses to the questionnaire. Distributed questionnaire sections B2.1.1- B2.1.5 were used to answer this objective.

Table 3. 1 Technical benefits of smart metering on Eskom's distribution networks

Research Sections	Research Variables
B2.1.1	The measurement accuracy of the customer for billing has been increased as the consumption data the energy meter is not recorded manually.
B2.1.2	The two-way communication between individual meters and Eskom center's eliminates the necessity of site visits for manual meter reading, minimize human labour.
B2.1.3	The immediately tampering reported by smart split meters to a central control system reduces the energy losses and improves energy efficiency.
B2.1.4	The transformer load on the LV network is accessible, and overload is remotely detected and manageable.
B2.1.5	I am satisfied with the technology used in smart prepaid meters for energy consumption management.

The trend analysis for change-point analysis, fitting the time series with a nonstationary parametric (Mann-Kendall and Spearman distribution) were used to know the severity of non-technical losses in terms of whether it is low or high after the smart split meters implementation on Eskom's electric power distribution network. To test the statistical model fitting for Diepkloof's energy losses data, exponential, Holt Winter and moving average trend models were used. The results are illustrated in Figures 3.1 and 3.2.

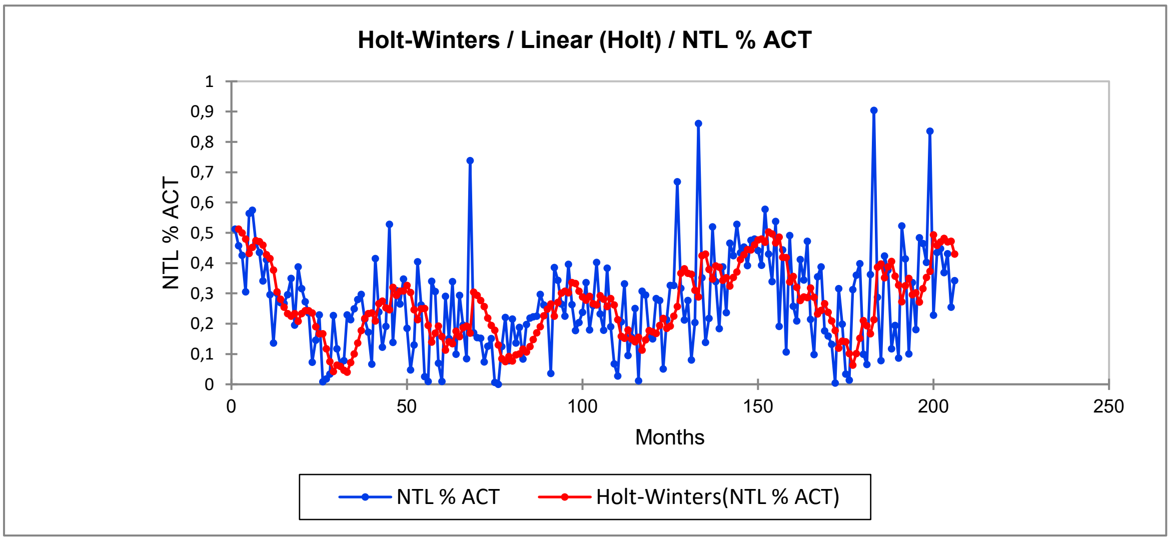


Figure 3. 1 Holt-Winters Model of actual NTL Data

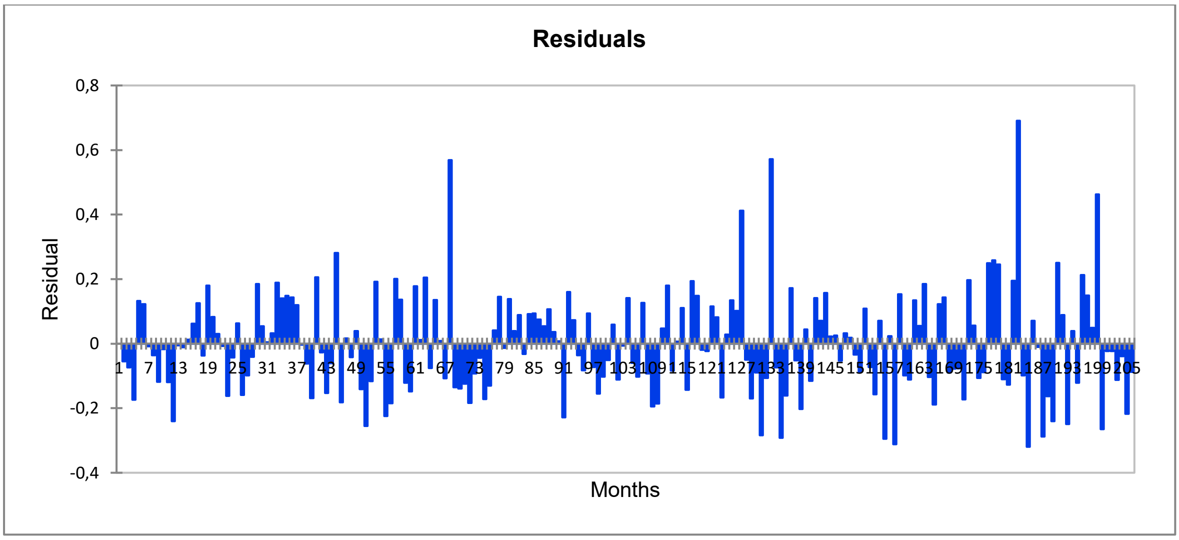


Figure 3. 2 Exponential Model of NTL Data

Table 3. 2 Summary of Best Statistical Model Fitting for NTL Data (2015-2019)

Statistics	**Exponential Value**	**Holt-Winters Value**	**Moving Average Value**
Observations	206	206	206
DF	205	202	206
SSE	4.775	5.155	3.630
MSE	0.023	0.026	0.018
RMSE	0.153	0.160	0.133
MAPE	151.987	137.247	117.068
MPE	-124.210	-103.752	-91.654
MAE	0.117	0.124	0.099
R^2	0.116	0.039	0.335

From the above two tables, 3.2 RMSE (Root Mean Square Error) with the lowest value depicts the best model fitting. Root mean square error is a standard way to measure the error of a model in predicting data. It measures the differences between values predicted by a model and the values observed. RMSE values <0.5 show that the model can predict the data accurately. In this case the value of RMSE is between 0-0.2 best fitting model. Thus, non-technical energy losses data fitting proved to be a vital fitting for analyzing time-series datasets. They depict the degree to which the measurement of the residual error taken at time (*t*) is correlated to the measurements that were taken at time *(t-k)*.

Research objective two was meant to measure the effectiveness of smart split metering for the utility and customers. First, a multi-regression model was used to test the hypothesized effects of smart split meters for improved electricity service delivery. Probit regression is used to measure linear or nonlinear differences in the distribution of data in any quantile. Thereafter one can compare the ordinary least squares (OLS) to the median regression quantile (t=0.5). OLS minimizes the sum of the squared errors while the sum of the absolute errors is minimized at median regression. By generalizing this to every other regression equation, one can measure the slope and intercepts for various equations by minimizing the number of absolute errors asymmetrically distributed. In this way, one has information about the presence of linear trends for other levels of the distribution of the data.

The significance of the slope is computed through bootstrap to highlight its effective significance level ɑ equal to 5% in metering. The regression analysis (effectiveness of smart split metering) *F= (a, b, c, d, e, f, g, h and i)* details some of the factors that support the effectiveness of smart split metering for the utility and customers.
Where: *F* is a binary logit function, *a* = age, *b* = gender, *c* = ethnic group, *d* = education level, *e* = period of service, *f* = respondent response to investing in smart split meters has a positive impact on energy losses and revenue recovery, *g* = respondent response to the information given by smart split meters has made it easier to manage energy consumption and have a monthly budget and *h* = respondent response to the issue of unpaid bills has been reduced as the customers pay for their electricity upfront and *i* = respondent response that the traveling expenses have been cut, there is no physical disconnection or re-connection of power supply as the smart meter automatically cuts or reconnects the customer where necessary.

Furthermore, using the responses to the collected questionnaire, this was analyzed using the logistic regression model. For this model, the dependent variable is the respondent affirmation of the effectiveness of smart split metering for the utility and customers to be significant. Table 3.3 presents descriptions and summary statistics of the independent variables (determinant factors) hypothesized to influence people's support for a smart split meter for improved electricity service delivery.

Table 3. 3 Research Variable Definitions

Independent Variable	**Dependent Variables**
The impact brought by the smart metering system to the utility and customer	Age
	Gender
	Educational Level
	Period of service
	Investing in the smart prepaid split meter has a positive impact on energy losses and revenue recovery.
	The information given by smart prepaid meters has made it easier to manage energy consumption and have a monthly budget.
	The issue of unpaid bills has been reduced as the customers pay for their electricity upfront.
	The traveling expenses have been cut, and there is no physical disconnection or re-connection of power supply as the smart meter automatically cuts or reconnects the customer where necessary.

The research method for objective two was meant to investigate the effectiveness of smart split metering for the utility and customers. This objective was achieved through MFA and FA response analyses from the questionnaire survey. Furthermore, the test for the null Hypothesis to the respondent response that affirmed the effectiveness of smart split metering in the utility and customers was ascertained through the use of the t-test, chi-square and one-way MANOVA test.

Table 3. 4 Summary of Section Scoring Pattern

		Strongly Disagree		Disagree		Neutral		Agree		Strongly Agree		Chi-Square
Statement Description		**Count**	**Row N %**	**Count**	**Row N %**	**Count**	**Row N %**	**Count**	**Row N %**	**Count**	**Row N %**	**p-value**
B2.1 Investing in the smart prepaid split meter has a positive impact on energy losses and revenue recovery.	B2.4.1	2	0.6%	15	4.6%	92	28.1%	136	41.6%	82	25.1%	0.000
B2.2 The information given by smart prepaid meters has made it easier to manage energy consumption and have a monthly budget.	B2.4.2	3	0.9%	17	5.2%	11	3.4%	130	39.8%	166	50.8%	0.000
B2.3 The issue of unpaid bills has been reduced as the customers pay for their electricity upfront.	B2.4.3	5	1.5%	24	7.3%	59	18.0%	171	52.3%	68	20.8%	0.000
B2.4 The traveling expenses have been cut, there is no physical disconnection or re-connection of power supply as the smart meter remotely cuts or reconnects the customer where necessary.	B2.4.4	7	2.1%	31	9.5%	79	24.2%	147	45.0%	63	19.3%	0.000

Research Objective three was meant to analyze the technical performance of both MV and LV power distribution networks before and after smart split metering roll-out. This objective was achieved through applying statistical tools on both the collected network performance data and responses from the questionnaire. The stationarity assumption test was first examined in the collected MV data, followed by change-point analysis, and trend fitting the time series to know how it varies with time. The Mann-Kendall test was enough to examine the increase or decrease impact after the rollout of the smart prepaid spilt meter, detail result was presented in Chapter Four.

Model testing and performance evaluation- Multi-Linear regression was used to find the value of the dependent (technical viability of smart metering system) and independent variable (factors responsible for its effective usages). Thereafter, a Multi-collinearity test was conducted to assess if there is a high correlation between the independent variables. Multi-collinearity is assessed by examining the Tolerance and Variance Inflation Factor (VIF). The value of the Tolerance should be 0.1 and the value of VIF is expected to be below 10. The coefficient of correlation (CC) and root mean square error (RMSE) are used for performance evaluation measures during testing and validation. They are defined as in the following equations:

$$CC = \frac{\sum_{i=n}^{n}\left[\left(Q_i - \bar{Q}_i\right)\left(P_i - \bar{P}_i\right)\right]}{\sqrt{\sum_{i=1}^{n}\left(Q_i - \bar{Q}_i\right)^2 x \sum_{i=1}^{n}\left(P_i - \bar{P}_i\right)^2}} \tag{5}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Q_i - P_i\right)^2} \tag{6}$$

Where: Q_i is the observed value at a time i, P_i, is the simulated value at time i and $\dot{P}$ is the mean for the observed values. Observed run-off is used for model calibration and validation. Correlations are useful for indicating a predictive relationship that can be exploited in practice. Best statistical model fitting was applied for Diepkloof LV and MV network performance actual data. Using exponential, Holt-Winter and moving average trend to model Diepkloof to determine the best fit statistical model to predict the MV Network performance data (2015-2019), the result of the best-fit appropriate model of the time series of interest, especially when dealing with annual trend measurement is illustrated in Figures 3.3 to 3.6.

