DISTRIBUTION NETWORK PERFORMANCE ANALYSIS WITH HIGH PENETRATION OF RTPV AND BESS

by

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Dedication

To our God and Father:

Be the glory forever and ever.

Amen.

Philippians 4:20

Acknowledgments

Appreciation and thanks to my industrial supervisor, Mr Dayahalan Chetty, for the technical guidance, coding support and thorough review. His visionary leadership has redefined the approach to power system analysis.

Appreciation and thanks to my supervisor, Prof. Innocent E Davidson, for the guided support, encouragement and thorough review.

Appreciation and thanks to the Eskom KZN Network Optimization team for their collective efforts towards achieving the first holistic temporal appraisal analysis, this combined research contributed towards the appraisal overview

Special thanks to my Wife and Son for their support and patience.

Abstract

The consequential effect of meeting electrical demands continues to burden the South African electrical infrastructure. Electrical violations tend to constrain a power system's ability to supply suitable energy whilst meeting growth demands. Often optimization techniques are utilized to reduce violations, however; constrained networks in dense and radial distribution systems don't have any quick or short-term solutions.

This thesis explores solar rooftop photovoltaics (RTPV) and battery energy storage systems (BESS) as a distributed energy resource to alleviate violations which are currently constraining medium voltage (MV) networks.

This research has studied the influential effect of hybrid RTPV systems, with and without BESS. The analysis, simulated with actual all-day load profiles, has uniquely considered RTPV installations for every residential customer connected to an MV network.

For the identification of networks that experience violations; informative analysis-results from over eight hundred MV feeders have been studied. These results have been utilized to develop a methodological approach for a technical priority ranking system. This system helps to categorize the severity of network constraints for distribution networks. By modelling a case study, this thesis demonstrates what impact RTPV will have on a technically violated/constrained MV network.

This thesis offers an alternative network optimization solution by using RTPV and BESS to address constrained/violated networks. This can assist Utilities to meet electrical demands while complying with statutory regulation limits.

Declaration of Publications

The following two publications were derived from this research investigation:

1) Reddy R, Davidson IE, Chetty D. “Evaluation and Impact Assessment of Solar Roof-Top PV on Electric Power Distribution Networks.” In 9th CIGRE Southern Africa Regional Conference, Johannesburg South Africa, Oct. 2019 [1].

2) Davidson IE, Reddy R. “Performance Evaluation of Solar Roof-Top PV on Eskom’s LV Electric Power Distribution Networks.” In 2019 7th International Conference on Smart Grid (icSmartGrid), pp. 97-102. IEEE, 2019 [2].

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List of Abbreviations

AC	Alternating current
BESS	Battery energy storage systems
CSP	Concentrated solar power
DC	Direct current
DER	Distributed energy resources
Dx	Distribution
EG	Embedded generation
ESI	Electrical supply industry
GW	Giga-watts
HV	High voltage
IPP	Independent power producers
kV	Kilo-volts
LSM	Living standards measure
LV	Low voltage
MTL	Master type library
MV	Medium voltage
NB	Network breaker
NERSA	National Energy Regulator of South Africa
NRS	National Regulatory Services
OC	Overcurrent
PV	Photovoltaic
RPP	Renewable power plant
RTPV	Roof-top photovoltaics
SSEG	Small scale embedded generation
Vmin	Minimum voltage

Chapter 1 Introduction

1.1 Background

The drive from the South African government to electrify customers has placed immense demands on South Africa's electric power infrastructure. Several new customers being connected in line with these government targets and plans are often connected to an already constrained network. The consequence of these types of connections has the potential to violate electrical parameters such as thermal loading and voltage regulation as well as increase the overall technical losses of the power delivery network. The electric power utilities' planning solutions to remedy these problems sometimes results in millions of Rands being spent to upgrade infrastructure and this may take many years to come into fruition. In many instances, quick or short-term solutions do not exist. When considering the rise of energy costs and capital expenditure, our South African economy needs sustainable solutions for the future of the Electrical Supply Industry (ESI), renewable energy is that solution!

This simulation-based research study investigates Roof-Top Photovoltaics (RTPV) as a renewable energy resource for reticulation networks in South Africa. This type of technology has the advantage of being easily integrated into existing infrastructure. Based on the National Energy Regulator of South Africa (NERSA) research and analysis, Solar Photovoltaic (PV) have a bigger demand in South Africa at the moment than other renewable technologies [3] [4]. RTPV is neither well documented in present Grid codes nor in ESI standards and guidelines. This paper will demonstrate situations where RTPV is a technical solution to eliminate network constraints.

This research's purpose is to demonstrate that with the introduction of RTPV's on Distribution (Dx) networks, that there is an improvement with voltage regulation, thermal loading and technical losses. This offers the opportunity to electrify more customers, increase sales and defer capital expenditure while reducing our carbon footprint.

1.2 Problem Statement

Reticulation networks feed predominantly residential loads and in most instances have lengthy backbones which in turn supply numerous branches or t-offs along the network. Due to the distribution of current and cumulative impedances along the backbone, the voltage reduces the further away it is from the source substation [5]. Though tap changers control the voltage regulation to a specified voltage set point to regulate the substations medium-voltage (MV) bus-bar, there is however a concern regarding the minimum voltage (Vmin) experienced within a reticulation network. In addition to 'voltage' concerns, there is also a demand placed on electrical networks to further support new electrification connections. This demand in some instances causes a network to exceed the normal operating 'thermal' limits of conductors and transformers.

With the imminent influx of solar RTPV, the results of this study will assist to further equip the South African ESI to understand the need and influence of RTPV within reticulation networks, 11/22 kilo-volts (kV). An objective of this study is to demonstrate to the ESI and customers, what the resultant effects of having RTPV installed at every residential customer within a network are [6].

1.3 Aims and objectives

To quantify the impacts and expectations for the electric power utility and the customer, this study demonstrates the minimum amount of installed RTPV required at each customer to reduce voltage and thermal constraints that might be experienced within reticulation networks [7]. This study is conducted with existing network infrastructure and topology to analyse the installation of RTPV. Objectives for this study include:

- Study the influence of RTPV on Reticulation networks
- Provide a methodological approach for Power System Engineers to model RTPV in MV/reticulation networks
- Showcasing the effect of RTPV to the Power Utility and the Customer

- Use power flow analysis to influence Planning/strengthening projects, by providing RTPV as a solution to deep rural supply applications
- Equipping the ESI for the readiness of RTPV in SA

Customers and Utilities have different expectations of distributed PV [8], this study aims to describe to a Utility the influence of large scale RTPV integration within Medium Voltage (MV) Network Breakers (NB's), and whether it is beneficial as an alternative to traditional planning and design concepts for additional customer connections, customer usage growth and economy growth.

From this research, a Utility can steer engineering personal for the preparation and readiness of RTPV into the local networks, by way of working or study groups to provide strategic planning and implementation. [9].

1.4 Key research questions

This paper showcases and provides results obtained through power system analysis in order to answer some strategic issues relating to Distributed Energy Resources (DER) namely:

- How much distributed generation can be expected in distribution networks to alleviate constraints?
- To what extent can RTPV alleviate…
    - Voltage constraints
    - Thermal constraints
    - Reduce Losses
- What effect will the DG have on the technical performance of the network?
- What effect will the DG have on the financial performance of the utility?

The extent to which RTPV can meet electrification demand requirements, as well as the extent to which RTPV can offset or defer capital strengthening projects will be evaluated.

1.5 Limitations and Delimitations

This thesis has analysed over eight hundred MV/Reticulation networks. Those networks with violations are regarded as priority feeders where technical solutions are required to rectify any shortcomings that have been identified. Data analysis is a fundamental part of any load-flow simulation. However, due to the complexities and changes that revolve around reticulation networks such as; Equipment type changes when upgrading plant or during breakdowns, newly added electrified plant/customers, changes to equipment control set-points, settings and co-ordination changes, etc - some assumptions or limitations need to be taken into account at the time of analysis:

- The networks have been simulated at its normal operational state and free of any abnormalities
- Sending voltages at the substation MV bus bars were simulated by considering the high-voltage (HV) power system
- All acquired topology data utilized for modelling of networks assumed correct
- Any Protection settings utilized from the database assumed to be correct and in-effect onsite
- All loading data that is utilized is assumed to be accurate and comparable to onsite measurements

Two of the major challenges encountered when conducting MV load studies are the lack of data during the acquisition phase and any sudden change to network load or topology. Theft or Illegal connections have a mushroom effect which is often associated with increasing load trends, deviating from forecasts. This creates challenges when trying to operate networks within National Regulatory Services (NRS) specifications.

1.6 Research, methodology and design

This study uses a power simulation package called Power Factory to conduct load flow analysis in-order to operationally manage/analyse electrical networks. Power Factory has the advantage of utilising script/coding to assist with large load-flow processing. This analysis has been carried out on reticulation or medium voltage networks, i.e. 11/22kV designed networks.

A methodological approach to the process adopted in this study is shown in Figure 1. Using a data repository called 'Smallworld' which contains network topology/type parameters for MV networks. The data extraction was imported into Power Factory to consolidate the individual network models into one casefile.

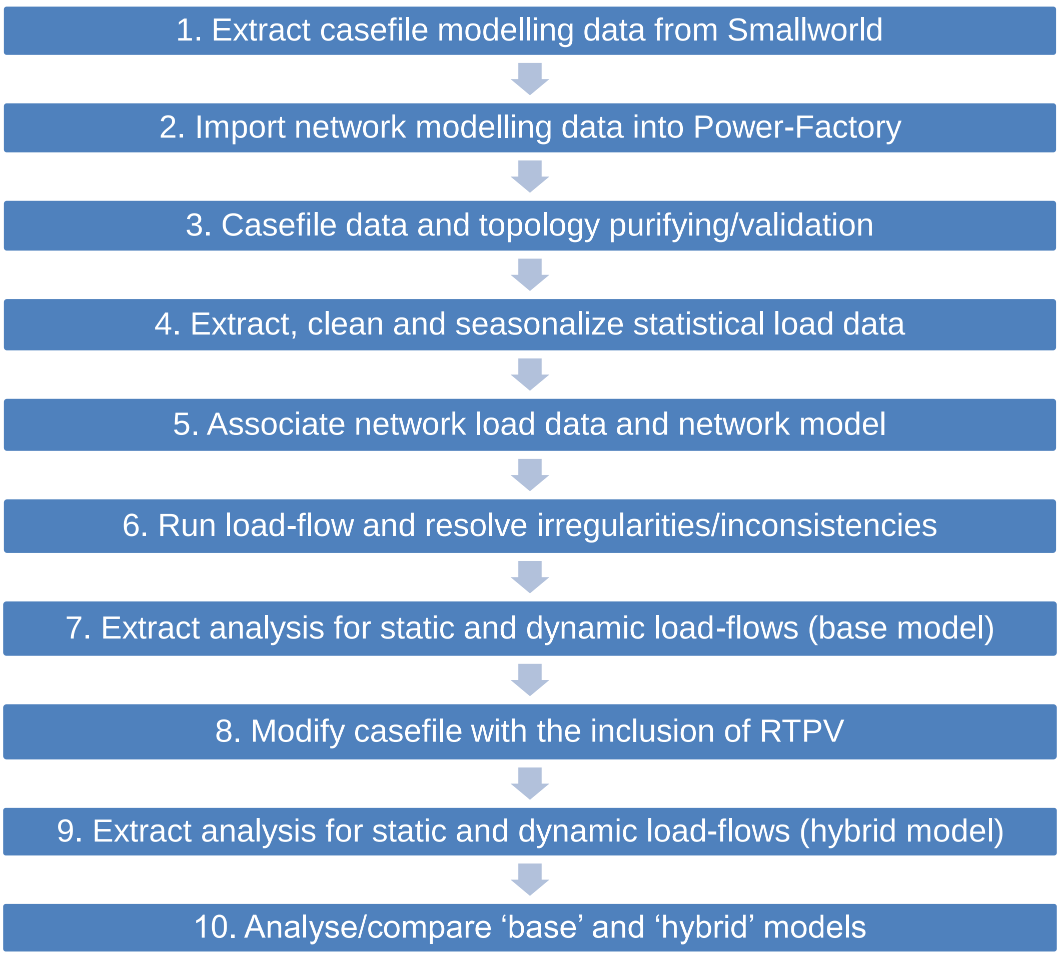

Figure 1 Methodology process overview

Within Power Factory, Eskom Distribution has established a Master Type Library (MTL) [10]. The MTL contains standard line/cable parameters for the vast majority of lines and cables utilised in Eskom Distribution [10]. The MTL provides a standardised set of line/cable parameters for all subscribing systems such as Power Factory. Therefore the data libraries in Power Factory has been referenced to view typical values [10] [11].

Obtained statistical metering data for each network within the casefile was extracted, cleaned and seasonalized into 30min intervals for each season's weekday and weekend. The metering data was associated with the relevant network model to accurately showcase network performance.

Power Utilities need to know the actual performance of existing electrical networks and to what extent would be the influence of small scale embedded generation (SSEG). This study demonstrates, by simulation modelling, how existing network violations will be addressed with the instalment of RTPV.

1.7 Significance of the study

Considering industry predictions and trends, also the declining price of solar panels [12], RTPV is going to be a significant role-player in renewable energy.

The IRP 2010–30 states that 9,770MW of solar PV capacity is planned to be installed in South Africa by 2030. The IRP 2010–30 Update also estimates that Embedded Generation (EG) residential and commercial PV could reach 22.5 giga-watts (GW) by 2030 based on Living Standards Measure 7 (LSM 7) households and 5kWp PV household installations [4].

The historic hindrance to customers when installing RTPV was always the cost factor. With high expectancy and the need for alternate energy sources in South Africa, RTPV will play an important role in the energy sector. The benefit can be both to the customers and supplying utility: Customers can view this as an opportunity to offset their utility bills or go completely off-grid. Utilities can view this as the means to reduce their carbon footprint, reduce the burden on the electrical system and deferring project capital expenditure.

When following the growth trends of RTPV worldwide [13], combining this with the high potential output of PV in South Africa [14]. This study will highlight to customers and utilities alike, the effect of RTPV installed at every residential customer. When this study is considered by engineers in different fields of office, such as Project engineering and Design, Network Planning, Settings & Co-ordination, etc., this will change the way we think about how the industry needs to be developed and sustained in the near future.

1.8 Publications

The following two publications have emanated from this thesis:

1) Reddy R, Davidson IE, Chetty D. “Evaluation and Impact Assessment of Solar Roof-Top PV on Electric Power Distribution Networks.” In 9th CIGRE Southern Africa Regional Conference, Johannesburg South Africa, Oct. 2019 [1].

2) Davidson IE, Reddy R. “Performance Evaluation of Solar Roof-Top PV on Eskom’s LV Electric Power Distribution Networks.” In 2019 7th International Conference on Smart Grid (icSmartGrid), pp. 97-102. IEEE, 2019 [2].

1.9 Outline of thesis

Chapter 2 Literature review - Power System Overview

- This chapter provides a power system overview of South Africa. It demonstrates the different generation sources, the peak demand, and the breakdown of contribution from each generating resource with an overview of solar roof-top photovoltaics.

Chapter 3 Research methodology of Regulatory parameters

- This chapter discusses the research methodology of the regulatory parameters applicable for the analysis of voltage, thermal, overcurrent, and reliability violations.

Chapter 4 Performance appraisal of electric power distribution networks

- This chapter demonstrates a network appraisal, by way of a holistic power system analysis. A network ranking criteria is defined and based on technical criteria evaluated in the network appraisal.

Chapter 5 Penetration of Roof-Top Photovoltaic (case study)

- This chapter discusses the case study for the implementation of RTPV for standalone or hybrid scenarios, with varied penetration levels.

Chapter 6 Conclusion and Recommendations

- This chapter concludes the thesis study highlighting challenges, future endeavours, recommendations and concluding remarks.

Additional annexures showing detailed appraisal results have been provided.

Chapter 2 Literature review - Power System Overview

2.1 Power System Overview

A power utilities responsibility is to produce, transmit and make available electricity at a customer’s point of supply, as seen in Figure 2. To transmit power from the point of generation to the customer, electrical energy is transmitted and controlled via various primary and secondary plant equipment.

In-order for a residential end-user to be supplied at either 230/400V - Electrical power which is supplied from a generating source needs to be transformed through the various voltage levels in a power system. This is done while being regulated at each transformation bus level and having the losses compensated for in the power system until the customer is supplied within regulatory specifications.

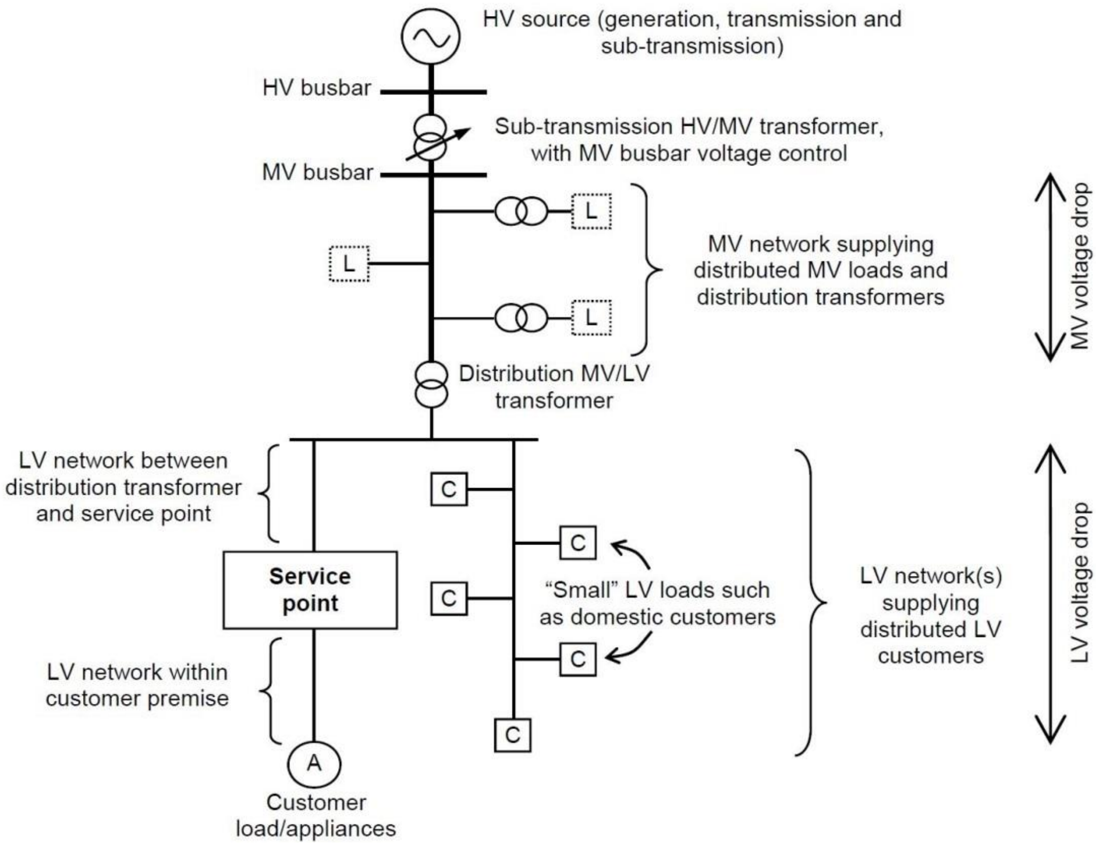

Figure 2 Overview of a distributed electrical power system [8]

Different types of sources are used to develop electricity, the generator types can be categorised as follows [15]:

1. Rotating machines coupled to synchronous AC generators - Steam turbines, Gas turbines, Diesel engines, Large water turbines.
2. Rotating machines coupled to induction generators - Small water turbines, Fixed speed wind turbines, Variable speed wind turbines (doubly-fed induction generators)
3. Alternating current (AC) current sources coupled via electronic inverter systems - Variable speed wind turbines, Wave and tidal devices
4. Direct current (DC) current sources coupled to electronic inverter systems - Fuel cells, Photovoltaics, Some wind turbines

The common historic view of a power system consisted of a generation source and a transmission system all the way down to a distribution level which supplies customers, as seen in Figure 2. This paper explores the “sun” as a renewable energy resource. This gives life to the term “Distributed Generation” (DG) which potentially enables every low voltage (LV) customer to become a generation source to either contribute to the electrical needs of a power system, or for their own internal consumption.

2.2 South African Power systems overview

South Africa is the largest electricity producer in Africa, accounting for 45% of the continents electricity production. 95% of electricity produced in South Africa is produced and supplied Eskom [16]. Figure 3, is a recreation of data reflected in [17]. This shoes the most common types of energy sources for rotating and non-rotating machines which include: Coal, Gas turbine, Hydro, Imported Hydro, Landfill gas, Nuclear, Solar concentrated solar power (CSP), Solar PV, Wind. The South African power system has a total generating capacity of 52.811 GW.

This is made up of 43.485 GW of fossil fuels, and 9.326 GW of Low-carbon sources (renewable/nuclear/imported hydro).

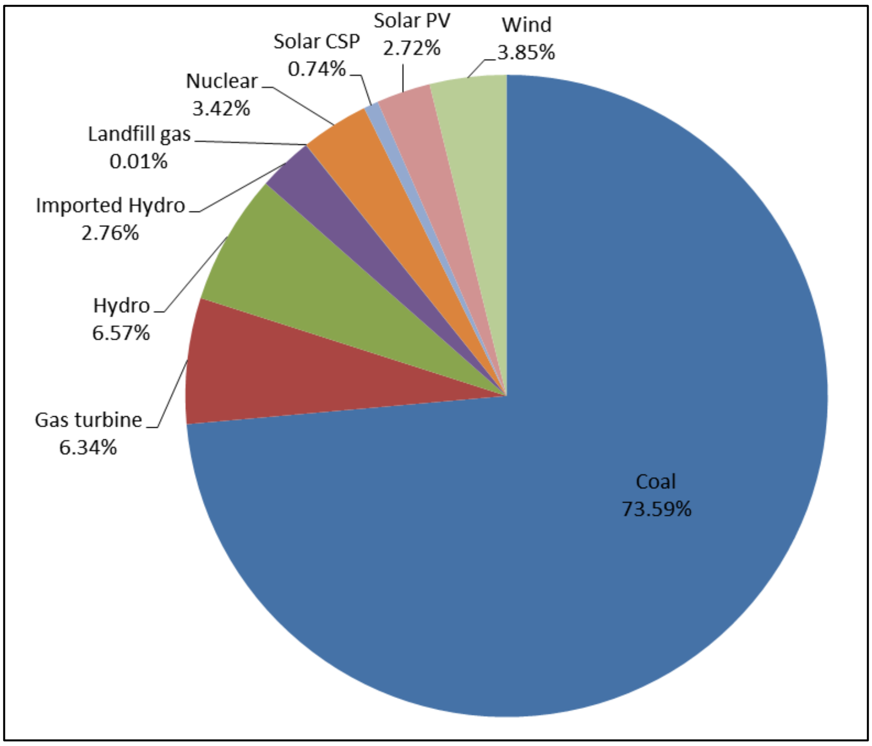

Figure 3 The South African energy makeup [17]

The South African electrical energy makeup is predominately produced by thermal power stations, while hydro-electric stations do offer grid support. Renewable energy sources (such as wind, sun and bio-mass) currently have little generation input to the South African electrical grid. Dispatched renewable energy can offer electrical relief to both localised corridors of an electrical grid with known constraints, as well as to provide network grid support for frequency management.