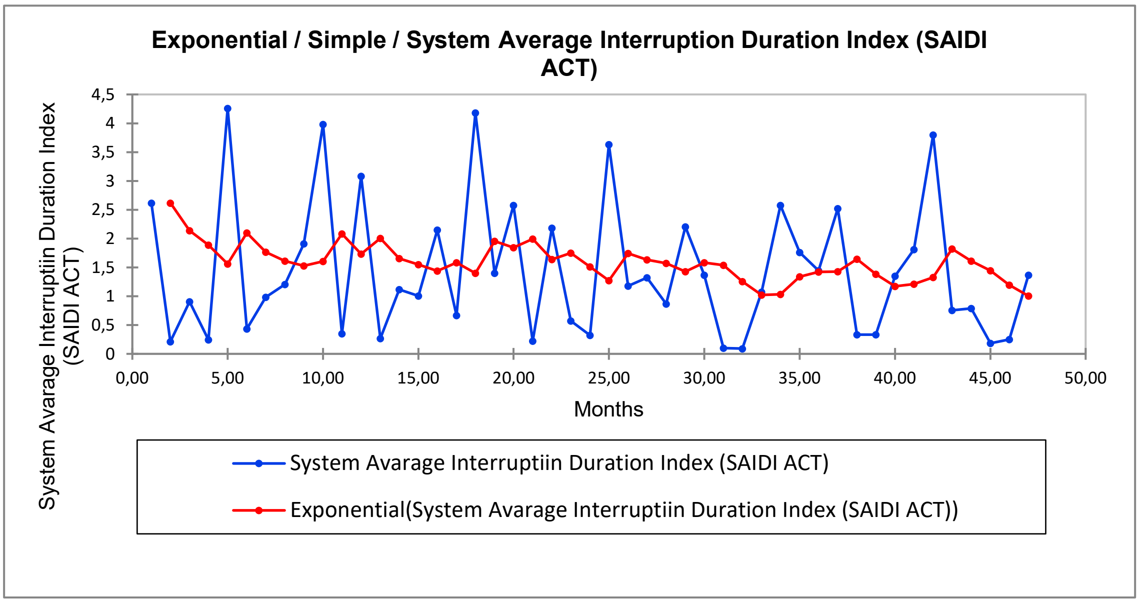


Figure 3. 1 Exponential / Simple / System Average Interruption Duration Index (SAIDI ACT)

Figure 3. 2 Exponential Model of Network Performance Data

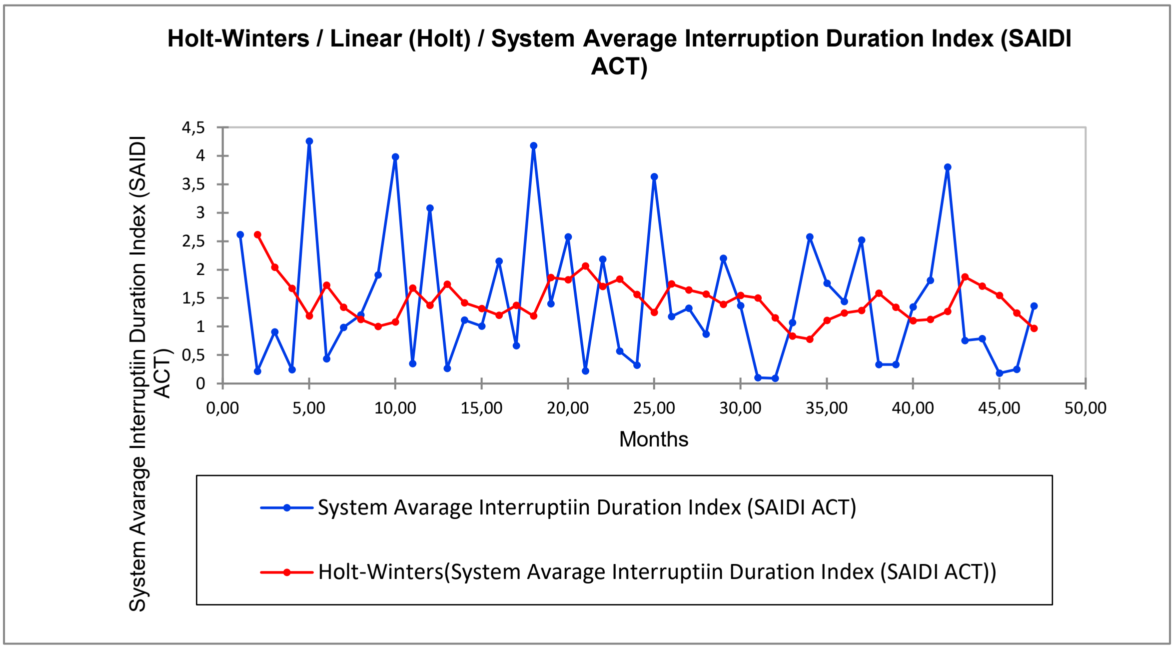


Figure 3. 3 Holt-Winters System Average Interruption Duration Index (SAIDI ACT)

Figure 3. 4 Holt-Winters Model of Network Performance Data

Table 3. 4 Summary of Best Statistical Model fitting for LV and MV Network Performance Data

Statistic	**MV Value**	**Exponential Value**	**Holt Value**
Observations	47	47.000	47
DF	47	46.000	43
SSE	52.706	79.225	79.017
MSE	1.121	1.722	1.838
RMSE	1.059	1.312	1.356
MAPE	151.792	234.401	205.268
MPE	-121.697	-203.518	-166.748
MAE	0.866	1.099	1.090
R^2	0.179		

From the above tables 3.5, CC and RMSE with the lowest value depict the best model fitting. Thus, MV network performance data fitting proved to be a very important fitting for analyzing time-series datasets. They depict the degree to which the measurement of the residual error taken at time *(t)* is correlated to the measurements that were taken at time *t-k.*

Research Objective four was meant to analyze the effectiveness of smart prepaid split metering for revenue collections. The responses from the questionnaire and collected revenue records were used for this analysis. Using Test Hypothesis, respondent responses affirmed the effectiveness of smart prepaid split metering for revenue collections. The t-test, chi-square and One -way ANOVA test were employed to determine the level of significance either to accept or reject the null hypothesis.

Chapter Four

Data Analysis, Results, and Discussion

4.0 Introduction

This chapter presents the results and discussion of findings obtained from the questionnaires and historical data collected for the study. The data collected from the responses were analyzed with SPSS version 26.0 and Microsoft Excel 2016. The results of the pre-data analysis and each of the objectives inferences are presented in the form of graphs, figures and cross-tabulations for visualization while the implication of analyzed information collected from respondents was expressed as percentage frequencies to facilitate its description and inferences.

4.1 The Research Instrument

The research instrument comprised of 22 items with a level of measurement at a nominal or an ordinal level. The questionnaire was divided into 2 sections with 5 questions which measured various subjects as illustrated in Table 4.1 below:

Table 4. 1 Research measured variables

A1	Biographical data
B2.1	Smart meters for smart grid development
B2.2	Technical benefits of smart metering on Eskom distribution networks
B2.3	Challenges created by smart metering transformation to the utility and customers
B2.4	The financial impact brought by the smart metering system to the utility and customers

4.2 Statistical Reliability

Reliability is the most important feature of data accuracy. In this study, reliability is determined by taking multiple measurements on the same subjects. For a newly developed instrument, a reliability coefficient of 0.60 or higher is considered as acceptable. Table 4.2 below represents the Cronbach's alpha score for all the items that established the questionnaire.

Table 4. 2 Questionnaire Sections and Description Reliability Summary

Section	Section Description	Number of Items	Cronbach's Alpha
B2.1	Smart meters for smart grid development	3	0.736
B2.2	Technical benefits of smart metering on Eskom distribution networks	5	0.853
B2.3	Challenges created by smart metering transformation to the utility and customers	4	0.669
B2.4	The financial impact brought by the smart metering system to the utility and customer	4	0.634

The results from table 4.2 above entail that reliability scores for all sections exceed the recommended Cronbach's alpha value of 0.600 for a newly developed construct. This indicates a degree of acceptable, consistent scoring for these sections of the research.

4.3 Data Analysis

4.3.1 Demographic Profile of the Study Area

One of the key inputs of the socio-demographic profile of the study area includes; age distribution, gender, race, level of their education distribution, level of awareness and period of smart prepaid split meter usage and service provided by Eskom distribution networks. This section summarizes the biographical characteristics of the respondents. Table 4.3 below illustrates the overall customer gender distribution by age.

Table 4. 3 Gender Distribution by Age

Age		Gender		Total
		Female	Male	
< 25	Count	2	2	4
	% within Age	50.0%	50.0%	100.0%
	% within Gender	1.0%	1.6%	1.2%
	% of Total	0.6%	0.6%	1.2%
26 - 30	Count	17	14	31
	% within Age	54.8%	45.2%	100.0%
	% within Gender	8.2%	11.0%	9.3%
	% of Total	5.1%	4.2%	9.3%
31 - 35	Count	29	18	47
	% within Age	61.7%	38.3%	100.0%
	% within Gender	14.0%	14.2%	14.1%
	% of Total	8.7%	5.4%	14.1%
36 - 40	Count	35	27	62
	% within Age	56.5%	43.5%	100.0%
	% within Gender	16.9%	21.3%	18.6%
	% of Total	10.5%	8.1%	18.6%
41 - 45	Count	31	24	55
	% within Age	56.4%	43.6%	100.0%
	% within Gender	15.0%	18.9%	16.5%
	% of Total	9.3%	7.2%	16.5%
46 - 50	Count	24	15	39
	% within Age	61.5%	38.5%	100.0%
	% within Gender	11.6%	11.8%	11.7%
	% of Total	7.2%	4.5%	11.7%
51 - 55	Count	25	7	32
	% within Age	78.1%	21.9%	100.0%
	% within Gender	12.1%	5.5%	9.6%
	% of Total	7.5%	2.1%	9.6%
56 - 60	Count	19	5	24
	% within Age	79.2%	20.8%	100.0%
	% within Gender	9.2%	3.9%	7.2%
	% of Total	5.7%	1.5%	7.2%
> 60	Count	25	15	40
	% within Age	62.5%	37.5%	100.0%
	% within Gender	12.1%	11.8%	12.0%
	% of Total	7.5%	4.5%	12.0%
Total	Count	207	127	334
	% within Age	62.0%	38.0%	100.0%
	% within Gender	100.0%	100.0%	100.0%
	% of Total	62.0%	38.0%	100.0%

The customer respondents' gender distribution by age displayed in the table above shows that 207 (62%) were female and 127 (38%) were male respondents. Since the customers were chosen randomly in the Diepkloof area, the results imply that female customers were more co-operative than the male customers who were requested to fill the questionnaires. The overall ratio of males to females is 2:3 (38.0%: 62.0%), which gives a p-value of 0.001. This indicated that the study gender is significant ($p < 0.001$). More respondents were within the age category of 36 to 40 years, with 10.5% female and 8.1% male. Within the category of 46 to 50 years, more males were co-operative, with 38.5% (age) and 11.8% (gender), which formed 4.5% of the total sample. For this study, there are significantly more respondents younger than 50 years old, which gives $p < 0.001$.

4.3.2 Sample Racial Composition

Figure 4.1 summarizes the racial groups of participants. The overall population of the Diepkloof area is 95067, with Africans occupying 87% of the population and other races constituting 13%. The results from the sample show that the African race group was more co-operative with 65.5% and the remaining race groups being almost equally divided. The p-value was found to be less than 0.001.

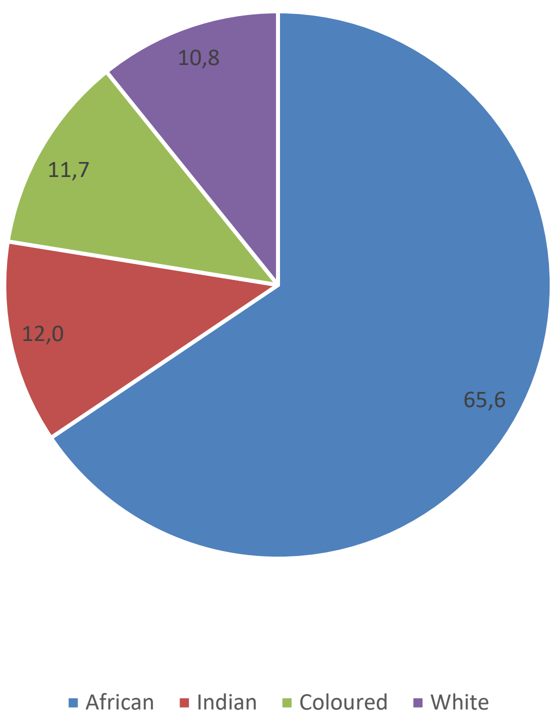


Figure 4. 1 Racial Composition of the Sample

4.3.3 Educational Level

Figure 4.2 shows that 75.0% of the customer respondents had a post-school qualification, while a little less than 30.5% had a diploma: with approximately a quarter (26.6%) having a degree level of education. This statistic indicates that a fair proportion of the respondents have higher qualifications and that the responses gathered were from informed sources who understand the research subject.