2.3 The South African energy demand

The South African electricity makeup is dominated by the country's Utility, known as Eskom. Eskom is responsible for the generation, transmission and distribution of electricity. The peak demand, as seen in Figure 4, is seen to be +/-34.5 gigawatts (GW) in the current year 2020 [18].

The sale of Eskom's electricity has 42% attribution to municipalities, followed by industrial consumers (23%) and mining (14%). The remaining sale of electricity is attributed to Eskom's direct customers: large power users, small power users and residential loads. When identifying the electrical consumption within South Africa by Industrial and Residential loads, this amounts to 41% and 37% respectfully [19].

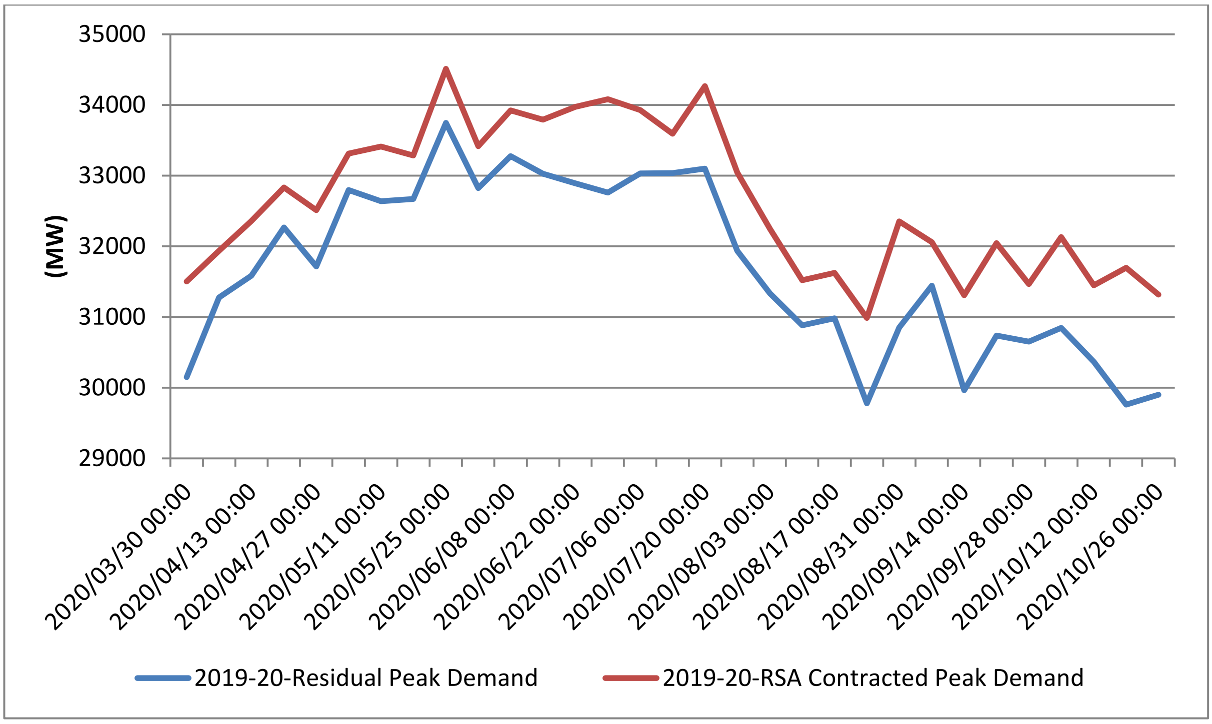

Figure 4 South African weekly peak demand [18]

Figure 4 show the South African peak load demand over the current (2020) peak period. The Actual Residual Demand is the aggregated metered hourly sent-out generation and imports from dispatchable resources and includes demand reductions. The Actual RSA Contracted Demand includes renewable generation. The South African electrical system experiences a peak loading period during its winter months, i.e. May to August.

2.4 Renewable energy in South Africa

According to the "The South African Grid Code for Renewable Power Plants" - Small scale rooftop solar photovoltaics falls under Category A1. This category includes renewable power plants (RPPs) with a rated power of less than 1 MVA and connected to LV systems. This category shall further be divided into 3 sub-categories, to which this study comes under Category A1: 0, 13.8 kVA - This subcategory includes renewable power plants (RPP's) of Category A with rated power in the range of 0 to 13.8 kVA [9].

The small-scale embedded generators that are connected to the grid and operated for commercial purposes must therefore be licensed or registered by the Energy Regulator. Even zero or net consumption customers must be licensed or registered, due to connection to the grid. Due to the high volumes of RTPV expected to be installed, NERSA decided, to have these installations registered instead of licensed [1].

South Africa has embraced the renewable energy expansion programme laid down by the Department of Energy in a race to reduce the carbon emissions by 34% in 2020. This has challenged Eskom's network and grid planners. Figure 5 displays the breakdown of installation capacity for inverter-based renewable generation sources on the South African grid, as at Oct 2020.

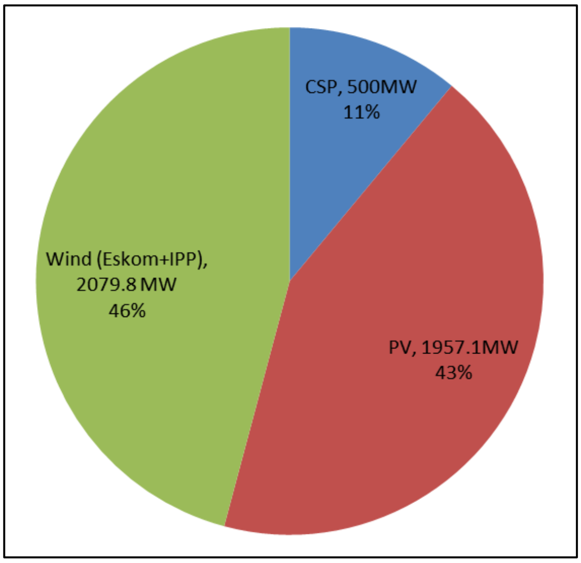

Figure 5 Inverter based renewable installed capacity [18]

South Africa has the biggest independent power producer (IPP) market in Africa. The dependency from coal power sources is expected to decline in the near future. Out of the 9.326 GW of Low-carbon sources (renewable/nuclear/imported hydro).

2.5 RTPV overview

The infeed from generation sources into the SA electrical grid has a diverse contribution, thankfully South Africa can exploit the benefit from RTPV due to the high solar irradiance within large customer density clusters, more so in Kwa-Zulu Natal. Therefore this thesis studies primarily roof-top PV as the main renewable resource, to list a few advantages:

- Allows for distributed generation at the point of need
- No harmful emissions
- Contributes to the world drive to reduce fossil fuels
- Estimated lifespan +/-20 years with minimal operating and maintenance costs;
- Size of a plant can be increased as desired

Thought historically PV systems have primarily served off-grid applications, however, over the past decade, there has been a large shift worldwide to incentivise grid-connected PV [20]. With the continuous improvement of renewable technology and its efficiencies, the cost of PV and BESS continue to decline [21] [12]. According to [12] the price of solar panels has dropped by 15% in 2019 when compared from 2006. It is expected that these installations will become increasingly attractive to residential customers seeking to reduce their electricity bills. Globally the solar PV market has increased by 12% or 115GW according to [22].

From the records of licenced/registered PV generates sources, as seen in Figure 3 a very small portion of Photovoltaics feeds into the South African electrical system, which is less than 3% of the total generated power in SA. The application of RTPV has two types of installations, i.e. with and without storage, this thesis explores both. There are three main components to an RTPV system: Solar panel, inverter and battery.

2.5.1 Photovoltaic panel

Solar photovoltaic (PV) power is the conversion of sunlight into electricity [22]. The PV cell is the basic building block, which is then manufactured into modules and panels for installation [22]. Figure 6 demonstrates the various materials available which are used in the development of solar panels. Individual material characteristics result in different efficiency abilities, comparatively. With improved efficiencies, the surface area necessary to generate the benchmarked 1kW output reduces, thereby showing improvement in manufacturing specifications and design. Historically the cost was the influencing factor in the choice of installation of PV.

Material	**Module efficiency (Standard modules)**	**Area for 1 kW_p**
Monocrystalline rear side contacts	20.4 %	5 m^2
Monocrystalline	17%	6 to 7 m^2
Polycrystalline rear side contacts	16,6 %	6 to 7 m^2
Polycrystalline	16 %	6 to 7 m^2
CIS	14,5%	7 to 8 m^2
CdTe	13,5 %	8 to 9 m^2
Amorphous	7,5 %	13 to 15 m^2
High efficiency means low area demand		Rule of thumb: **1 kW_p = approx. 10 m^2**

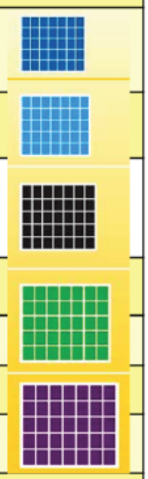

Figure 6 PV panel materials and associated efficiencies [23]

From Figure 6, it is found that PV efficiencies are much lower when compared to alternate forms of generation sources. These are also attributed to the internal losses in a photovoltaic panel such as reflection losses, insufficient/over excitement of photons, recombination of the free charge carriers, high resistive components, etc. These factors contribute to the reduced output efficiencies of solar panels [24].

PV output

The rating of a PV panel is rated according to its output, which in most cases must be converted by inverters to alternating current (AC) for it to be utilised by electrically connected AC loads types [22]. PV output is dependent on numerous factors, such as solar radiation, panel orientation, shading, size, technical performance, etc. [24]. Due to PV technology which is constantly improving, the following formula will serve as a guide to sizing the generated output of RTPV [25]:

$$E = A * r * H * PR \qquad (1)$$

Where:

E	is Energy, in (kWh)
A	is the total solar panel area, in (m2)
r	is the solar panel yield or efficiency, in (%)
H	is the annual average solar radiation on tilted panels
PR	is the performance ratio, coefficient for losses

2.5.1 Inverters

As with the PV panels, inverters come in a wide range of types and sizes, they are typically rated by their maximum continuous power output. Inverters convert the direct current (DC) generated by solar PV modules into alternating current (AC). This thereafter feeds either into the electrical grid or supplies customer load. Invert based systems are generally applicable to photovoltaics and wind turbine systems. In PV systems, its typical application is to convert the DC voltage generated by the PV cells into conventional household AC voltages.

There are two types of solar inverters:

- Pure sine wave – Provides a more natural sinusoidal waveform output as compared to a modified sine wave inverter. The application of this type allows sensitive devices to operate efficiently without distortion or disturbances.
- Modified sine wave – These inverter types are cheaper and they don’t work for all applications. They can interfere with the proper functioning of sensitive electronic devices such as TV’s, fluorescent lights, etc.

An isolation switch or change-over switch built inherently into a smart meter needs to be employed, for the protection of anyone working on the electrical LV system, to mitigate against back feeding power into the electrically connected system, and protecting a customer’s residence against short circuit fault currents from the power utility or other supplies. There is also a need to cater for isolation to in cases of fire to prevent damage to equipment.

2.5.3 Battery storage

PV is a non-firm generation source, unless PV has battery storage it cannot be employed to dispatch power in a similar fashion as other energy sources. Batteries that are used for solar energy storage are widely available in two main types, lead-acid and lithium-ion. While there are several other types available, this thesis focuses on the application of the common technology types available. The dispatchable power from these batteries differs as lithium-ion can supply +/-90% of their capacity, while lead-acid only has a depth of discharge of +/-50%. However the price comparison between the two is significant, hence lead acid is more commonly sold.

There are fundamentally four main solar battery type systems, DC-coupled systems, AC coupled systems, AC Battery Systems and Hybrid Inverter Systems. Focuses are drawn on the hybrid type as seen in Figure 7. Batteries in this hybrid type configuration can be connected between the solar array and inverter or directly to a compatible hybrid inverter, the latter is the preferred setup as smart inverter-based technology can be used to regulate internal, battery charging and grid discharging.

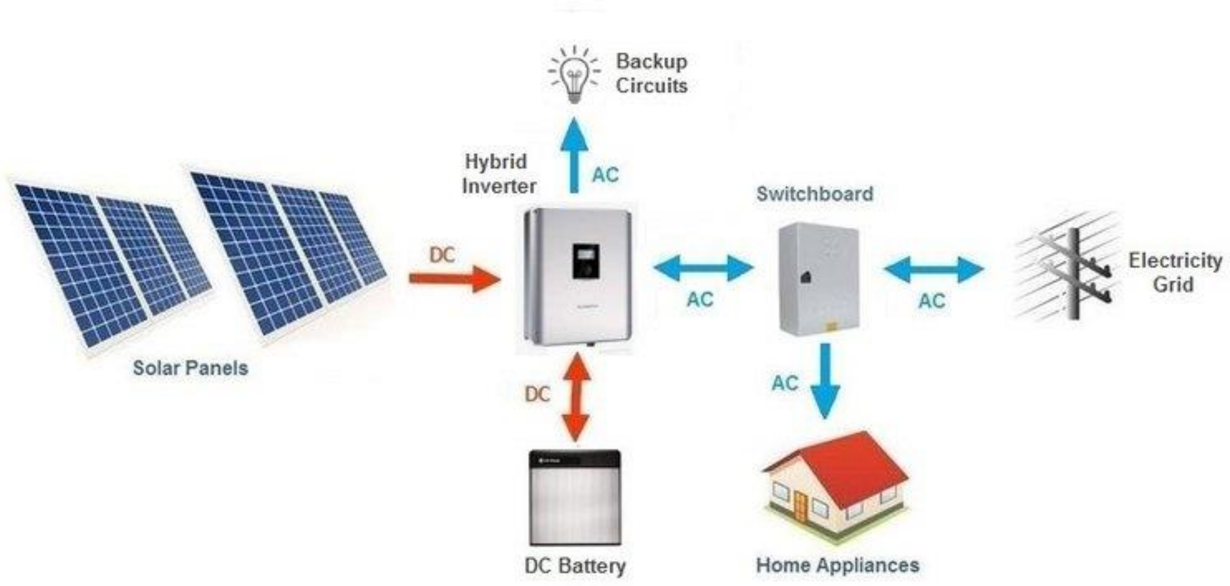

Figure 7 Basic layout diagram of a hybrid solar inverter with a DC battery system [26]

The advantages of a hybrid setup includes - simple installations, compact design, minimal cable design and improved efficiency, however, may not function as a complete backup source. Therefore this makes an ideal type of installation for residential considerations and for a power utility to consider in determining the penetration potential of RTPV within MV networks.

2.6 Summary

When considering the high exposure of sunlight and large population densities, solar energy is a renewable resource which South Africa can experience an abundance of which is a meaningful resource to consider for the South African electrical power system.

One of the challenges that a Power Utility faces is that residential customers are installing RTPV without meeting the required compliance limits or obtaining requisite connection licences. This raises the risk not only for the safety of customers but also for the safety of electrical operating personnel. This aims to encourage the ESI to try and stabilise these problems by setting industry standards so the future of RTPV can be sustainable, managed and maintained.

This thesis demonstrates the effect of utilising RTPV for load demand offset and when incorporating battery storage schemes, having the functionality to be dispatched as an ancillary service, whether it’s for peak load shaving or some form of fast frequency response.

There are three main types of solar power systems; i.e. On-grid, Off-grid and Hybrid. This thesis exclusively explores the hybrid type. This type offers the flexibility for an electricity service provider to consider standalone RTPV and also RTPV with battery energy storage systems (BESS).

From the current choices, while taking into account the vast development within the photovoltaics, inverter and battery storage sectors, this thesis has opted to utilise generic/commonly available technology design types. With only a minimum amount of RTPV and BESS, the results show the desired technical benefit for power utilities and offer customers a means to reduce their utility bills. BESS shows promising potential to be used as part of the solution to elevate the stress that utilities are experiencing [27].

Chapter 3 Research methodology of Regulatory parameters

Measurable limits are vital in order to specify the operating technical specification of the system in order to enable effective real-time management of the network. It provides an assessment of the level of compliance to license obligations, grid codes and other regulatory standards.

Power Utilities needs to adhere to the regulatory framework and to do so need to analysis their networks. This is referred to as an appraisal analysis. In order to conduct an effective appraisal analysis, a proper guide to what tolerable limits will be adhered to need to be defined. Therefore it is important to know the extent and severity of violations, and how will the Utility address any violations. Effectively it comes down to electrical parameters being run at either normal or abnormal limits.

- Normal limits: The “normal” limits for MV networks are intended for the planning and design of new networks, as well as for extensions to and strengthening of existing MV networks. These limits are associated with the networks functioning in a ‘network normal state’, having no abnormal conditions such as any reconfiguration state or loss/disconnection of any parts of the network.
- Abnormal limits: The “abnormal” limits for MV networks are intended for evaluating network contingencies and/or stating the exceedance of tolerable limits. Networks are not designed to operate indefinitely at the abnormal limits.

A set of regulatory limits have been identified, as follows, which plays a significant role in power system analysis. These parameters help to identify any short comings, and by way of conducting a case study shows how rooftop solar photovoltaics can alleviate/reduce the electrical burden experienced within a MV power system.

3.1 Voltage limits

Voltages on the power system need to be managed and maintained within an acceptable range of the nominal voltage to ensure that supply voltage at customer terminals are within limits specified in customer supply contracts and government regulations. Voltage can have the biggest effect when generators are connected to an LV or MV network. There can be a drastic voltage rise when a generator is connected to an LV or MV network.

Voltage regulation management is required in order to maintain voltages at customer terminals within acceptable ranges of the nominal voltage, defined by either supply contracts or government regulation. Effective voltage grading has the potential to minimise strengthening and expansion costs and enable additional connections with present infrastructure.

The maximum and minimum voltages must be kept within the limits specified in [28]. Voltages are dependent on the combined effect of the entire network including voltage control settings, transformers and lines/cables. The voltage drop over a line/cable should be such that the combined effect of the entire network results in acceptable voltages.

Table 1 Deviations from standard or declared voltages [29]

1	2
Voltage level V	**Compatibility level** %
< 500	± 10
≥ 500	± 5

With a majority of customers been supplied from MV and LV systems, MV voltage limits have been established to govern and ensure that Eskom supplies customers with electrical power of suitable voltage quality. The risks associated with low voltages on the MV power system can violate NRS-048 limits, indicated in Table 1, and a Power Utility can be held liable for any damage to customer equipment.

As stipulated in the South African Electricity Act and NRS 048, the nominal LV voltage for existing and new customer supplies <500V is 400/230V, with an allowable voltage variation of +/-10%. Prior to 1990, the standard Eskom LV supply contract was for 380/220V +/-7.5%.

3.1.1 Voltage Drop

The voltage regulation on an MV distribution network depends on the amount of load transferred as well as the impedance of the line. In the electrification context, the amount of load is determined by the number of customers as well as the average load requirement of each customer, while the impedance is mainly determined by the line length and conductor type [30]. Voltage drop plays a significant role in network operations, planning and design.

From Figure 8, It is evident that the expected reliability and the voltage regulation on the network are related by the feeder length and number of customers connected to the network.

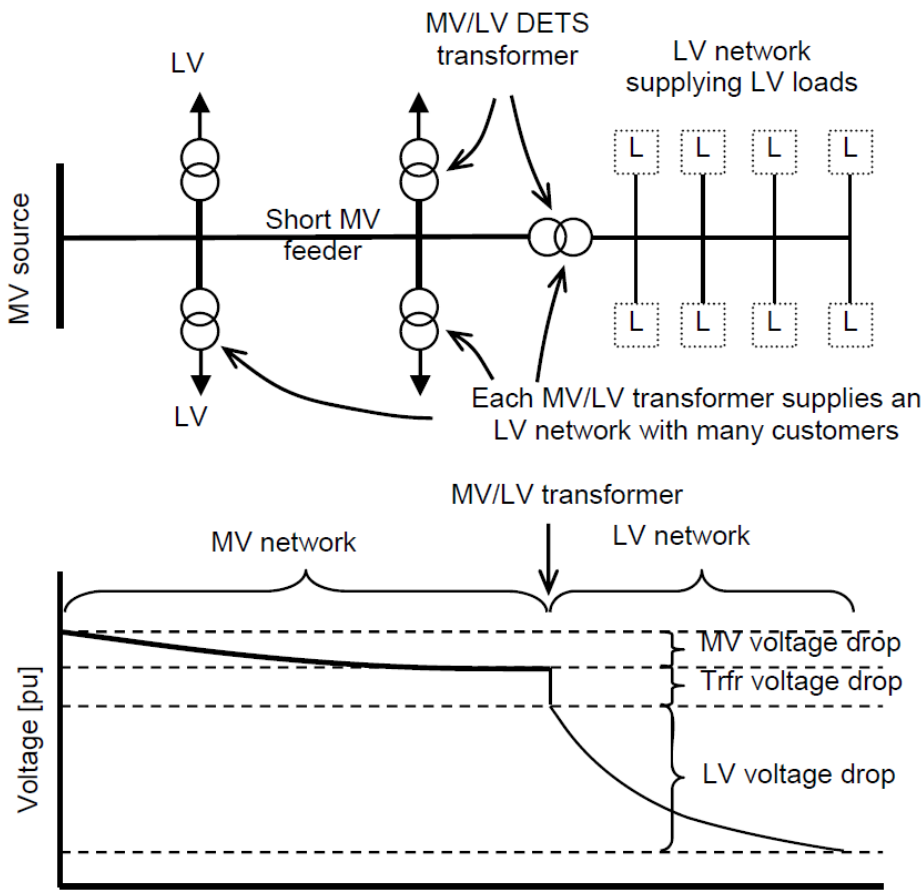

Figure 8 Observation of MV and LV voltage drop [31]

While there are voltage controlling devices, such as tap changes, etc.; voltage suppression still occurs due to numerous reasons:

- Voltage control point settings
- Distribution transformer specifications including nominal secondary voltage, impedance, tap step and tap range
- Distribution transformer and feeder loading levels
- Contractual obligations at the service point (voltage limits)
- Voltage drops within the customers' LV networks to the equipment or appliances

On the contrary voltage rise phenomenon are also of concern. These can arise by:

- Reactive power compensation, either by capacitor banks or by altering the generator control mode to absorb reactive power under specific operating conditions.
- Active power injection on a network by an embedded generator.
- Incorrect or abnormal functioning of voltage control devices such as on-load tap changer or voltage regulators.