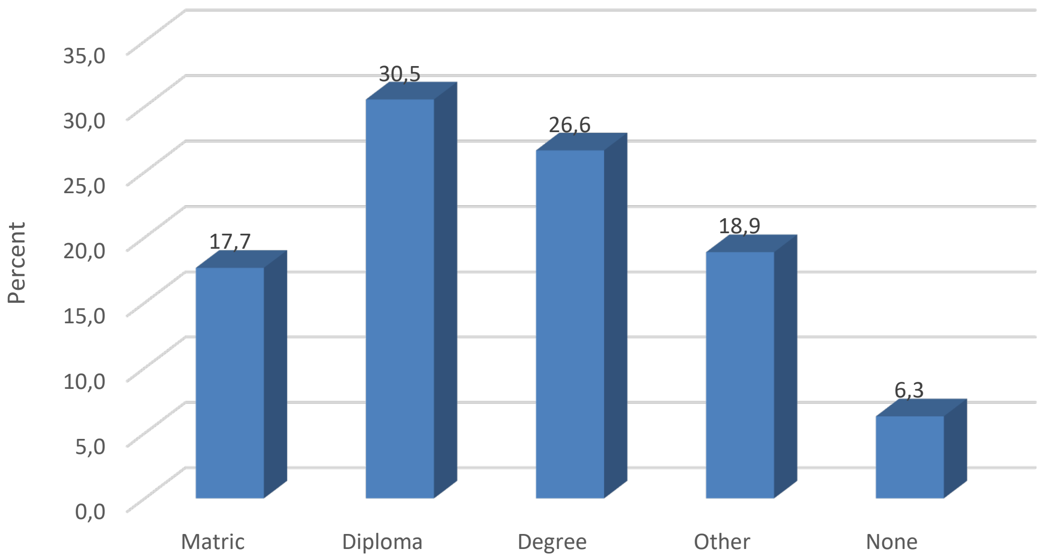


Figure 4. 2 Education Level of Respondents

4.3.4 Smart Split Meter Period of Service

In total, 334 were questionnaires were returned which gave a 92 % response rate. In this rate, 7 respondents were not aware of the new smart prepaid split meter system and they were eliminated from the technical analysis, but included in the biographical data analyses. The results show that 66.0% of the respondents have the installation of smart prepaid split meters for more than 2 years with, 34 % having the installation for less than 2 years. This implies that more respondents have been using these meters for a while which is a useful fact as it indicates responses from experienced users.

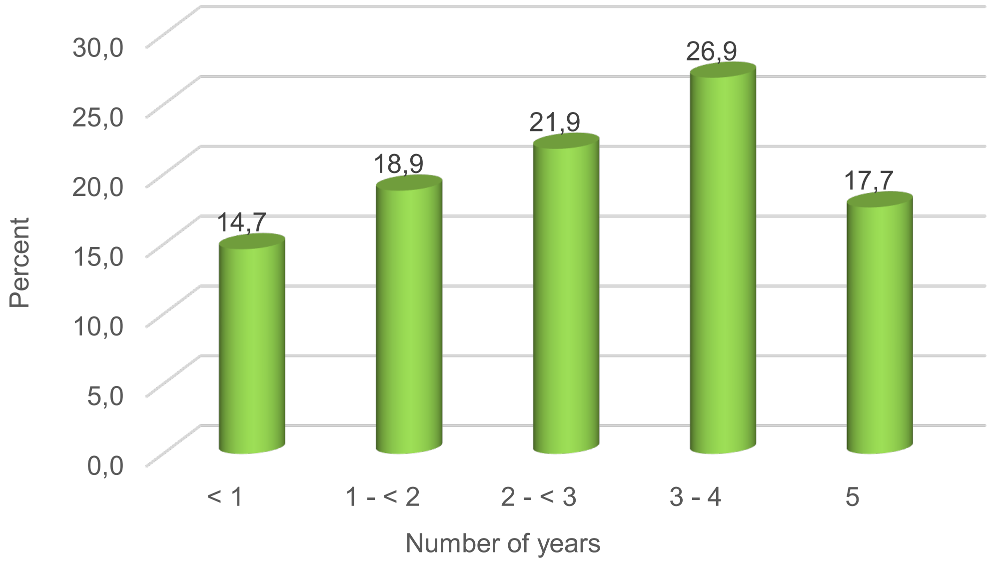


Figure 4. 3 Smart Prepaid Split Meter Length of Service

4.4 Cross-tabulations

To test cross-tabulations between statements, a second chi-square test was used. A chi-square statistic tests how expectations correlate with the actual data or model results observed. The null hypothesis implies that the two are not associated. The alternative hypothesis implies that there is an association. Table 4.4 summaries the results of the chi-square tests that were performed to determine whether there was a statistically significant relationship between the variables (rows vs columns).

Table 4. 4 Summary of the Demographics - Factor and Variable Chi-Square Tests

Variables	Tests	Age	Gender	Ethnic Group	Edu. Level	Period of service
The technics used for smart prepaid split meters communication has improved the grid operation.	Chi-square	23.056	4.347	13.835	20.778	21.991
	df	32	4	12	16	16
	Sig.	0.877	0.361	0.311	0.187	0.143
The smart prepaid metering system has solved the problem with the reliability of power supply	Chi-square	40.50	0.481	21.921	14.336	22.170
	df	32	4	12	16	16
	Sig.	0.144	0.975	.038*	0.574	0.138
Monitoring of power outage for grid control has been improved after smart meter installation	Chi-square	33.031	4.189	15.608	14.856	13.905
	df	32	4	12	16	16
	Sig.	0.417	0.381	0.21	0.535	0.606
Measurement accuracy for customer billing has been increased as the consumption data of energy meter is not recorded manually.	Chi-square	34.554	7.860	11.765	19.633	11.366
	df	32	4	12	16	16
	Sig.	0.347	0.097	0.465	0.237	0.786
The two-way communication between individual meters and Eskom centre’s eliminates the necessity of site visits for manual meter reading, minimize human labour and this is economical to Eskom operations.	Chi-square	39.204	8.188	19.199	19.584	10.589
	df	32	4	12	16	16
	Sig.	0.178	0.085	0.084	0.24	0.834
The immediately tampering reported by smart prepaid split meters to a central control system reduces the energy losses and improves energy efficiency.	Chi-square	45.192	10.143	20.621	15.108	20.388
	df	32	4	12	16	16
	Sig.	0.061	.038	0.056	0.517	0.203
The transformer load on the LV network is accessible and overload is	Chi-square	52.747	6.549	17.883	11.184	20.099

remotely detected and easy to deal with.						
	df	32	4	12	16	16
	Sig.	.012	0.162	0.119	0.798	0.216
I am satisfied with the technology used in smart prepaid meters for energy consumption management.	Chi-square	46.984	8.753	16.641	13.192	18.215
	df	32	4	12	16	16
	Sig.	.043	0.068	0.164	0.659	0.311
Smart prepaid split meter training for technical officials is costly.	Chi-square	32.969	2.012	17.664	13.742	13.066
	df	32	4	12	16	
						16
	Sig.	0.42	0.734	0.126	0.618	0.668
It is difficult to understand the operation of the smart meter as the customer.	Chi-square	23.505	6.083	51.257	10.772	14.933
	df	32	4	12	16	16
	Sig.	0.862	0.193	.000	0.823	0.53
The costs of monthly electricity bills have been increased after smart prepaid split meter installation.	Chi-square	27.035	3.966	17.063	9.712	15.016
	df	32	4	12	16	16
	Sig.	0.716	0.411	0.147	0.881	0.523
When the smart meter is faulty on-site, the faulty finding is possible without contacting the Eskom control center.	Chi-square	36.539	2.107	24.733	32.746	17.108
	df	32	4	12	16	16
	Sig.	0.266	0.716	.016*	.008	0.379
Investing in the smart prepaid split meter has a positive impact on energy losses and revenue recovery.	Chi-square	26.725	4.121	14.853	22.765	16.225
	df	32	4	12	16	16
	Sig.	0.731	0.39	0.25	0.12	0.437
The information given by smart prepaid meters has made it easier to manage energy consumption and have a monthly budget.	Chi-square	30.652	2.293	22.650	17.897	13.355
	df	32	4	12	16	16
	Sig.	0.535	0.682	.031	0.33	0.647
The issue of unpaid bills has been reduced as the	Chi-square	46.526	2.297	6.536	11.768	15.563

customers pay for their electricity upfront.						
	df	32	4	12	16	16
	Sig.	.047	0.681	0.887	0.76	0.484
The traveling expenses have been cut, there is no physical disconnection or re-connection of power supply as the smart meter remotely cuts or reconnect the customer where necessary.	Chi-square	32.318	2.158	23.045	12.984	14.346
	df	32	4	12	16	16
	Sig.	0.451	0.707	.027	0.674	0.573

Using the chi-square cross-tabulation helps to know which variables contribute to model the technical and financial viability benefit of smart split meters on the Eskom power distribution system. For each of these variables, the value in the column marked sig. (p-value) was checked. This indicated whether this predictor made a statistically significant contribution to the effectiveness of smart split usage. The implication is that this variable makes the strongest unique contribution to explaining the dependent variable, which is explained by the other variables that control the model. In this case, for example, the correlation value between the ethnic group and smart split metering system has solved the problem with the reliability of power supply is 0.38. This implies a significant relationship between the two variables.

This section of the study explores the demographic factor to model the technical and financial effectiveness of smart split meters usage on the Eskom electric power distribution system. The section uses the multiple regression model (predictors - demographic) to depict the relationship between the effective usage of smart meters and determine the influence of its usage. Table 4.5 shows the statistical summary of the collected data on smart meter usage, while Table 4.6 shows the values of the model predictor parameters.

Table 4. 5 Mean and Standard Deviation of the Demographic Variables

Summary	Count	Sum	Average	Variance
	10.00	269.07	26.91	1228.34
A	5.00	59.58	11.92	47.84
G	5.00	261.98	52.40	172.11
EG	5.00	165.00	33.00	868.81
Edu.L	5.00	100.00	20.00	87.51
PS	5.00	100.00	20.00	21.71
MF	5.00	297.90	59.58	2753.77
OF	5.00	100.00	20.00	251.22
OC	5.00	100.00	20.00	599.73
IMER	5.00	100.00	20.00	292.89
MEM	5.00	100.00	20.00	549.18

From Table 4.6 below, the probability value for the statistic test (0.48) is less than 2.63 critical (5% level significance), which indicates that the model is adequate. This means that the contribution of the predictors significantly contribute together to predict the effectiveness of smart split meter usage for NTL reduction and revenue collecting to warrant its continuous coverage demand.

Table 4. 6 Summary of the Model Predictor Parameters

ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F-crit**
Rows	1146.68	4.00	286.67	0.48	0.75	2.63
Columns	11296.00	9.00	1255.11	2.11	0.05	2.15
Error	21432.37	36.00	595.34			
Total	33875.04	49.00				

As a further measure of the strength of the model fit, Table 4.7 depicts the demographic factor variables correlation matrix for smart meters. The multiple correlation coefficient, R represent, between the observed factors and the model predicted values of the dependent variable. The cross-correlation coefficients stipulate similarities in the mechanisms that cause a phenomenon to be established amongst the various variables.

Table 4. 7 Statistical Summary of the Correlations Matrix

	Age	**Gender**	**Eth. Group**	**Edu. Level**	**Period of service**	**B2.2.1**	**B2.2.2**	**B2.2.3**	**B2.2.5**
Age	**1**	-0.784	-0.278	-0.365	0.460	0.681	0.546	0.548	0.674
Gender	-0.784	**1**	0.290	0.541	-0.248	-0.583	-0.344	-0.380	-0.577
Ethnic Group	-0.278	0.290	**1**	-0.472	-0.464	-0.156	-0.330	-0.357	-0.159
Edu. Level	-0.365	0.541	-0.472	**1**	0.212	-0.397	-0.067	-0.025	-0.394
Period of service	0.460	-0.248	-0.464	0.212	**1**	0.788	0.924	0.971	0.800
B2.2.1	0.681	-0.583	-0.156	-0.397	0.788	**1**	0.838	0.894	0.999
B2.2.2	0.546	-0.344	-0.330	-0.067	0.924	0.838	**1**	0.966	0.859
B2.2.3	0.548	-0.380	-0.357	-0.025	0.971	0.894	0.966	**1**	0.908
B2.2.5	0.674	-0.577	-0.159	-0.394	0.800	0.999	0.859	0.908	**1**

For R^2, values greater than 0.5 are deemed appropriate for the determination coefficient. The correlation coefficient results are mostly above 0.5 except Gender, Ethnic Group and Educational Level, which are of a negative value (and less than 0.5), which implies that the variable does not contribute to the explanation of the dependent variable. Therefore, modeling the technical analysis of smart prepaid split meters on the Eskom electric power distribution network to depict whether it has effectively aided the power utilities and effective usage is based on a questionnaire survey.