During all loading and generation patterns, voltage rise and voltage drop need to be kept within specific limits so that voltage variation at customer points of supply are within required limits as specified in [14].

The simplified circuit represented in Figure 9, shows a generic equivalent view of any electrical network. Due to equipment parameters and line lengths the receiving voltage, with the absence of additional generator points, will reflect a voltage drop [32].

$$U = I * Z \qquad (2)$$

$$I = I_p - {}_jI_q \qquad (3)$$

$$Z_L = R_L + jX_L \qquad (4)$$

$$U = I_p * R_L + I_q * X_L \qquad (5)$$

Where:

U — or V, is the change in voltage, in volts (V)

j — is the "j operator" [$j^2 = -1$]

Ip and Iq — are the active and reactive components of the Current I, in amperes (A)

RL and XL — are the resistive and reactive components of the circuit impedance, ZL, in Ohms (Ω)

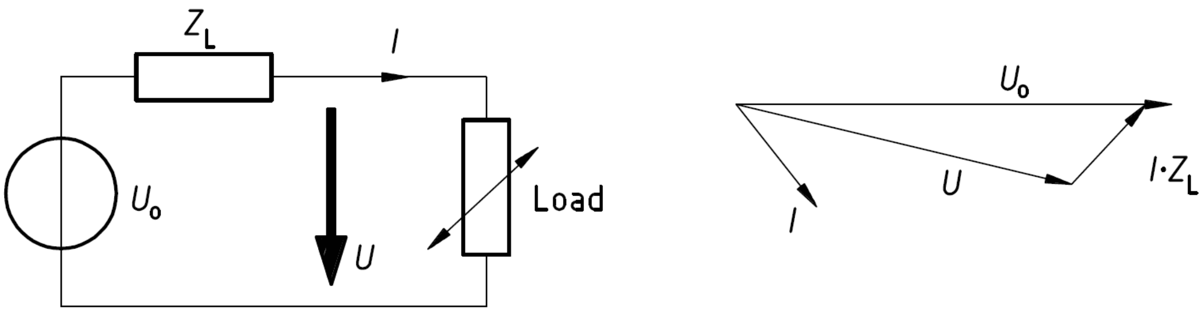

Figure 9 Equivalent circuit and vector diagram [29]

Most loads absorb lagging VARs to supply the magnetising currents of transformers, induction motors, etc. The passage of reactive power through the inductance of the line therefore causes the greater part of the voltage drop in the transmission line. The calculation of expected voltage drops is performed in Power System Simulation tools. This study uses Digsilent-Power Factory as the primary simulation tool to ensure that expected voltages and voltage drops are within acceptable limits. Consideration of NRS 048-02 limits for voltage variation of +/-10% of the nominal voltage at the service point meter must be maintained.

Voltage drop causing low voltages at the receiving end is largely made up of two components, as seen in Figure 10: The product of the real power component of the current and the line resistance; and the product of the reactive power component of the current and the line reactance.

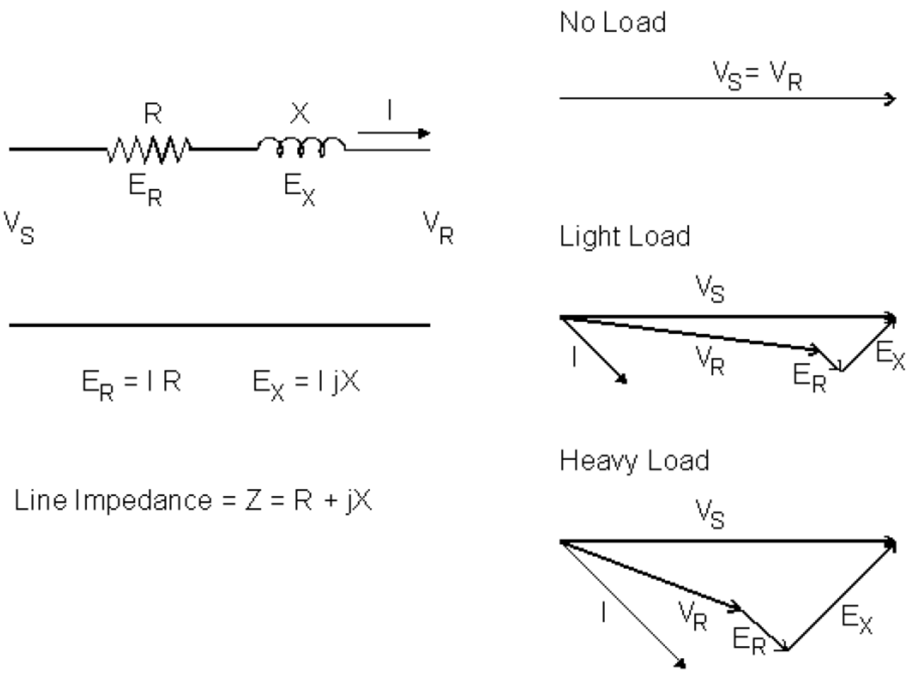

Figure 10 Voltage drop over a short radial line/cable [11]

For short lines/cables the capacitive component is small and is considered to be negligible. When the sending voltage (U) is applied to the sending end of a short circuit with no load the sending and receiving voltages are the same. However when load current flows through lines/cables, the current causes a resistance a reactance volt drop which causes a volt drop across these network components and results in reduced receiving voltage.

3.1.2 Network category classing

The voltage apportionment limits allowable for MV and LV voltage drop can therefore be standardised for a set of network categories. These apportionment limits, in Figure 11, have been calculated based on typical South African networks [33].

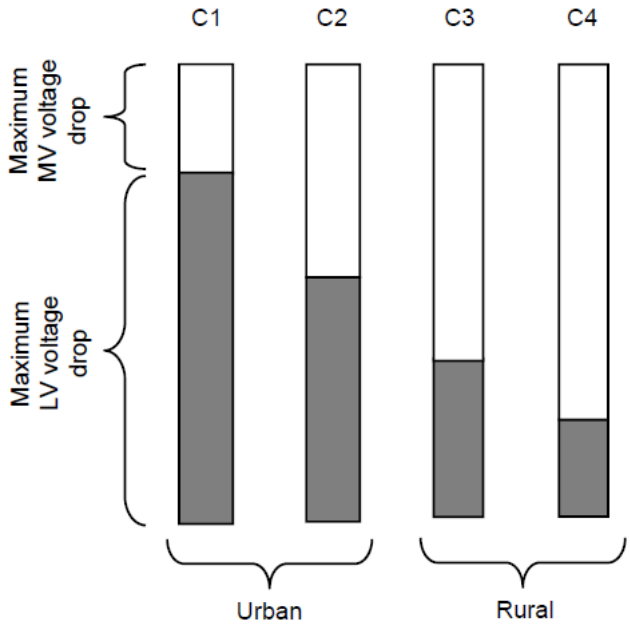

Figure 11 Network classes [33]

Classes C1 and C2 will typically be used in urban networks where the voltage drop in the MV network is relatively small and the LV voltage drop can be large. Classes C3 and C4 will typically be used in rural networks, where the LV network voltage drop is relatively small and a larger allowance is made for the MV voltage drop [28].

Table 2 Network class definitions [28]

1	2	3	4
Network Class	**Typical network type**	**Typical load density (after diversity)**	**Comments**
C1: MV voltage drop is typically one-third of the LV voltage drop	Urban, but can also be used in rural networks with good MV voltage regulation	>200kVA/km^2	There are no restrictions on the distribution transformers
C2: MV voltage drop is typically equal to the LV voltage drop	Rural networks with urban type loads, but can also be used in urban networks with relatively poor MV voltage regulation	<200kVA/km^2	There are no restrictions on the distribution transformers
C3: MV voltage drop is typically double the LV voltage drop	Rural with no significant electrification (urban) type load	<100kVA/km^2	Should not be utilised in networks containing 380/220V transformers
C4: MV voltage drop is typically triple the LV voltage drop	Rural with no electrification (urban) type load	<100kVA/km^2	Should not be utilised in networks containing 380/220V or 400/230V transformers

In order to use the appropriate voltage limits distribution networks must be classified as C1, C2, C3 or C4.

- C1: Urban MV cable networks that are not supplied by rural MV overhead networks (typically medium to large towns supplied in close proximity (<5 km) to the MV source).
- C2: Rural MV overhead networks supplying electrification and/or small rural towns.
- C3: Rural MV overhead networks that do not supply electrification or towns (urban loads).
- C4: Not to be used as a default.

3.1.3 Acceptable sending and receiving voltages

Based on transformers nominal secondary voltages, as indicated in Table 3, transformers are specified with a secondary voltage of 415/240V, 420/242V, 380/220V or 400/230V to provide voltage adjustments. Due to the relatively low secondary LV voltage, this would determine a voltage constraint. The tap changer for reticulation transformers is off-line tap changers. These tap changers are only able to tap in a de-energised state. The tap step size of 2.5%, 3%, 4.5% varies between the different transformer specifications.

Table 3 Standard tap settings (boost level) for MV/LV distribution transformers [28]

1	2	3	4
Distribution transformer	**Tap Zone**		
	TZ1	**TZ2**	**TZ3**
	106% ≥ MV_{Max} > 103%	**103% ≥ MV_{Max} > 100%**	**MV_{Max} ≤ 100%**
420V 3φ	-2.5%	0%	+2.5%
415V 3φ	-3%	0%	+3%
400V 3φ	0%	+2.5%	+5%
380V 3φ	+2.5%	+5%	+5%
242V 1φ	0%	0%	+5%
242V 1φ rev *	0%	0%	+2.5%
240V 1φ	0%	0%	+5%
240V 1φ rev *	0%	0%	+3%
230V 1φ	0%	0%	+5%
220V 1φ	0%	+5%	+5%
240V Dφ	-3%	0%	+3%

Considering data reflected in Figure 11 and Table 3, each network class has a set of normal and abnormal sending voltages which an MV network needs to operate to safely consider reasonable expected voltages at customer points of connection. Table 4 reflects, for the different classes and tap zones, what the recommended sending voltage from the regulated source bus bar should be set to. The benefit of utilising these limits will ensure that during low or high load conditions that a customer remains within +/-10% of the limits described in Table 1.

Table 4 Maximum MV voltage limits [33]

1	2	3	4
	Tap Zone		
	TZ1	**TZ2**	**TZ3**
Normal	105%	103%	100%
Abnormal	106%	105%	102%

With the understanding of network classing, voltage drop and tap zoning; Table 3 identifies the maximum sending voltage. It is also expedient to identify the tolerable minimum voltages, Table 6, showcases what are the acceptable minimum voltage limits. Ensuring adherences are kept to these limits will ensure customers are fed within NRS [29] limitations.

Table 5 MV/LV transformer Tap Zone summary [33]

1	2	3
Tap zone	Maximum normal MV voltage	Relative level of tap boosting
TZ1	105% ≥ MVMax > 103%	Minimum
TZ2	103% ≥ MVMax > 100%	Moderate
TZ3	MVMax < 100%	Maximum

The recommended tap setting of reticulation transformers, shown in Table 5, will result in the customer being fed a tolerable voltage within the NRS requirements. These tap zone settings can be cross-referenced to the transformers listed in Table 3 due to the various secondary voltages and tap step ranges. A network may contain one or more tap zones depending on the types of voltage control equipment installed on a particular network.

Table 6 Minimum MV voltage limits [33]

1	2	3	4	5
Network Class		**Tap Zone**		
		TZ1	**TZ2**	**TZ3**
C1	Normal	101.5%	**99.5%**	97.0%
	Abnormal	99.5%	**97.0%**	94.5%
C2	Normal	98.0%	**95.5%**	93.5%
	Abnormal	95.5%	**93.5%**	91.0%
C3	Normal	95.5%	**93.0%**	91.0%
	Abnormal	93.0%	**91.0%**	88.5%
C4	Normal	92.5%	**90.0%**	87.5%
	Abnormal	90.0%	**87.0%**	85.0%

Due to the relatively low capacities of distribution MV and Low Voltage (LV) networks, distribution connected generators may have a significant impact on voltage regulation. As power is transferred from the generator through an LV or MV feeder to the source, the voltage rises between the MV feeder source and the generator terminals. Since Eskom Distribution MV/LV transformers are operated on a fixed tap, this voltage rise could have a direct impact on customers [15].

3.2 Thermal rating

The line thermal loading limit is the maximum current that the line can carry. Thermal overload is caused by excessive current flow causing overheating (due to the I^2R effect), which results in a maximum conductor temperature being reached. Thermal limits on networks refer to the overloading of lines, cables, transformers and other connected electrical apparatus. The loading of cables and conductors is an important measure to monitor. In order to know the thermal loading on lines and cables, which doesn't contain any analogue measuring instruments, peak network analysis will need to be conducted.

Overloading cables above its respective ratings results in a high probability of failure in the cable and this also poses a danger to personnel in close proximity. Conductor sag below statutory limits poses danger to the environment as well as increases the likelihood of faults occurring on the network due to parting conductors, clashing of conductors etc.

Understanding the severity of loading violations can assist operations and asset creation departments to prepare and plan adequately in order to prevent or reduce the impact of such violations on the power system. In order to acquire this informative data, this will involve the monitoring of loading of each piece of conductor/cable on the network in comparison to their respective thermal ratings.

The majority of the rural type loads considered for this study is predominately supplied by overhead conductors/lines. Three ratings are applied for lines: A, B and C. From a power flow aspect, the following applies [34] [11]:

- Type A - Maximum operating current under normal conditions. Previously known as 75°C rating. Risk of exceedance (Conductor temp. > templating temp.) is 9.83%
- Type B - Maximum operating current under emergency conditions. Previously known as the 90°C rating. Not limited to a time period. Risk of exceedance is 49.11%.
- Type C - Short time current rating. It is the ultimate maximum operating current under emergency conditions preceding load shedding. Maximum 15 minute time period only. Function of the thermal inertia of conductor.

Table 7 Assumed network characteristics for calculating customer number limits [30]

Network type	Feeder type	Network class[2]	Network voltage (kV)	Conductor size/type	Maximum allowed MV voltage drop across backbone	Maximum allowed MV line/cable loading
Urban	Cable	C1	11	185 mm^2	2%	50% of normal to allow for N-1
Urban	Cable	C1	22	95 mm^2	2%	50% of normal to allow for N-1
Rural	Overhead	C2	11	Hare	7.5%	90% of rate A[3]
Rural	Overhead	C2	22	Hare	7.5%	90% of rate A

The maximum allowed MV voltage drop across the backbone, in Table 7, is based on typical standard conductor sizes. The allowable load rating is reflected for Rate A of the conductor's rating/characteristic. This 90% load rating, for reticulation networks (11/22kV), is an ideal guide for network planning and when conductors are found to be in violation, it signifies that no further load connection is recommended and that the power utility needs to implement de-loading actions.

Additional loading capability due to the consideration of load profiles is not to be utilised for planning studies, therefore planning needs to consider the thermal loading of a line at its Rate A limit, whereas operationally Rate B can be utilised [11].

The thermal loading limits for normal and contingency conditions (Type A and B) should not exceed the normal and emergency loading limits. If these limits are violated it may result in equipment damage and pose a safety risk to persons.

3.3 Overcurrent setting

The protection philosophy must seek to minimise damage to power system equipment and components under fault conditions. It is a lawful requirement to safeguard life and minimise injury that may result from contact with any live apparatus [35]; this is the key objective of any protection system. Further to this; an advantage is also to protect Utilities equipment, which by fast-acting protection, is not exposed to the full effects of fault currents.

Fault level assessments are necessary to determine if fault currents remain within equipment withstand capabilities. Exposing the power system to levels exceeding design capability places both personnel and plant equipment at risk.

Short-circuit or fault studies are conducted to determine the magnitude of currents flowing through the electrical system during faults. Short-circuit studies ensure that the wide range of electrical equipment used to generate, transmit, and distribute electrical power is sufficiently sized to interrupt or withstand short-circuit current. Short-circuit studies are required to identify the maximum fault currents that will flow in the network under faulted conditions. The maximum fault current is required to determine whether the existing equipment is adequately rated for the fault level.

A network is equipped with automatic circuit breakers; this is commonly referred to as the network breakers and section breakers. While there are other current/supply limiting devices, for the purposes of this study, these breakers are designed to automatically interrupt and/or reclose electrical supply in an alternating circuit. Utilising secondary plant relaying, a breaker has the ability to interrupt supply. These breakers have the ability to open for faults and auto-reclose after a predefined period of a completed dead time cycle. There are numerous set points that are commissioned in relays; such has for sustained earth faults, earth faults, overcurrent faults, etc. For the purposes of power system analysis, the focus is on a breakers ability to open for excessive load current and to interrupt fault current.

Equations (6-8) are representative of a normal inverse overcurrent setting. Power flow is restricted to this setting and may be interpreted as the maximum amount of load flow permissible beyond a breaker. The overcurrent setting is both magnitude and time based, however when load flows reach the overcurrent (OC) set-point, this would cause interruption of electrical supply. Therefore the time delay isn't as valuable to power system analysis as the OC set-point is [36]:

$$PS = \left(\frac{Il}{CTR}\right) * 1.2 \qquad (6)$$

$$PSM = \left(\frac{If}{CTR * PS}\right) \qquad (7)$$

$$TMS = \frac{t(PSM^{0.02} - 1)}{0.14} \qquad (8)$$

Where:

- PS is plug setting, in set increments
- PSM is plug setting multiple , in set increments
- TMS is time multiplier setting, in seconds (s)
- CTR is current transformer ratio, as found in equipment type
- Il is load current, in amps (A)
- If is fault current, in amps (A)

Phase overcurrent protection is set to use an inverse time-current characteristic so as to achieve faster operating times at higher currents. Time multiplier setting (TMS) is a setting which describes an adjustable factor that may be provided by a relay manufacturer which is applicable to the theoretical curve of the time versus current characteristic. Many protective relays include an option to set a maximum operating time for phase overcurrent protection. The scope of this study is to note that each breaker has a pre-set OC set point, which has the ability to interrupt supply should the set point be exceeded.

Connecting a generator to a network has the effect of increasing the fault levels in the network at the point of generation connection. This may result in the violation of equipment fault level ratings. Generators contribute fault currents in response to network faults. Generating plants will therefore increase the existing network fault level [15]. Further to this, as fault levels increase, it is recommended that protection grading and coordination gets reviewed to safely account for new generator connections to the power system.

3.4 Reliability Criteria

When a network is simulated at peak, the minimum voltage and maximum thermal loading will be evident. The maximum number of customers that can be supplied per MV feeder, without exceeding the voltage regulation limits defined in Table 8, Table 9 and Table 10 is determined by network voltage, backbone length of the feeder, Line type (cable vs overhead), maximum allowable voltage drop and maximum allowable loading. The limits defined in Table 8 are considered for the typical network classing of C1 TZ2. With this, the severity of the violations have been coloured as reflected below.

Table 8 Standardized criteria for MV constrained networks [37]

Criteria	Severity	red	Orange	green
Min MV voltage at end of feeder (%)	Licence requirement	<= 93%	>93% and <96%	>= 96%
Max thermal backbone loading (%)		>= 95%	<95% and >85%	<= 85%
Number of customers[2]	Reliability requirement	In consultation with Table 3 & 4 of the Reliability Standard 240 – 76613395		
Total Line Length[2]	Reliability requirement	In consultation with Table 3 & 4 of the Reliability Standard 240 – 76613395		

Where:

- Red: Indicates that new load connections are unlikely as the network is considered to be constrained
- Orange: Indicates that limited new loads can be connected based on detailed simulation studies as defined by the methodology for connecting new load to a constrained network

- Green: Indicates that new load can be connected based on detailed simulation studies as defined by the methodology for connecting new load to a constrained network

Table 9 Maximum number of customers allowed per network type [30]

Network type	Maximum backbone (BB) length (km)	Approximate total feeder length (km)	Preferred maximum no. of customers connected	Absolute maximum no. of customers connected
11 kV cable	10	20	2000	2000
22 kV cable	15	30	2800	2800
11 kV overhead	10	25	3800	3800
22 kV overhead	30	70	3800	5000

Table 10 Maximum MV overhead distribution feeder length as a function of customer numbers and voltage [30]

Number of customers	11 kV	22 kV
0 - 1000	35 km BB (88 km total)	150 km BB (375 km total)
1000 - 2000	18 km BB (45 km total)	70 km BB (175 km total)
2000 - 2800	13 km BB (33 km total)	55 km BB (138 km total)
2800 - 3800	10 km BB (25 km total)	40 km BB (100 km total)
3800 - 5000	Not supported	Not recommended, but 30 km BB (70 km total) allowed

Table 9 and Table 10 describes the recommended number of customers permissible to be connected on a reticulation network, for a given backbone length and voltage level. If the actual number of customers on an MV overhead distribution feeder is less than the maximum indicated in Table 9 then the refer to Table 10 to determine the maximum allowed feeder length for the actual number of customers.

Reliability can be greatly improved by using the correct protection devices and switches to minimise the impact of sustained faults on the network. These devices include transformer fuses, automatic re-closers, automatic sectionalisers, isolating links, back-feeding and network visibility.

MV distribution feeders have to comply with the voltage regulation standards required by the NRS048, therefore adherences to the above guides will ensure that the MV distribution network operates within the set voltage regulation [30].

3.4 Summary

The traditional power system in South Africa involves centralised power generation and the transportation of energy to consumers, over very long distances. This is as a result of both the location of primary energy recourses and the location of end-use customers.

These vast distances of transportation coupled with various levels of transformation required, reduce the efficiency of power delivery, where energy is lost due to Joule heating. It is extremely advantageous to increase power delivery efficiency ultimately, saving money. Cost-saving further translates to cheaper tariffs, a benefit to existing customers and an attraction to future customer connections.

The optimal voltage control methodology, settings for existing networks, tap zone study and tap settings must be conducted for every reticulation network. These responsibilities reside in the power systems environment.

The technical constraints experienced in reticulation analysis are based on - minimum voltages, thermal limitations, overcurrent settings, reliability criteria and technical losses. The technical constraints are further categorised in Chapter 4 and showcased in Table 11 Priority and ranking criteria guide.

This thesis considers these constraints within reasonable tolerances and examines the influences of DER’s on reticulation networks with and without storage. The advantage of using RTPV as an energy resource is that high solar irradiance is abundantly available at the point of need in general in South Africa [14].