Multiple regression analysis was used to obtain a model of smart prepaid split meter usage for the study area. The regression equation is:

$$Y = A_0 + A_1X_1 + A_2X_2 + A_3X_3 + A_nX_n + E \tag{7}$$

Where Y is a dependent variable: A_1, A_2, A_3, *to* A_n are coefficients of regression while X_1 to X_n are auxiliary variables and E is Standard error. The questionnaire for this section of the survey contained the different purposes that smart split meter was used for: either reducing the NTL, effectively aiding the power utilities to fulfill the reliability of power supply easily and to monitor and manage power flow automatically. The total number of samples considered for this analysis was 327 (number of households). A linear regression multiple regression model is formulated in Table 4.8. The regression equation is presented as follows:

$$Y = -39.9818 - 0.352xEL + 1.24233xPOS + 0.7525xB2.21 - 0.0499xB2.2.2 \qquad (8)$$

Table 4. 8 Parameters of Model Regression

Source	δ Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Intercept	-39.982	0.000			-39.982	-39.982
Age	0.000	0.000	0.300	0.003	0.000	0.000
Gender	0.000	0.000	0.002		0.000	0.000
Ethnic Group	0.000	0.000	0.267		0.000	0.000
Educational Level	-0.352	0.000	0.003		-0.352	-0.352
Period of service	1.242	0.000	0.001		1.242	1.242
B2.2.1	0.752	0.000	0.234		0.752	0.752
B2.2.2	-0.050	0.000	0.234		-0.050	-0.050
B2.2.3	0.000	0.000				

For each of these variables, the value in the column marked sig. (p > value) was checked. This showed whether this predictor made a statistically significant contribution to effective smart meter usage. This depends on which variables are included in the equation. In general, if p-values are less than 0.05, the variables made a significant contribution to the prediction of effective smart meter usage. For values greater than 0.05, variables did not make a significant contribution to the prediction of effective smart meter usage. In this case, respondents as, gender and Education made statistically significant contributions to the prediction for smart split meter usage. The δ value for B2.2.3 (The two-way communication between individual meters and Eskom centres eliminates the need for site visits) was 000 and made the least contribution. Table 4.10 is the residual Type III Sum of Squares Analysis (B2.2.5):

Table 4. 9 Type Three Sum of Squares Analysis

Source	DF	Sum of squares	Mean squares	F	Pr > F
Age	1	0.000	0.000	0.000	1.000
Gender	1	0.000	0.000	0.000	1.000
Ethnic Group	1	0.000	0.000	0.000	1.000
Educational Level	1	16.129	16.129	0.000	1.000
Period of service	1	14.081	14.081	0.000	1.000
B2.2.1	1	196.637	196.637	0.000	1.000
B2.2.2	1	1.009	1.009		
B2.2.3	0	0.000			

Figure 4.4 shows the Standardized coefficients (B2.2.3) error of the variables used for fitting the regression equation, while Table 4.9 shows the summary of the model fitting performance determination predictor statistics. Figure 4.5 shows the smart meter demand linear regression for the standardized coefficient and depicts the educational level, while B.2.2.3 has a positive effect and the rest are of negative significance. In Figure 4.5, the ordinary least square of the pooled regression indicates the educational level as the independent variable. The result shows a negative relationship between age, gender, period of service and B2.2.1. The rate of literacy is also negatively influenced by gender. The result confirms that a unit increase in demographic factors leads to an increase in the effective smart meter demand. The r-squared shows that the result has a good fitness of 95%.

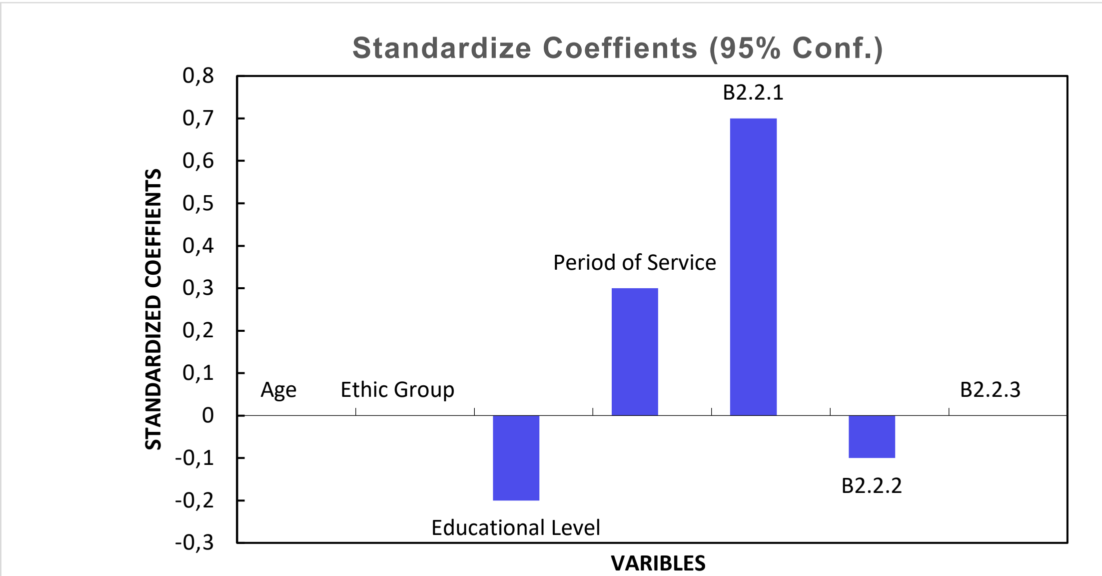


Figure 4. 4 Smart Split Meter Linear Regression for Standardized Coefficient

4.5 Results Discussion

Given the p-value of the F statistic computed in the ANOVA table (Table 4.6) and given the significance level of 5%, the information brought by the explanatory variables is significantly better than what a basic mean would bring. Additionally, based on the Type III sum of squares (Table 4.9), the following variables do not bring significant information to explain the variability of the dependent variable B2.2.5: Age, Ethnic Group, Period of service, B2.2.1. Among the explanatory variables, based on the Type III sum of squares, the variable Age is the most influential. The questionnaire for this section of the survey contained the different purposes that split prepaid split meters were used for: either reducing energy losses, effectively aid the power utilities to fulfil the power demand easily or automatically controlling and managing power flows.

The result shows that a higher education level gives the respondent greater confidence in their option of using smart metering. This shows how education is a powerful force to rectify an erroneous world outlook and promote a rational causal attribution that is fundamental to nurture a spirit of self-worth and a realistic assessment of the value of one’s adaptation measures.

4.6 Test for model fitting

Table 4. 10 Coefficient of statistical performance

R^2	1.000
Adjusted R^2	1.000
MSE	0.000
RMSE	0.000
MAPE	0.000

Based on the analysis, R^2 and *RMSE* shows satisfactory performance to account for steady revenue and effectiveness of smart split meters as income for the Eskom service provided.

Table 4. 11 Correlation matrix for the multicollinearity of the four independent variables

B2.4.1	Investing in the smart prepaid split meter has a positive impact on energy losses and revenue recovery.
B2.4.2	The information given by smart prepaid meters has made it easier to manage energy consumption and have a monthly budget.
B2.4.3	The issue of unpaid bills has been reduced as the customers pay for their electricity upfront.
B2.4.4	The traveling expenses have been cut, and there is no physical disconnection or re-connection of power supply as the smart meter remotely cuts or reconnect the customer where necessary.

The results in Figures 4.6 and 4.7 indicate that there is no multi-collinearity issue found in all presented variables because the value of Tolerance for each variable is above 0.1 and VIF is below 10. The MFA and regression analysis of Diepkloof Extension 48 Months (Energy Losses Data) help energy lost measurement, utilities satisfaction and customer effective billing. Table 4.13 shows the multi-collinearity of 4 independent variables.

Table 4. 12 Correlation Matrix Results

Correlation matrix:				
Variables	B2.4.1	B2.4.2	B2.4.3	B2.4.4
B2.4.1	**1**	0.652	0.920	0.962
B2.4.2	0.652	**1**	0.669	0.586
B2.4.3	0.920	0.669	**1**	0.979
B2.4.4	0.962	0.586	0.979	**1**

Table 4. 13 Multicollinearity Statistics Results

Multi-collinearity statistics:				
Statistic	B2.4.1	B2.4.2	B2.4.3	B2.4.4
R^2	0.982	0.876	0.992	0.996
Tolerance	0.018	0.124	0.008	0.004
VIF	56.317	8.088	126.879	259.475

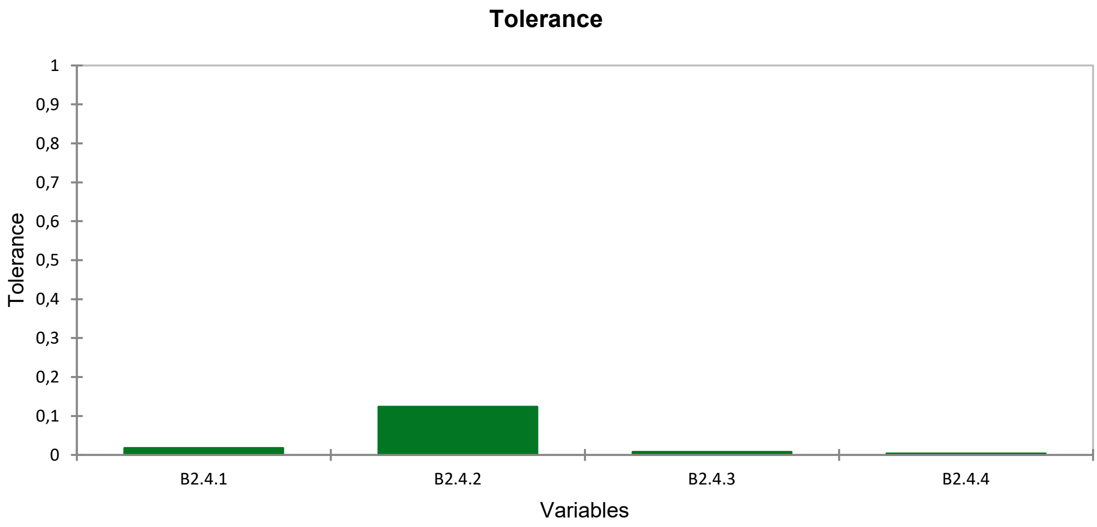


Figure 4. 5 Tolerance Results of Variables

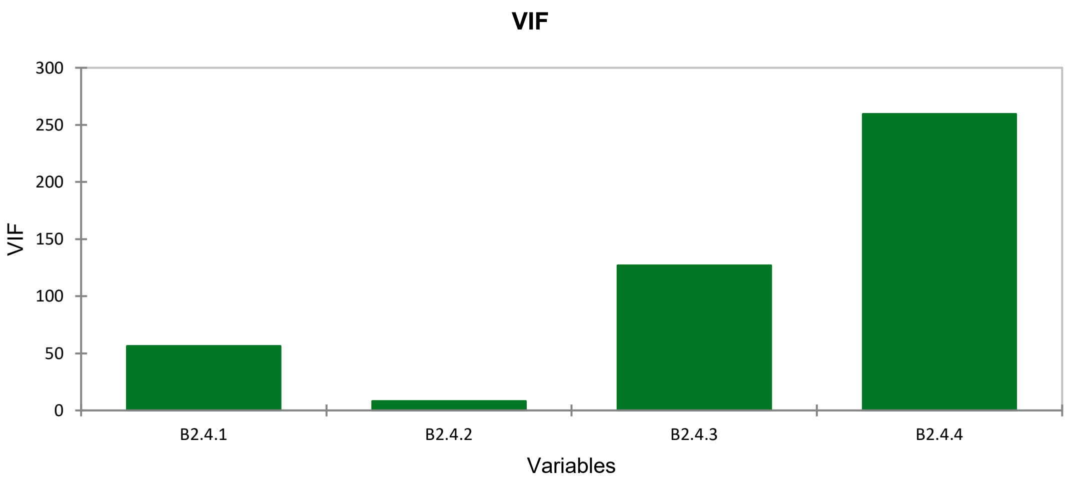


Figure 4. 6 VIF Results of Variables

4.7 The Multi-Factor Analysis

Factor analysis is a statistical technique whose main goal is data reduction. The typical factor analysis was used to represent a number of questions with a small number of hypothetical factors. It reduces attribute space from a larger number of variables to a smaller number of factors through its principal component analysis. The Principal Component Analysis (PCA) as a choice of MFA explains the contribution of the unobserved common features in a target event from observed ones. They can be combined to create a new variable.

In this section of the study, Kaiser Meyer Olkin (KMO) and Bartlett's Test were used to abstract the factor analysis for the primary data collected. This test measures the strength of the relationship amongst the variables. The KMO determines if the responses given with the sample are adequate or not, thus the result from this test should be 0.5 or more for satisfactory factor analysis to proceed. Bartlett's Test is another indication of the strength of the relationship amongst the subject variables. This tests the null hypothesis that the correlation matrix is an identity matrix, hence the result from this test should be 0.05 or less for satisfactory factor analysis to proceed as presented in Table 4.14 below.

Table 4. 14 KMO and Bartlett's Tests Results

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.801
Bartlett's Test of Sphericity	Approx. Chi-Square	1598.350
	df	120
	Sig.	0.000

Table 4.14 above shows two tests which indicate the suitability of data for structure detection. The Kaiser-Meyer-Olkin Measure of Sampling Adequacy indicates the proportion of variance in data variables that might be caused by underlying factors. High values close to 1.0 indicate that a factor analysis is useful with your data. If the value is less than 0.50, the results of the factor analysis is not useful. Bartlett's test tests the correlation matrix which indicate that variables are related or unrelated and indicates the possibility of structure detection. Small values less than 0.05 of the significance level indicate that a factor analysis is useful with data [81]

In all instances for this data, the conditions are satisfied which allows for further factor analysis procedures. The Kaiser-Meyer-Olkin Measure of Sampling Adequacy value is 0.801 which is greater than 0.5 and the Bartlett's Test of Sphericity significant value is 0.000, which is less than 0.05.

4.7.1 Factor Analysis Rotated Component Matrix

Factor analysis is done only for the Likert scale items. This is explained in the rotated component matrix. The Factor Analysis (FA) from PCA established the structural relationship between the effectiveness of smart prepaid meters and factor response for its usage. It helps to understand what the data (latent class) underlies, as shown in Table 4.15. The bold squared co-sine values depict the most significant variables that affect the effective use of smart prepaid split meters based on the questionnaire survey. Based on the pre-screening of the data using P_{CA}, the data were classified into four main components, namely P_{C1}, P_{C2}, P_{C3} and P_{C4}.