The changes in the economic and commercial environment of power systems design and operation have necessitated the need of DER's to generate electricity closer to the customer supply points [38], hence improving power delivery efficiency by eliminating the large transmission distances between generation and end-use customers.

Chapter 4 Performance appraisal of electric power distribution networks

4.1 Data purification

Analysing a power system is required by a power utility to closely monitor and assess the performance of the electrical power system. Load research studies have shown the demand pattern of most distribution systems particularly those serving domestic customers in rural/semi-urban areas; these load characteristics have early morning and evening peaks with very low consumption for the rest of the day [38]. The varying load factor coupled with the fluctuating demand, present a challenge in the design and operation of reticulation networks [38] [9]. For this study, the primary plant models/topology data have been obtained, validated and purified. Some of the common reasons for data modelling errors stem from:

- Zero readings from statistical meters – Loss of recorded metered data, comms issue, Brkr tripped/out of service
- Long duration of missing data –NB out of service, newly established NB, No communications
- Sudden jumps in load data – New electrification/large power user connected, NB used to interconnect with another NB
- Newly added or removed sections of networks – Resulting from bulk electrification projects or network splitting
- Rapid growth of illegal connections – offsets and causes inaccurate load flows

To conduct dynamic network analysis, purification of the network models and load data has been conducted. This study has associated the corresponding loading of each network to its respective network topology. Due to the diversity of network loading, this study considers analysis throughout the day. The power system assessments allow an understanding of network dynamics and characteristics enabling engineers to identify potential network issues.

The method adopted in the analyses is referred to as 'Feeder Temporal Analysis'. Temporal Analysis is defined as the analysis of a quantity over time. Feeder Temporal analysis is the analysis of multiple network technical parameters over a one year period. Because of loads being cyclic the load periods have been statistically recycled into eight profiles (a typical weekend and weekday profile per weather season), with each containing an entire days load profile in 30-minute intervals [39]. The 8-day profiles in 30-minute intervals translate to 384 samples utilized in this analysis i.e. 384 load flows and write-outs for each sample. This allows for better resolution in terms of network performance parameters hence allowing more flexibility in analyzing networks. This results in more options for network configuration management under contingency scenarios and various other network studies. The profiles also make provision for energy type assessments (area under demand curves, technical loss curves etc.)

4.2 Network appraisal

Plant performance indices don't describe the technical state of the system; therefore a view is needed to identify whether an electrical system is functioning optimally. A network appraisal is a mechanism used to promote electrical efficiency and improve reliability by providing knowledge of:

- System constraints including where additional customers and/or cannot be connected, allows network planning (and associated capital plans) to effectively address identified constraints.
- Compliance/non-compliance to licensing conditions, including the extent, severity and impact of violations.
- Direction to manage capital projects by prioritizing network solutions based on the level of constraints.

- Trending characteristics (ongoing) to see if non-compliance is improving or deteriorating and if desired targets are being achieved.
- Informs the utility to focus on short term remedial actions, such as changing voltage control settings, normally open points etc.

From the results of an appraisal, a Power Utility or Business sector will have an overview of the state of electrical networks, this will influence or restrict: electrification, capital projects, network planning, etc. This study focuses on utilising the network appraisal to support the implementation of RTPV to address electrical violations.

4.3 Defining the criteria used to rank MV NB's

When analysing bulk appraisal results, a priority system must be implemented to rank MV networks. This system is necessary for a Power Utility to understand the technical characteristics of networks. In order for a Power Utility to initiate plans, projects and corrective measures to rectify any technical violations, an appraisal of all networks needs to be conducted [40].

For this study, technical analysis was conducted on 'eight hundred and twenty-two' medium voltage networks (11/22kV). The result from this analysis, combined with tolerable limits stated in "Chapter 3 Research methodology of Regulatory parameters", this has led to the development of a set of technical criteria used to rank and prioritise medium voltage networks, see Table 11 Priority and ranking criteria guide.

The priority of this study is to address the common operational problems that are encountered with MV NB's. The identified common problems/violations are associated with minimum voltage, thermal loading, overcurrent setpoint encroachment, violating established reliability criteria, backfeedability and technical losses; see Figure 12.

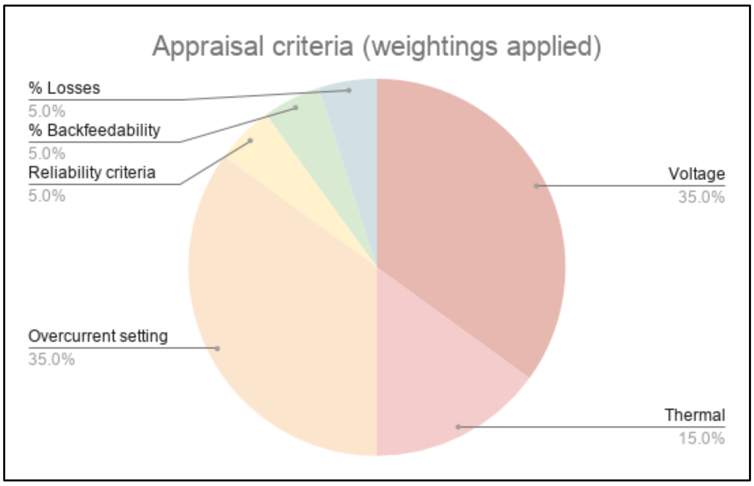

Figure 12 Appraisal criteria with applied weightings

Each of these technical issues has been categorized into the four levels of "constraint". When the analysis is conducted and extracted for each of the individual criteria, this method provides every medium voltage network with a unique weighting. This weighting is then sorted to provide a priority listing.

Table 11 Priority and ranking criteria guide

Voltage Criteria weighting =			35%
C1 Range	C2 Range	SF	Violation category
<=95	<=90	1	Severely Constraint
95-97	90-93.5	0.6	Constraint
97-99.5	93.5-95.5	0.4	Medium Constraint
>=99.5	>=95.5	0	No Constraint

Thermal Criteria weighting =		15%
Range	SF	Violation category
>120	1	Severely Constraint
110-120	0.8	Severely Constraint
100-110	0.6	Severely Constraint
95-100	0.4	Constraint
80-95	0.2	Medium Constraint
<=80	0	No Constraint

OC setting weighting =		35%
Range	SF	Violation category
>=95%	1	Severely Constraint
90-95	0.7	Constraint
80-90	0.4	Medium Constraint
<=80	0	No Constraint

Reliability Criteria weighting =		5%
Range	SF	Violation category
Violation	1	Medium Constraint
No Violation	0	No Constraint

% Backfeedability weighting =		5%
Range	SF	Violation category
0%	1	Constraint
1-33%	0.8	Constraint
33-66%	0.6	Constraint
66-99%	0.2	Medium Constraint
>100	0	No Constraint

% Losses weighting =		5%
Range	SF	Violation category
>=12%	1	Severely Constraint
9-12%	0.8	Severely Constraint
6-9%	0.6	Constraint
3-6%	0.2	Medium Constraint
<=3	0	No Constraint

The decisive factors for apportioning the weightings are based on electrical and operational requirements: The two large categories, Voltage and Overcurrent setting' are given the highest priority.

The voltage drop along networks is the resultant outcome of the cumulative impedances along the backbone of an MV network. A reduced supplied voltage will negatively affect 'constant power' type loads such as motor type loads; these are accounted to refrigeration/pumps/etc. This is used by residential, small and large power users. For these load types, any drop in voltage will cause an indirect rise in current which can result in damage to customer's sensitive equipment.

The overcurrent (OC) setting is a limit that is drawn to prevent damage to any connected apparatus on a network as a result of overloading. The voltage and OC categories of violations are deemed vital to maintaining electrical supply.

The thermal criteria are seen to be less vital due to the flexibility of conductor ratings. Conductors have a slightly higher tolerable rating, which is time-based. Provided that the current does not exceed a conductor's absolute maximum rating, the above-normal current can flow through conductor provided it does not surpass a pre-defined allowable duration. This study provides analysis at Rate A, which is a safe continuous rating of the installed conductors. A conductor has the ability to be loaded to a higher tolerable limit (Rate B). The protective measure taken to prevent overloading is the overcurrent setting of the source feeder breaker. For complete consideration potential overloading of Rate B is already considered in the 'OC setting criteria' above. Therefore the OC criteria have been given higher priority because it is directly addressing equipment overloading while the 'Thermal criteria' is highlighting an encroaching network constraining factor.

The Reliability, Backfeedability and Losses criteria have been given equally low priority ratings due to it providing a view of future/upcoming view of possible violations. By having this category of violations it separates undoubtedly the network which has the full ability to connect additional load, as compared to networks that need to be timely monitored by infrastructure planning departments.

4.4 Bulk analysis of network appraisal data

The appraisal analysis for the 'eight hundred and twenty-two' networks is detailed in Annexures A to F. The data in Figure 13 reflects the severity, in percentage form, for each category of violations.

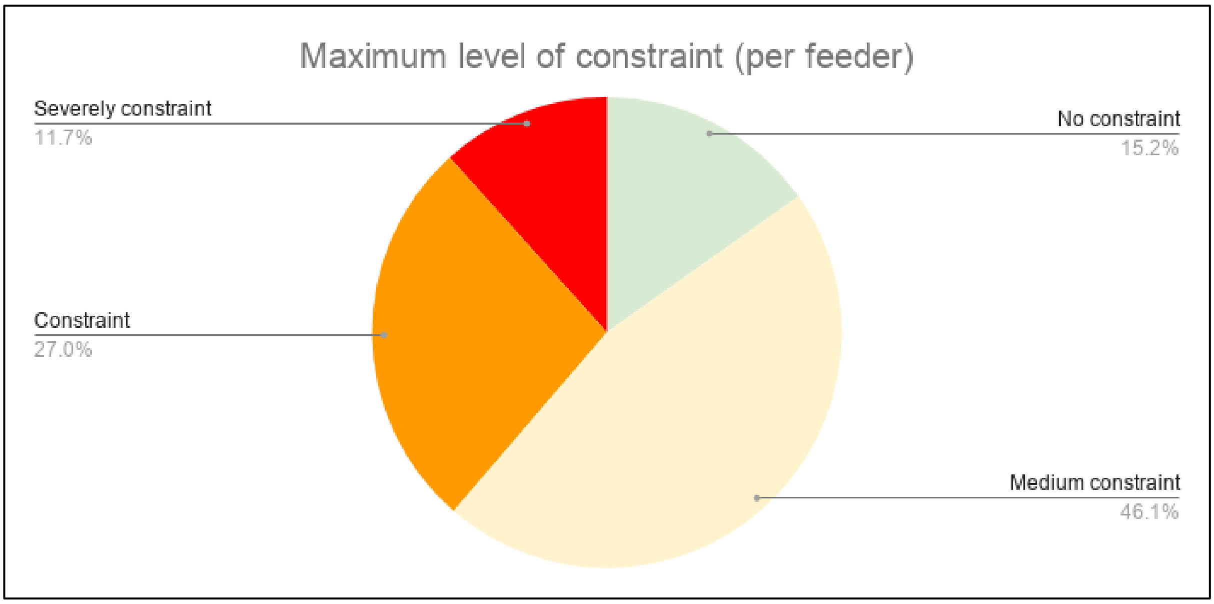

Figure 13 Maximum level of constraint (per feeder)

Figure 13 shows a consolidated view of the maximum level of constraint experienced per feeder, it demonstrates a holistic view of the severity of technical violations/constraints defined in Table 11. From this, it is identified that while some networks may have none-to-moderate levels of constraint; other networks are more severely constrained.