Table 4. 15 Rotated Component Matrix

Rotated Component Matrix				
	Component			
	1	2	3	4
The technics used for smart prepaid split meters communication has improved the grid operation.	0.283	0.033	**0.737**	0.030
The smart prepaid metering system has solved the problem with the reliability of power supply	0.210	0.037	**0.779**	0.117
Monitoring of power outage for grid control has been improved after smart meter installation	0.391	-0.074	**0.625**	0.067
Measurement accuracy for customer billing has been increased as the consumption data of energy meter is not recorded manually.	**0.760**	0.051	0.080	0.033
The two-way communication between individual meters and Eskom centre's eliminates the necessity of site visits for manual meter reading, minimize human labour and this is economical to Eskom operations.	**0.824**	0.050	0.256	0.029
The immediately tampering reported by smart prepaid split meters to a central control system reduces the energy losses and improves energy efficiency.	**0.789**	-0.016	0.296	0.015
The transformer load on the LV network is accessible and overload is remotely detected and easy to deal with.	**0.670**	0.016	0.314	0.035
I am satisfied with the technology used in smart prepaid meters for energy consumption management.	**0.767**	0.037	0.050	0.078
Smart prepaid split meter training for technical officials is costly.	0.149	**0.611**	-0.205	-0.022
It is difficult to understand the operation of the smart meter as the customer.	-0.054	**0.770**	0.137	-0.213
The costs of monthly electricity bills have been increased after smart prepaid split meter installation.	-0.108	**0.728**	0.113	-0.153
When the smart meter is faulty on-site, the faulty finding is possible without contacting the Eskom control centre.	0.127	**0.679**	-0.050	0.208

Investing in the smart prepaid split meter has a positive impact on energy losses and revenue recovery.	-0.002	-0.087	0.079	**0.724**
The information given by smart prepaid meters has made it easier to manage energy consumption and have a monthly budget.	0.081	-0.283	-0.140	**0.701**
The issue of unpaid bills has been reduced as the customers pay for their electricity upfront.	0.045	-0.091	0.356	**0.602**
The traveling expenses have been cut, there is no physical disconnection or re-connection of power supply as the smart meter remotely cuts or reconnect the customer where necessary.	0.049	0.230	0.045	**0.676**
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.				
a. Rotation converged in 5 iterations.				

With reference to the table above:

The principal component analysis was used as the extraction method, and the rotation method was Varimax with Kaiser Normalization. This is an orthogonal rotation method that minimizes the number of variables that have high loadings on each factor and it simplifies the interpretation of the factors.

i. Factor analysis or loading shows inter-correlations between variables.
ii. Items of questions that loaded similarly imply measurement along with a similar factor.
iii. An examination of the content of items loading at or above 0.5 (and using the higher or highest loading in instances where items cross-loaded at greater than this value) effectively measured along with the various components.

4.7.2 Factor Analysis Results and Discussion

Table 4.14 depicts the P_{CA}'s most significant variables that affect the effective usage of smart prepaid split meter usage, while the FA predictors results in Table 4.14 relate to the unsuspected relationships and the revenue generated. The result in Table 4.15 shows that positive values indicate a directly proportional relationship between the variables, and a negative value indicates an inverse relationship. P_{C1} is a more significant component than, P_{C2}, P_{C3} and P_{C4} respectively. Using the corresponding factors loading value, the scores on P_{C1} can be computed as in equation 7 below, while the scores on P_{C2} can also be estimated as in equation 8. Similar to other P_{C3} and P_{C4}

$$P_{C1} = 0.760xA + 0.824xB + 0.789xC + 0.789xD + 0.670xE + 0.767xF \quad (9)$$

$$P_{C2} = 0.611xG + 0.770xH + 0.728xI + 0.728xJ + 0.679xK \quad (10)$$

$$P_{C3} = 0.737xL + 0.779xM + 0.625xN \quad (11)$$

$$P_{C4} = 0.724xO + 0.701xP + 0.602xQ + 0.676xR \quad (12)$$

It can be observed that factor loading explains most of the variability associated with the variables. This implies that the statements that constituted these sections perfectly measured what they set out to measure.

4.8 Sections Analysis

This part of the chapter analyses the scoring patterns of the respondents per subject variable in each section. The results are first presented using summarized percentages for the variables that constitute each section, the results are then further analyzed according to the importance of the statements. To determine whether the scoring patterns per statement were significantly different per option, a chi-square test was done. The null hypothesis claims that similar numbers of respondents scored across each option for each statement (one statement at a time). The alternate states that there is a significant difference between the levels of each section statement.

4.8.1 Section B2.1

This section deals with smart prepaid split meters for smart grid development. Table 4.16 below summaries the scoring patterns for the subject variables

Table 4. 16 Smart Meters for Smart Grid Development

Section Statements		**Strongly Disagree**		**Disagree**		**Neutral**		**Agree**		**Strongly Agree**		**Chi-Square**
Tests		Count	Row N %	Count	Row N %	Count	Row N %	Count	Row N %	Count	Row N %	p-value
The technics used for smart prepaid split meters communication has improved the grid operation.	B2.1.1	5	1.5%	36	11.0%	66	20.2%	202	61.8%	18	5.5%	0
Smart prepaid metering system has solved the problem with reliability of power supply	B2.1.2	8	2.4%	47	14.4%	93	28.4%	156	47.7%	23	7.0%	0
Monitoring of power outage for grid control has been improved after smart meter installation	B2.1.3	4	1.2%	53	16.3%	74	22.7%	173	53.1%	22	6.7%	0

This results from the table above summarizes the respondents' views on smart grid performance with the use of smart prepaid split meters technology for electric power distribution networks. The significant values (p-values) are less than 0.05 for the level of significance, which implies that the distributions were not similar and that there is a significant difference between the ways in which respondents scored agree, neutral, and disagree in the questionnaire.

Graphical Representation of Smart Meters for Smart Grid Development

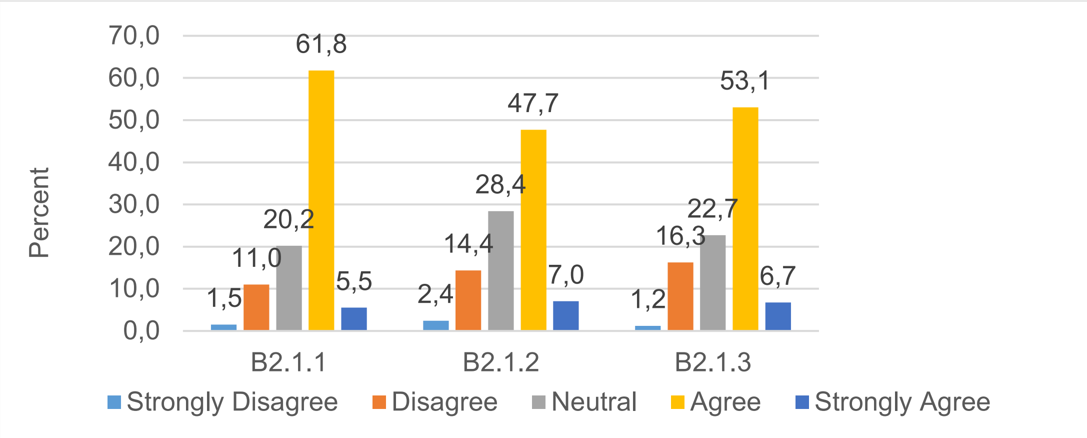


Figure 4. 7 Scoring Patterns Results of Smart Meters for Smart Grid Development

The above Figure results show that some statements have significantly higher levels of agreement whilst other levels of agreement are lower but still greater than levels of disagreement. There are no statements with higher levels of disagreement. The significance of the differences is tested using the p-value and is shown in Table 4.16. The patterns of scoring per statement are almost similar, which indicates that respondents viewed the section in a similar manner, implying that the application of smart prepaid split meters to the smart grid played an increasingly important role in the improved efficiency of electricity consumption and grids operation. Electrical power networks with smart meter technology implementation support and provide for multiple interpretation points of intelligence grid for power transmission from supply sources to consumption with monitoring capabilities.

4.7.1 Section B2.2

This section deals with the technical benefits of smart metering on Eskom's distribution networks.

Table 4.17 below summarizes the scoring patterns for the subject variables.

Table 4. 17 Technical Benefits of Smart Metering on Eskom Distribution Networks

Section Statements		**Strongly Disagree**		**Disagree**		**Neutral**		**Agree**		**Strongly Agree**		**Chi-Square**
Tests		Count	Row N %	Count	Row N %	Count	Row N %	Count	Row N %	Count	Row N %	p-value
Measurement accuracy for customer billing has been increased as the consumption data of energy meter is not recorded manually.	B2.2.1	3	0.9%	29	8.9%	46	14.1%	153	46.8%	96	29.4%	0.000
The two-way communication between individual meters and Eskom centre's eliminates the necessity of site visits for manual meter reading, minimize human labour and this is economical to Eskom operations.	B2.2.2	7	2.1%	23	7.0%	99	30.3%	135	41.3%	63	19.3%	0.000
The immediately tampering reported by smart prepaid split meters to a central control system reduces the energy losses and improves energy efficiency.	B2.2.3	6	1.8%	34	10.4%	80	24.5%	152	46.5%	55	16.8%	0.000
The transformer load on the LV network is accessible and overload is remotely detected and easy to deal with.	B2.2.4	14	4.3%	49	15.0%	94	28.7%	123	37.6%	47	14.4%	0.000
I am satisfied with the technology used in smart prepaid meters for energy consumption management.	B2.2.5	2	0.6%	23	7.0%	49	15.0%	158	48.3%	95	29.1%	0.000

This result summarizes the respondents' views on the technical benefits of the smart metering system on power distribution networks. The significant values (p-values) are less than 0.05 for the level of significance. This implies that the distributions were not similar and the differences between the way respondents scored agree, neutral, disagree were significant.

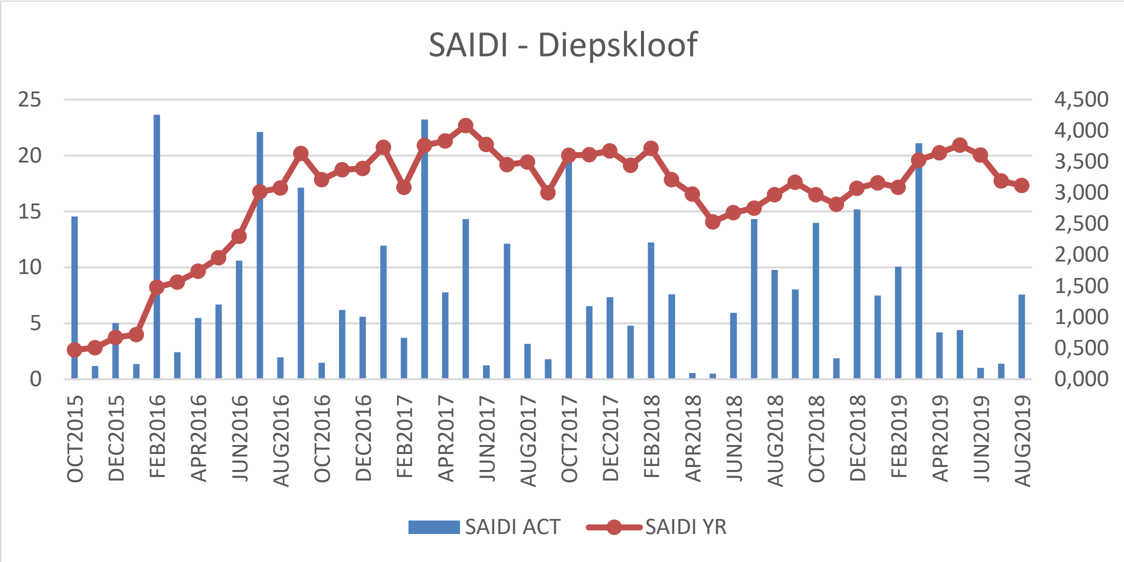


Figure 4. 8 Actual Reliability Measures of Before and After Smart Prepaid Split Meter

This section was used to analyze the technical performance of both MV and LV power distribution networks before and after a smart prepaid split metering roll-out. This analysis was done through statistical tools of change-point analysis, and trend visualization, as shown above in Figure 4.8. The point in the graph at which one detects the impact of the smart prepaid split metering roll-out was in October 2016 where the slope was not rapidly increasing but started to be linear. Likewise, the availability of highly skewed and kurtortic distributions in Table 4.18 of the MV and LV power distribution data analysis has helped depict the effectiveness of smart prepaid meter introduction in billing and revenue collection.

Table 4. 18 Skewed and kurtortic distributions results

Statistic	**Data**	**Parameters**
Mean	-0.459	-0.459
Variance	11.569	11.513
Skewness (Pearson)	-6.098	0.000
Kurtosis (Pearson)	42.060	0.000

Table 4. 19 Summary of Kolmogorov-Smirnov test Results

Kolmogorov-Smirnov test:	
D	0.444
p-value (Two-tailed)	< 0.0001
alpha	0.05
Test interpretation:	
H0: The sample follows a Normal distribution	
Ha: The sample does not follow a Normal distribution	
As the computed p-value is lower than the significance level alpha=0.05, one should reject the null hypothesis H0, and accept the alternative hypothesis Ha.	

The above independence and normality table of the residuals evaluated by visual inspection of the plots and the Kolmogorov-Smirnov test shows that the sample does not follow a normal distribution. Table 4.20 and Figure 4.10 depict the Mann-Kendall trend test and the Sen's slope plot for the MV network performance Data (2015-2019)

Table 4. 20 Summary of Mann Kendall's tau Test Results

Kendall's tau	-0.050
S	-54.000
Var(S)	5403.722
p-value (Two-tailed)	0.471
alpha	0.05
An approximation has been used to compute the p-value.	
H0: There is no trend in the series	
Ha: There is a trend in the series	
As the computed p-value is greater than the significance level p=0.05, one cannot reject the null hypothesis	

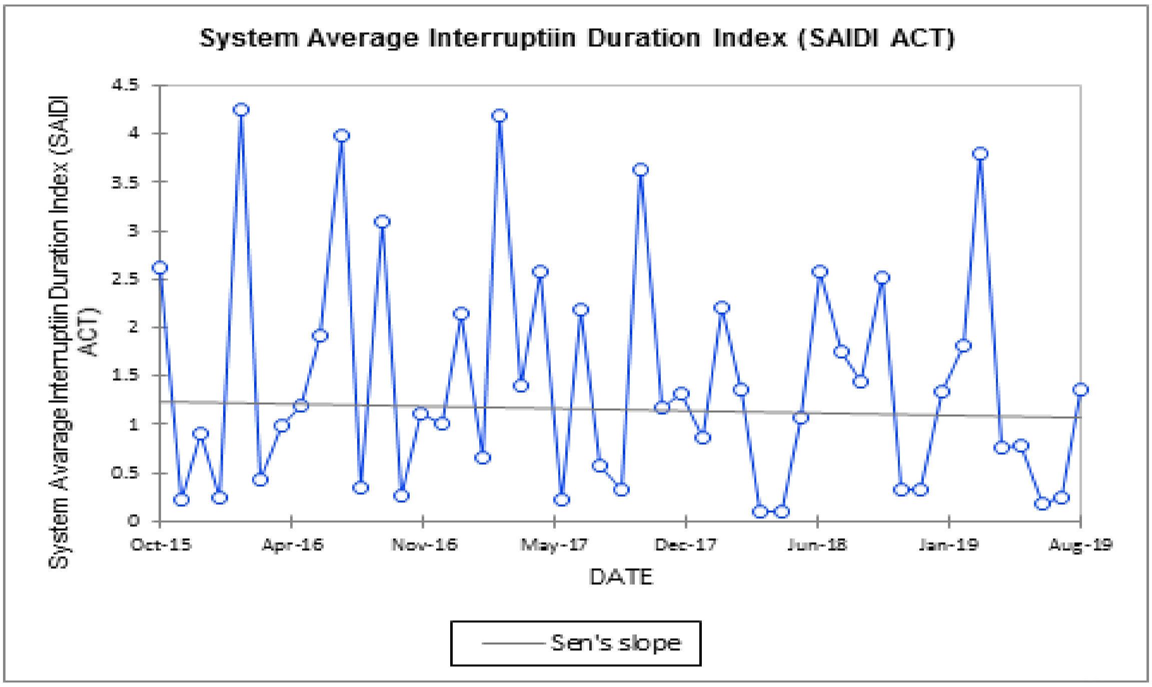


Figure 4. 9 Sen's Slope Plot of The System Average Interruption Duration Index (SAIDI ACT)

Table 4. 21 Results of Pettitt's Test System Average Interruption Duration Index (SAIDI ACT)

Pettitt's test (System Average Interruption Duration Index (SAIDI ACT)):	
K	98.000
t	Mar-19
p-value (Two-tailed)	0.242
alpha	0.05
The p-value has been computed using 10000 Monte Carlo simulations. Time elapsed: 0s.	
99% confidence interval on the p-value:	
Test interpretation:	
H0: Data are homogeneous	
Ha: There is a date at which there is a change in the data	
As the computed p-value is greater than the significance level alpha=0.05, one cannot reject the null hypothesis H0.	

The autocorrelation function (ACF) and the partial autocorrelation function (PACF) have proven to be two very important concepts in analyzing time series. They show the degree to which a measurement taken at time *t* is correlated to the measurements taken at time *t-k*.

Autocorrelation at lag *k* is the correlation between a measurement *X (t)* taken at time *t* and a measurement *X (t-k)* taken at time *t-k*. The KPSS test stationarity is depicted in Table 4.22.

Table 4. 22 Results KPSS test (Level System Average Interruption Duration Index (SAIDI ACT)

KPSS test (Level / Lag Short / System Average Interruption Duration Index (SAIDI ACT)):	
Eta (Observed value)	0.128
Eta (Critical value)	0.455
p-value (one-tailed)	0.498
alpha	0.05
H0: The series is stationary.	
Ha: The series is not stationary.	
Summary:	
Series\Test	
System Avarage Interruptiin Duration Index (SAIDI ACT)	
As the computed p-value is greater than the significance level alpha=0.05, one cannot reject the null hypothesis H0	

The table shows that a measurement *X (t)* taken at a given time *t* is positively correlated to the previous measurement (lag = 1) and to the measurement just before (lag = 2). Likewise, the figure depicts that a measurement *X (t)* is negatively correlated to the measurement taken six months before and positively correlated to the measurement taken 12 months before. Partial autocorrelation at lag k is the correlation between a measurement *X (t)* taken at time t and a measurement *X (t-k)* taken at time *t-k*, but which eliminates the effect of all measurements taken between *t* and *t-k*.

Graphical representation of technical benefits of smart prepaid split metering on Eskom distribution networks

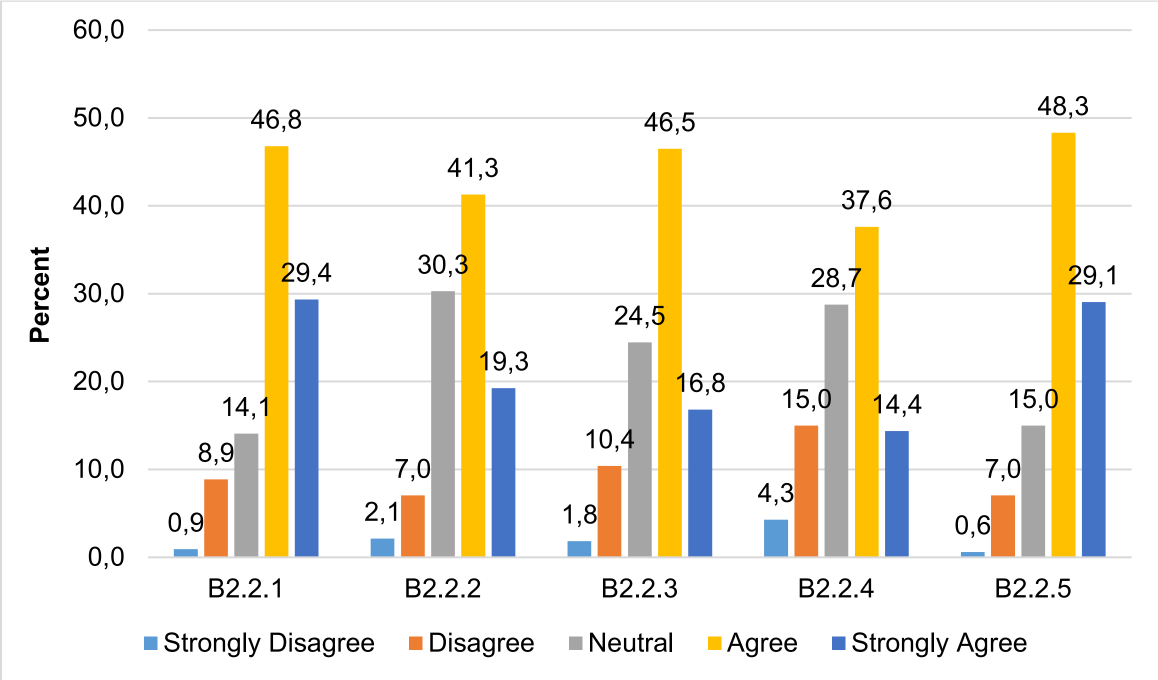


Figure 4. 10 Scoring Patterns Results of Technical Benefits of Smart Prepaid Split Metering

The above graphical representation results show that some statements have significantly higher levels of agreement, whilst other levels of agreement are lower but still greater than levels of disagreement. There are more neutral scores in this section. The level of significance of the differences is tested and shown in Table 4.17. The patterns of scoring per statement are not similar, which indicates that respondents did not view the section in a similar way. This implies that customers agreed that the implementation of smart meters through smart grid solution enables the electricity network to bring additional benefits to customers through the improved quality of the power supply more, accurate billing and better management of power consumption.

4.8.2 Section B2.3

This section deals with challenges created by smart metering transformation to the utility and customers. Table 4.23 below summarizes the scoring patterns for the subject variables.

Table 4. 23 Challenges Created by Smart Metering Transformation to the Utility and Customers

		Strongly Disagree		Disagree		Neutral		Agree		Strongly Agree		Chi-Square
		Count	Row N %	Count	Row N %	Count	Row N %	Count	Row N %	Count	Row N %	p-value
Smart prepaid split meter training for technical officials is costly.	B2.3.1	10	3.1%	99	30.3%	122	37.3%	85	26.0%	11	3.4%	0.000
It is difficult to understand the operation of the smart meter as the customer.	B2.3.2	18	5.5%	202	61.8%	18	5.5%	73	22.3%	16	4.9%	0.000
The cost of monthly electricity bills has been increased after a smart prepaid split meter installation.	B2.3.3	16	4.9%	135	41.3%	109	33.3%	59	18.0%	8	2.4%	0.000
When the smart meter is faulty on-site, the faulty finding is possible without contacting the Eskom control centre.	B2.3.4	41	12.5%	130	39.8%	85	26.0%	55	16.8%	16	4.9%	0.000

This result from the table above summarizes the respondents' views on the technical benefits of the smart metering system for power distribution networks. The significant values (p-values) are less than 0.05 for the level of significance, which implies that the distributions were not similar and the differences between the way respondents scored agree, neutral, disagree were significant.

Graphical representation of Challenges created by smart metering transformation to the utility and customers

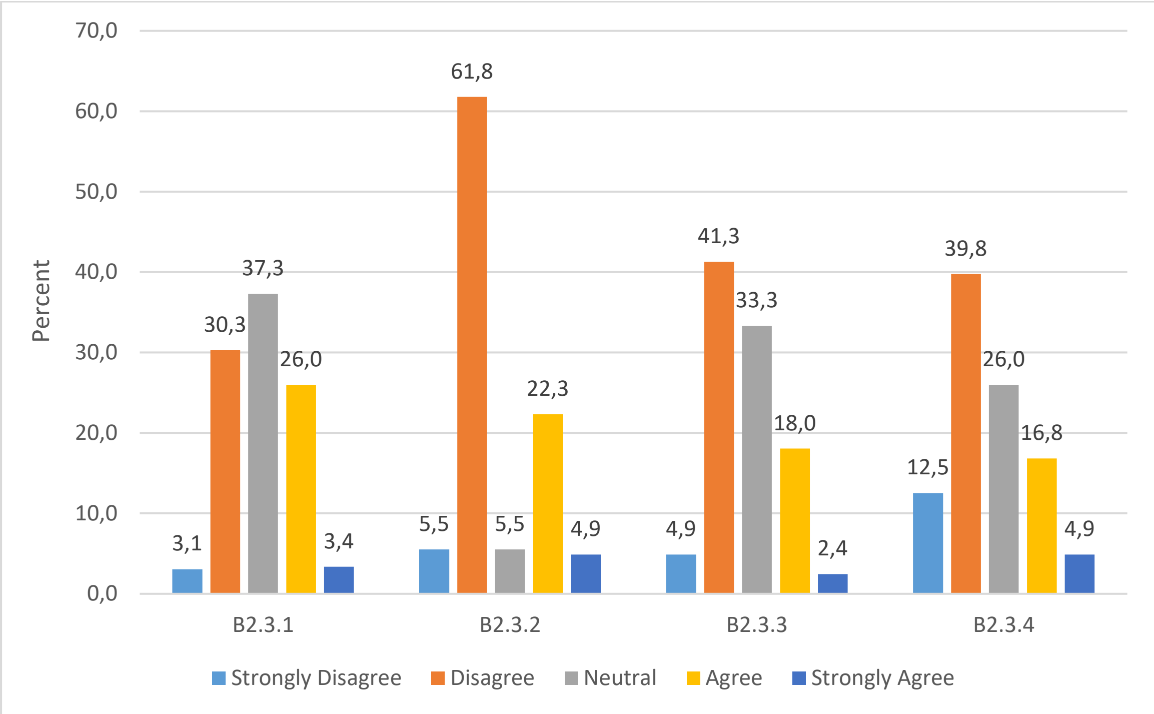


Figure 4. 11 Scoring Patterns Results of Challenges Created by Smart Metering Transformation

The above graphical representation results show that some statements have significantly higher levels of disagreement, whilst other levels of disagreement are lower but still greater than levels of agreement. However, there are more neutral scores in this section. The level of significance of the differences is tested and shown in Table 4.23. The patterns of scoring per statement are almost similar, which indicates that respondents did view some sections in a similar way. Moreover, this section also has more neutral scores which implies that customers and the utility experienced challenges during the transforming. Customers were used to consuming electricity for free with tampered meters. However with split meters, they have to pay upfront to have access to electricity consumption and at the early roll-out of smart meter implementation, they were unable to easily adapt to buying electricity. The technology is new to customers they are at the learning stage, currently it is not easy for customers to perfectly understand the technical operation of these meters hence Eskom has the necessity to conduct awareness to customers and minimize costs for technical officials to be dispatched to the field for faulty connections that can easily be dealt with.

4.8.3 Section B2.4

This section deals with the financial impact brought by the smart metering system to the utility and customers. Table 4.24 below summaries the scoring patterns for the subject variables.

Table 4. 24 Financial Impact Brought by the Smart Metering System to the Utility and Customers

		Strongly Disagree		**Disagree**		**Neutral**		**Agree**		**Strongly Agree**		**Chi-Square**
		Count	Row N %	Count	Row N %	Count	Row N %	Count	Row N %	Count	Row N %	p-value
Investing in the smart prepaid split meter has a positive impact on energy losses and revenue recovery.	B2.4.1	2	0.6%	15	4.6%	92	28.1%	136	41.6%	82	25.1%	0
The information given by smart prepaid meters has made it easier to manage energy consumption and have a monthly budget.	B2.4.2	3	0.9%	17	5.2%	11	3.4%	130	39.8%	166	50.8%	0
The issue of unpaid bills has been reduced as the customers pay for their electricity upfront.	B2.4.3	5	1.5%	24	7.3%	59	18.0%	171	52.3%	68	20.8%	0
The traveling expenses have been cut, there is no physical disconnection or re-connection of power supply as the smart meters remotely cut or reconnects the customer where necessary.	B2.4.4	7	2.1%	31	9.5%	79	24.2%	147	45.0%	63	19.3%	0

The table above summarizes the respondents' views on impact brought by the smart metering system to the utility and customers. The significant values (p-values) are less than 0.05 for all the segmented question levels. This implies that the distributions were similarly significant and the differences between the way respondents scored agree, neutral and disagree were significant.

Graphical representation of financial impact brought by the smart metering system to the utility and customers

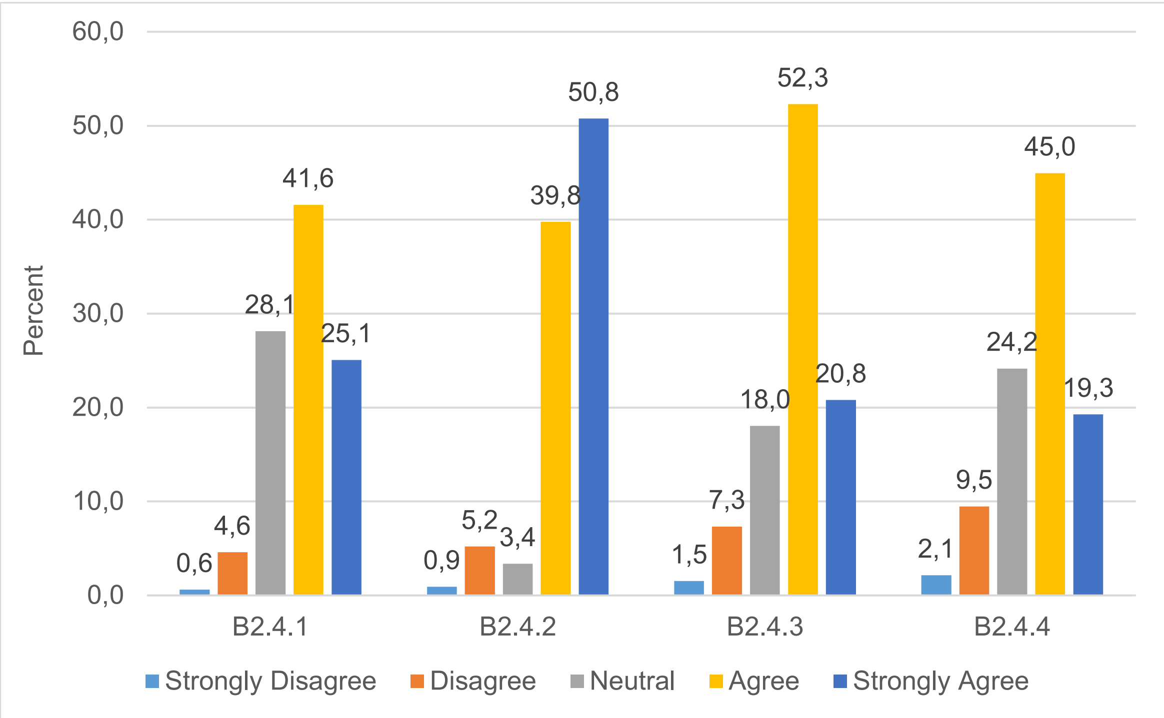


Figure 4. 12 Scoring Patterns Results of financial impact brought by the smart metering system to the utility and customers

The above Figure shows that some statements have significantly higher levels of agreement whilst other levels of disagreement and neutral are high but still lower than levels of agreement. The level of significance of the differences is tested and shown in Table 4.24. The patterns of scoring per statement are different from section to section, which indicates that respondents viewed the section on different levels. For smart grid enhancement, smart meter technology plays a critical role in distribution network improvement, however, it is costly for the utility to introduce more network communication systems rapidly. Smart prepaid split meters have a positive impact in Eskom as it reduces traveling costs for manual meter readings, and it provides the utility with the ability to access power flow data at any intervals, minimizing the unpaid bills as the customer pay upfront before consuming power.

For customers with the meter installed for the past few years, they are empowered with the ability to monitor their consumption, with no power disconnections as a result of unpaid bills.

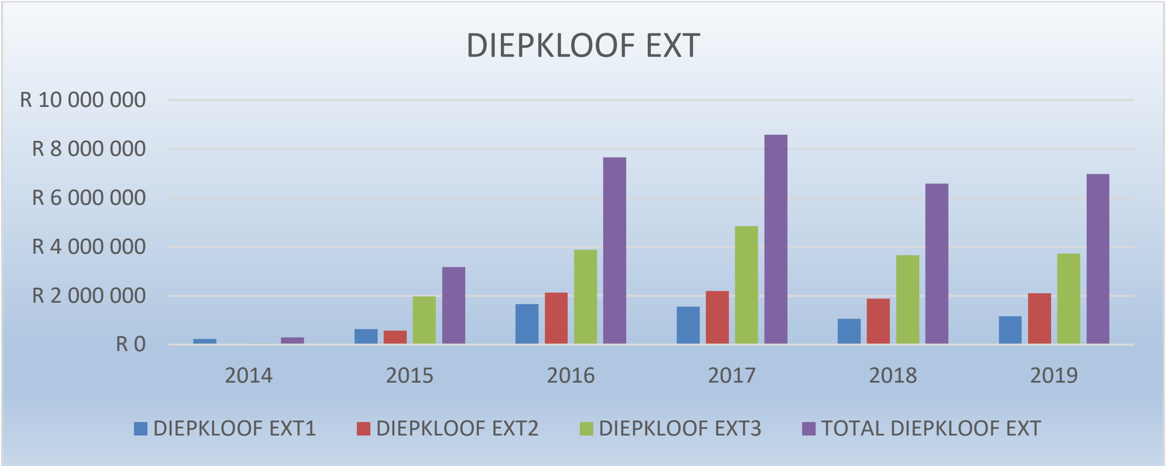


Figure 4. 13 Financial Analysis of Smart Prepaid Split Meters for Each Diepkloof Section. on Eskom Electric Power Distribution Network

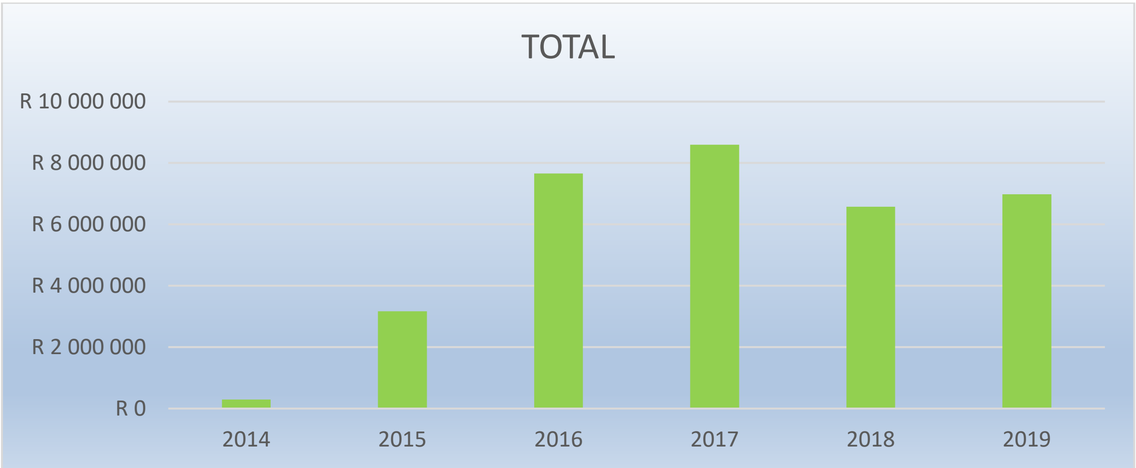


Figure 4. 14 Total Financial Analysis of Smart Prepaid Split Meters for Diepkloof Area

Furthermore, the financial impact brought by the smart metering system to the utility and customers was also analyzed based on the revenue collection data analysis. As shown in Figures 4.14 and 4.15, the visual trend shows a significant increase in revenue collections from the year 2016 compared to the years prior to the introduction of smart prepaid split meters. This has built the confidence that the implementation of smart metering in distribution networks has maximized revenue recovery for this area. This was associated with the implementation of prepaid split meters that is currently at 85% and there was a high possibility of accurate results as the sampling was easier and more effective for low customer base areas with smart meter installations.

4.9 Statement of Findings, Interpretation and Implication of the Results

A multivariate analysis of the impact of independent variables on the effectiveness of smart prepaid split metering for the utility and customer satisfaction was examined. Bio-demography was examined against all technical and financial variables. Certain demographic factors show no statistically significant effect on the effective usage of a smart meter for energy monitoring. Given unequal access to official training services and differences in measures of actual total energy loss, the result shows positive interaction. This depicts that the training and re-training of Eskom officials are vital to maintaining effective usage of smart metering and to the revenue collection.

Although there exists a significant level between gender and non-technical loss, the result might indicate optimistic bias amongst females and educational levels about the successful usage of smart prepaid split metering systems in the area. In all, the respondents affirm the effectiveness of smart prepaid metering for the utility and customers satisfaction. The later insignificant values in Table 4.24 could be attributed to high uncertainty that distorts value judgments, which may be due to theft and damage to electrical infrastructure in ensuring adequate billing and power usage. The correlation value between “Smart prepaid metering system has solved the problem with the reliability of power supply” and “The issue of unpaid bills has been reduced as the customers pay for their electricity upfront” is 0.204.

This is a directly related proportionality, in which respondents indicate that the greater the power reliability due to the smart prepaid meters, the more the issue of unpaid bills has been resolved. Negative values imply an inverse relationship (as one increases, the other decreases), which indicates that the variables have an opposite effect on each other. The correlation value between “I am satisfied with the technology used in smart prepaid meters for energy consumption management” and “The costs of monthly electricity bills have been increased after smart prepaid split meter installation” is -0.011. This is a negative relationship which implies that the more satisfied customers are with the technology, the lower the power costs as they will be able to understand the consumption patterns and be able to manage their bills.

From Table 4.18, the probability value for the F-test statistic (0.000) is less than 0.05 (5% level of significance), which indicates that the model is adequate, i.e. the combination of the predictors significantly come together to predict the effectiveness of smart prepaid split meter usage. The multiple correlation coefficients, (R), are the linear correlations between the observed and the model-predicted values of the dependent variable (Average household smart meter effectiveness). The value of R obtained was 0.641 and R Square was 0.410. This shows that about 41.0% of the variation in Average Household smart prepaid split meter usage is explained by the model. The probability value for the statistic test (0.000) is less than 0.050 (5% level of significance). The demographic educational level factor showed a statistically significant impact of smart pre-paid usage $P < 0.010$) and $P < 0.050$) in utility and customer usage respectively.

The result shows that a higher level of education makes smart meter usage very effective. This shows how education is a powerful force to rectify an erroneous world outlook and promote a rational causal attribution that is fundamental to nurture a spirit of self-worth and a realistic assessment of the value smart technology. Table 4.4 illustrates that age has $P < 0.050$, a statistically significant influence on how smart usage and technical viability imply a better perception of success in demographics. Therefore, arguably, there is better access for education and the extension of services would make one less amenable to religious influence, which would give an individual better causal attribution to smart technology.

Chapter Five

Summary, Conclusion and Recommendations

5.0 Introduction

This chapter presents a summary of the findings, the conclusion as well as the recommendations based on the study.

5.1 Key Research Contributions to Knowledge

This study has examined the technical and financial analysis of smart split meters on Eskom's electric power distribution. The study has offered a quantitative assessment of smart split meter effectiveness for monitoring household energy consumption and provides suggestions for Eskom's financial aggregator's operation section towards the cost-effectiveness of electric demand billing and measurement. The study has also illustrated the SWOT analysis of smart metering technology in modelling household energy consumption in distribution networks. The developed forecasting trend fitting on simulations of electrical energy consumption profiles for customers based on remoted meter reading reliability will be a good tool to monitor MV and LV power distribution networks. The overall results showed the adequacy of multi-variance correlations and factors statistical analysis that might be responsible for developing a modelling framework. The framework used is able to satisfy the technical and financial household requirement for an effective power delivery system and smart meter usage for efficient smart distribution networks control.

5.2 Summary of Findings

The tested hypotheses:-

1. Respondent responses affirmed the severance of non-technical losses in distribution networks before and after smart split metering roll-out to be significant. The t- test, chi-square and Kolmogorov-Smirnov test were employed to determine the level of significance and the null hypothesis was accepted with p-value = 0.00 for the t- test, chi-square and p-value = 0.05 for the Kolmogorov-Smirnov test

which is within than 5%. This indicates that smart metering has solved the problem of unpaid bills and improves the accuracy of data collected for billing purposes.

2. Irrespective of the time period, respondent responses affirmed that smart split metering system usage has a positive/significant level of effectiveness in the utility and for the customer. The t- test , chi-square and One -way ANOVA test was employed to determine the level of significance and the null hypothesis was accepted with p-value= 0.00, which is less than 5% (for null hypothesis to be accepted), indicating that the model for testing is adequate.

3. Respondents affirmed the technical performance of both the MV and LV power distribution networks to be more significant after smart split metering was rolled-out. The t- test and chi-square were employed to determine the level of significance and the null hypothesis was accepted with p-value= 0.00, which is less than 5%.The patterns of scoring per statement were almost similar and this indicates that respondents viewed the section in a similar manner which implies that the application of smart split meters in the smart grids have played an increasingly important role in improving electricity consumption efficiency and network operation.

4. Respondent responses affirmed the implementation of smart split metering has increased revenue collections when comparing before and after smart split meters introduction. The t- test , chi-square and One -way ANOVA test was employed to determine the level of significance and the null hypothesis was accepted with p-value= 0.00, which is less than 5%. Then, the visual trend analysed from historical records shows a significant increase in revenue collections from the year 2016, compared to the years before the introduction of smart split meters. This has built the confidence that the implementation of smart metering in distribution networks has maximized revenue recovery for this area.

A Smart metering quantitative assessment has provided more rapid access to detailed information about energy flows and consumption. The smart metering roll-out has positive impacts on the organization's energy losses. However, some of the challenges are that customers did not fully accept the implementation. They were breaking the new metering infrastructure to gain access and tamper with their smart meters, which caused a delay in finishing up the project. The integration of electrical grid components with smart meter information has improved the network performance (SAIDI) in terms of network technical performance. Revenue collection increased significantly from the year 2015 and slightly dropped in 2018 due to metering infrastructure breaking and tampering attempts.

5.3 Recommendations

According to the above, technical officials responsible for smart metering should be well-trained to ensure that these metering technologies, most of which are still in the early stages of development, can function efficiently. Due to the higher investment and overall life-cycle costs of advanced metering compared to conventional metering, utilities should avoid looking at advanced metering as a quick-fix solution for deep-seated social problems like unwillingness to pay for electricity services.

The use of smart split meters information should be integrated with other information systems such as outage management systems (OMS) and geographic information systems (GIS), which will enable utilities to create detailed outage maps, monitor and minimize SAIDI and SAIFI on MV and LV networks. Thirdly, the use of voltage monitoring integrated with AMI system information provides another promising benefit stream of smart split meter usage. Utilities can use AMI voltage monitoring capabilities to enhance the effectiveness of automated controls for voltage and reactive power management, particularly for conservation voltage reduction (CVR) programs.

5.4 Suggestions for further studies

More efficient communications networks are the backbone of not only a smart grid but smart cities as well. Several sectors adopted long-term, comprehensive smart grid strategies that included building communications networks with large capacities to handle future smart grid applications, and with high bandwidth to accommodate city services beyond electricity metering, such as gas water metering and internet services.

The study advocates, amongst others a study on:

i. The Empirical analysis of smart meter technologies' impact on the future distribution network;
ii. Cost-benefit model for Urban Micro-grids with distributed energy resources;
iii. Modeling the electrical energy consumption profile for residential Buildings; and
iv. Monte Carlo simulations based on automated meter reading reliability;

5.5 Conclusion

From literature review in the study background, it can be concluded that the implementation of smart meters is the better option for improved electrical power security within power utilities, as it empowers the customers to control and manage their daily consumption. The technology used in smart prepaid split meters with intelligent networks assists the power utilities to deal with challenges of energy losses, unpaid electricity bills, and power outage locations.

The research analysis results show smart metering usage as an emerging technology, in which both the utilities and customers lack adequate know-how/ knowledge. More coverage usage and awareness will continue to mature. More so, its benefits will continue to improve customer affinity for its usage and encourage valid official billing, which will make its usage become a more attractive technology. Using smart meters brings numerous benefits for utilities and presents a potential long-term solution to power-related issues faced by utilities.

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Appendices

Mean Values

Descriptive Statistics					
	N	Minimum	Maximum	Mean	Std. Deviation
The technics used for smart prepaid split meters communication has improved the grid operation.	327	1.00	5.00	3.59	0.82
Smart prepaid metering system has solved the problem with reliability of power supply	327	1.00	5.00	3.43	0.91
Monitoring of power outage for grid control has been improved after smart meter installation	326	1.00	5.00	3.48	0.89
Measurement accuracy for customer billing has been increased as the consumption data of energy meter is not recorded manually.	327	1.00	5.00	3.95	0.93
The two way communication between individual meters and Eskom centre's eliminates the necessity of site visits for manual meter reading, minimizing human labour and this economical to Eskom operations.	327	1.00	5.00	3.69	0.93
The immediately tampering reported by smart prepaid split meters to central control system reduces the energy losses and improves energy efficiency.	327	1.00	5.00	3.66	0.94
Transformer load on LV network is accessible and overload is remotely detected and easy to deal with.	327	1.00	5.00	3.43	1.05
I am satisfied with the technology used in smart prepaid meters for energy consumption management.	327	1.00	5.00	3.98	0.88
Smart prepaid split meter training for technical officials is costly.	327	1.00	5.00	2.96	0.91
It is difficult to understand the operation of smart meter as the customer.	327	1.00	5.00	2.59	1.05
The costs of monthly electricity bills has been increased after smart prepaid split meter installation.	327	1.00	5.00	2.72	0.90
When the smart meter is faulty on site, faulty finding is possible without contacting Eskom control centre.	327	1.00	5.00	2.62	1.06
Investing on smart prepaid split meter has positive impact on energy losses and revenue recovery.	327	1.00	5.00	3.86	0.87
The information given by smart prepaid meters has made it easier to manage energy consumption and have monthly budget.	327	1.00	5.00	4.34	0.85
The issue of unpaid bills has been reduced as the customers pay for their electricity upfront.	327	1.00	5.00	3.83	0.89

The travelling expenses has been cut, there is no physical disconnection or re-connection of power supply as the smart meter remotely cuts or reconnect the customer where necessary.	327	1.00	5.00	3.70	0.96

Chi-Square Test

	Chi-Square	df	Asymp. Sig.	Sections
Age	64.156	8	0.000	A1.1
Gender	19.162	1	0.000	A1.2
Ethnic Group	293.281	3	0.000	A1.3
Educational Level	58.455	4	0.000	A1.4
Period of service	14.503	4	0.006	A1.5
Are you familiar with the new meter installation?	908.515	3	0.000	A1.6
The technics used for smart split meters communication has improved the grid operation.	388.673	4	0.000	B2.1.1
The smart split metering system has solved the problem with the reliability of power supply	220.202	4	0.000	B2.1.2
Monitoring of power outage for grid control has been improved after smart meter installation	267.773	4	0.000	B2.1.3
Measurement accuracy for customer billing has been increased as the consumption data of energy meter is not recorded manually.	217.205	4	0.000	B2.2.1
The two-way communication between individual meters and Eskom centre's eliminates the necessity of site visits to read the meter, minimizing human labour and this economical to Eskom operations.	171.058	4	0.000	B2.2.2
The immediately tampering reported by smart split meters to the central control system reduces the energy losses and improves energy efficiency.	188.612	4	0.000	B2.2.3
The transformer load on the LV network is accessible and overload is remotely detected and easy to manage.	112.924	4	0.000	B2.2.4
I am satisfied with the technology used in smart prepaid meters for energy consumption management.	237.572	4	0.000	B2.2.5
Smart split meter training for technical officials is costly.	164.3	4	0.000	B2.3.1
It is difficult to understand the operation of the smart meter as the customer.	392.22	4	0.000	B2.3.2
The costs of monthly electricity bills have been increased after smart prepaid split meter installation.	191.456	4	0.000	B2.3.3
When the smart meter is faulty on-site, faulty finding is possible without contacting the Eskom control centre.	117.755	4	0.000	B2.3.4
Investing in the smart split meter has positive impact on energy losses and revenue recovery.	191.547	4	0.000	B2.4.1
The information given by smart split meters has made it easier to manage energy consumption and have a monthly budget.	359.162	4	0.000	B2.4.2
The issue of unpaid bills has been reduced as the customers pay for their electricity upfront.	253.229	4	0.000	B2.4.3
The travelling expenses have been cut, and there is no physical disconnection or re-connection of power supply as the smart meter remotely cuts or reconnect the customer where necessary.	174.972	4	0.000	B2.4.4

Components Factor Analysis

Component Transformation Matrix				
Component	1	2	3	4
1	0.820	0.039	0.530	0.210
2	0.104	0.039	0.530	0.210
3	-0.227	0.570	-0.003	0.789
4	0.514	0.024	-0.848	0.127
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.				

Questionnaire

A Technical and Financial Analysis of Smart Prepaid Split Meters on Eskom Electric Power Distribution Network

Durban University of Technology, Department of electrical power engineering

Researcher: Sindi Ndaba

For improvement on energy losses, power flow management communication between utility, costumers, and time-wise billing, smart metering was introduced on Eskom distribution networks in 2013. Smart metering involves the installation of an intelligent meter at residential customers and the regular reading, processing, and feedback of consumption data to the customer. Smart prepaid split meters are the upgraded metering devices that are used by developing power utilities for automated measurements and to remotely communicate information for billing customers and operating their electric power system components through control centers. Smart metering contributes to significant improvements on the electrical distribution system by collecting the energy consumption information, monitoring the network performance, and the energy usage characteristics of the load on the grid.

1. **SECTION A: Demography Information**

1.1 Please indicate your age.

Age	**Tick**
Under 25	
26-30	
31-35	
35-40	
41-46	
46-50	
51-55	
56-60	
>60	

1.2 Please indicate your Gender.

Gender	**Tick**
Female	
Male	

1.3 Please indicate your ethnic Group

Race	**Tick**
Black	
Indian	
Coloured	
White	

1.4 Please indicate education Level

Highest education Level	**Tick**
Matric	
Diploma	
Degree	
Others	
None	

1.5 Please indicate your period of service.

Period (Years)	**Tick**
Under 1 year	
1-2	
2-3	
3-4	
5	

1.6 Are you familiar with the new meter installation?

Answer	**Tick**
Yes	
No	

2. SECTION B: Smart Prepaid Split meter system on Distribution Networks

2.1 Smart meters for smart grid development

Please state the level you agree or disagree with the following statements by ticking a number for each question.	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
2.1.1 The technics used for smart prepaid split meters communication has improved the grid operation.	1	2	3	4	5
2.1.2 The smart split metering system has solved the problem with the reliability of power supply.	1	2	3	4	5
2.1.2 Monitoring of power outage for grid control has been improved after smart meter installation.	1	2	3	4	4

2.2 Technical benefits of smart metering on Eskom distribution networks

Please state the level you agree or disagree with the following statements by ticking a number for each question.	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
2.2.1 Measurement accuracy of customer for billing has been increased as the energy meter data is not recorded manually.	1	2	3	4	5
2.2.2 The two-way communication between individual meters and Eskom centre's eliminates the necessity of site visits for manual meter reading, minimize human labour and this is economical to Eskom operations.	1	2	3	4	5
2.2.3 The immediately tampering reported by smart split meters to central control system reduces the energy losses and improves energy efficiency.	1	2	3	4	5
2.2.4 The transformer load on the LV network is accessible, and overload is remotely detected and easy to manage.	1	2	3	4	5
2.2.5 I am satisfied with the technology used in smart prepaid meters for energy consumption management.	1	2	3	4	5

2.3 Challenges created by smart metering transformation to the utility and customers

Please state the level you agree or disagree with the following statements by ticking a number for each question.	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
2.3.1 Smart split meter training for technical officials is costly.	1	2	3	4	5
2.3.2 It is difficult to understand the operation of the smart split meter as the customer.	1	2	3	4	5
2.3.3 The costs of monthly electricity bills have been increased after smart split meter installation.	1	2	3	4	5
2.3.4 When the meter is faulty on-site, it is faulty finding is not possible without contacting the Eskom control centre.	1	2	3	4	5

2.4 The financial impact brought by smart metering system to the utility and customer

Please state the level you agree or disagree with the following statements by ticking a number for each question.	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
2.4.1 Investing in the smart split meter has a positive impact on energy losses and revenue recovery.	1	2	3	4	5
2.4.2 The information given by smart split meters has made it easier to manage energy consumption and have a monthly budget.	1	2	3	4	5
2.4.3 The issue of unpaid bills has been reduced as the customers pay for their electricity upfront.	1	2	3	4	5
2.4.4 The traveling expenses have been cut, and there is no physical disconnection or re-connection of power supply as the smart meter automatically cuts or reconnect the customer where necessary.	1	2	3	4	5

Thank you for your cooperation.