Defining each violation/constraint category:

- No Constraint – 15.2% from the total sum of 'eight hundred and twenty-two' networks indicates that no constraints/violations are experienced.

These networks have the ability to connect new load/customers, based on detailed simulation studies.

- Medium Constraint – 46.1% of networks are exceeding normal limits/encroaching close to normal allowable limits. Based on ‘reliability criteria’ these networks have high potential to exceed normal/allowable limits. Indicates that limited new load might be connected based on detailed simulation studies.
- Constraint – 27% of networks are exceeding abnormal limits. Indicates that new load connections are unlikely as the network is considered to be constrained.
- Severely Constraint – 11.7% of networks are in far exceedance of abnormal limits. Indicates that new load connections should not occur as the network is considered to be severely constrained.

The appraisal analysis of all ‘eight hundred and twenty-two’ have been provided in Annexures A to F. The severity of each violation has been identified for each category (Voltage, Thermal, OC setting, Backfeedability, Losses and Reliability)

From the appraisal analysis, 11.7% of networks are severely constrained which requires immediate remedial solutions. Figure 13 describes that there is an evident operational challenge which requires some sort of an intervention. While capital strengthening projects for cash strapped Utilities is a challenge, this study provides a solution to address these violations with the installation of Solar Rooftop Photovoltaics.

4.5 Summary

From the summary of the appraisal results, in Table 12, data has been captured to reflect the technical view of the analysed medium voltage networks. Note: refer to Annexures A to F for a further detailed view of the appraisal results. The significance of each criteria is identified by its percentage weighting. The analysis reveals how the severity of the violations is categorically broken down into each 'violation category'.

Table 12 Consolidated appraisal results (with criteria view)

Voltage Criteria weighting =			35%	Analysis results
C1 Range	C2 Range	SF	Violation category	
<=95	<=90	1	Severely Constraint	2.9%
95-97	90-93.5	0.6	Constraint	4.9%
97-99.5	93.5-95.5	0.4	Medium Constraint	7.1%
>=99.5	>=95.5	0	No Constraint	85.2%

Thermal Criteria weighting =		15%	Analysis results
Range	SF	Violation category	
>120	1	Severely Constraint	3.0%
110-120	0.8	Severely Constraint	3.4%
100-110	0.6	Severely Constraint	2.4%
95-100	0.4	Constraint	3.5%
80-95	0.2	Medium Constraint	10.1%
<=80	0	No Constraint	77.6%

OC setting weighting =		35%	Analysis results
Range	SF	Violation category	
>=95%	1	Severely Constraint	1.8%
90-95	0.7	Constraint	0.7%
80-90	0.4	Medium Constraint	3.4%
<=80	0	No Constraint	94.0%

Reliability Criteria weighting =		5%	Analysis results
Range	SF	Violation category	
Violation	1	Medium Constraint	15.2%
No Violation	0	No Constraint	84.8%

% Backfeedability weighting =		5%	Analysis results
Range	SF	Violation category	
0%	1	Constraint	15.2%
1-33%	0.8	Constraint	5.5%
33-66%	0.6	Constraint	10.2%
66-99%	0.2	Medium Constraint	8.2%
>100	0	No Constraint	60.9%

% Losses weighting =		5%	Analysis results
Range	SF	Violation category	
>=12%	1	Severely Constraint	1.8%
9-12%	0.8	Severely Constraint	3.3%
6-9%	0.6	Constraint	22.0%
3-6%	0.2	Medium Constraint	42.5%
<=3	0	No Constraint	30.4%

- Voltage: The data reveals that 2.9% of networks are in severe violation of compliance limits, having minimum voltages of less than 90% for C2 class networks. The networks in this violation category are deemed 'requiring urgent attention'; a more defined view of these violations can be found in "Annexure A – Voltage appraisal analysis". Whilst there are some mitigation steps that can be adopted, such as to improve customer receiving voltages by MV/LV tap boosting, these networks are ideal to consider for RTPV integration. The lesser violated categories will draw attention to grid/network planners to initiate refurbishment and/or further protocols.

- Thermal: The data reveals that 8.8% of networks experience loading above 100%. This may seem alarming, however, the analysis has been conducted from an operational view and therefore reflects thermal ratings associated with “Rate A” of conductors. Any loading greater than 90% should spark immediate interest with grid/network planners. Refer to “Annexure B – Thermal appraisal analysis” for a more detailed view.
- Overcurrent setting: This data reveals a close relationship to the above thermal criteria; however this poses a more realistic view of actual overloading that can result in supply loss due to breakers opening. The severely constraint 1.8% portion requires immediate attention, for an expanded view of this analysis refer to “Annexure C – Overcurrent loading appraisal analysis”. There is some relief that the normal inverse overcurrent setting is time-based which affords a peaking condition some leniency due to the currents encroaching pattern. However, protection settings need to be revised, if possible, to mitigate this risk.
- Reliability: While this criteria doesn’t directly impact a power system, it reflects a poorly designed and/or distributed network, see “Annexure D – Reliability appraisal analysis” for this view. The 15.2% violated networks that have been identified need to be optimised which might potentially reduce the severity of this violation.
- Percentage backfeedability: This criteria demonstrates a networks ability to be backfed should a loss of a feeder source be encountered. The significance of this criteria, as seen in “Annexure E – Backfeedability appraisal analysis”, is that while RTPV offers relief, it signifies that RTPV also increases a networks backfeedability due to curbing the network peak demands and inherently the constraining violations.
- Percentage losses: While losses from a business perspective are not preferred, this criteria is dependent on network topology. The violations here have been adjusted to consider a separation between the larger

groups of “lossy” feeders. As seen also in “Annexure F – Losses appraisal analysis” there are 5.1% of networks that are significantly lossy. To a Utility, this would imply the need for strengthening projects and also opportunity to consider optimising these networks. Addressing these lossy feeders would free up capacity and save on operational costs. Management of technical losses can have a significant impact on primary energy costs.

Chapter 5 Penetration of Roof-Top Photovoltaic (case study)

Disclaimer: The information contained within Chapter 5 has been published previously; these publications can be identified in [1] and [2].

5.1 Network model selection and appraisal

The approach of Power Utilities to address any constraints or violations, experienced within medium voltage networks, should be based on extensive technical evaluation. While overvoltage is a concern if RTPV penetration is not regulated [41], this study will show the benefit of RTPV and/or including BESS, as this offers relief for constrained networks. The results attained from the network appraisal analysis, Chapter 4 Performance appraisal, guides Utilities to focus business efforts to where it's needed the most.

Real-time power system analysis deals with two critical criteria, from the network appraisal, this being Voltage and Thermal constraints/violations. From the analysis contained in, Chapter 4 Performance appraisal, a network was identified which has both Voltage and Thermal violations. This study explores the technical influence that RTPV has on MV networks.

From the appraisal analysis, a most fitting network type was identified which is found most common amongst the feeders that were analysed. The predominate network classification is found to be a C2, TZ2 type network [33] [28]. In-line with the investigative violations (voltage and thermal) these networks have a tolerable minimum voltage of 95.5% during normal conditions, and 93.5% during abnormal conditions. The thermal limit defined in Table 7 mentions this to be alarming above 90% of its rated capacity.

Table 13 Madadeni NB36 appraisal results

Parameter	Value	Units
Nominal Voltage	11	kV
Time of Feeder Peak	Winter-WD-18:30	Seasonal Time
Feeder Peak S	4.35	MVA
Feeder P at Peak S	4.23	MW
Feeder Q at Peak S	0.58	MVARs
Feeder PF at Peak S	0.97	pf
OC Setting	250	A
Load % of OC Setting	93%	%
Feeder Minimum Voltage p.u.	92.7	%
Max Equip Loading %	102%	%
MV/LV (11-22kV/400-230V) Trfr Count	65	Count
Installed Capacity	5.29	MVA
Total Line Length	23.77	km
Backbone Length	13.79	km
Customer Base	3378	Count

The MV network selected for this study is Madadeni NB36. Table 13 shows the appraisal results of Madadeni NB36; this network has been selected due to having both voltage and thermal violations. This study goes on to showcase how RTPV and/or BESS influences the violations identified on NB36.

As stated in Table 13, NB36 peaks during a winter's weekday at 18:30. Annual statistical metering data was analysed and using statistical analysis methods, data has been fashioned into four, twenty-four hours, thirty-minute intervals; seasonal profiles. The load profile for a winter's weekday demonstrates the peak loading period and is used throughout this paper to demonstrate the effective influence of RTPV and/or BESS.

Figure 14 shows a typically generated PV profile which have been defined to represent each season [42] [39]. The duration of sunlight hours differs between each season. To be consistent with the network analysis, the winter PV profile was selected to match the network breakers winters statistical load profile.

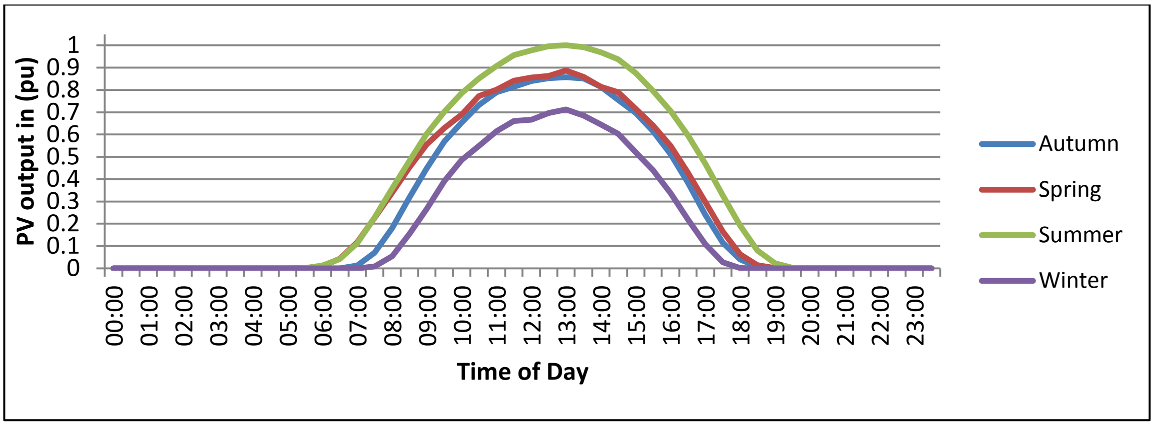

Figure 14 Typical pu generated seasonal PV output profile

When considering RTPV, some configurations should be considered to decide on the most cost-effective or technically beneficial solution for both the Utility and Customer. This paper considers the following configurations:

1. BESS alone
2. RTPV alone
3. RTPV with BESS
4. Varied levels of BESS

Power simulation has been conducted in Power Factory, the results have been extracted, analysed and stated in the legends field within the figures below, where applicable.

5.2 Installed RTPV determination

The scope of this study relates to RTPV installations connected to every customer connected to an MV network, this is defined as the high penetration of RTPV. The equipment type used in this study is found to be commonly available in South Africa.

While some studies consider large PV installation's sizes to show benefits to customers [43], this study utilises an average solar panel output of a single 200W panel installed at every connected customer [44], this is a very conservative approach taking into account that panel outputs degrade over time due to ageing and associated output reduction [45], the build-up of dirt/residue, orientation, etc.

Further to this the battery technology assumed in the assessments, also commonly available, are lead-acid type batteries. These batteries have a depth of discharge rate (DOD) and while it is common to find a DOD of 80%, for the purposes of this study it is assumed that a 100-ampere hour battery with a DOD or 50% is utilised offering 600W of power. Inverter capabilities [46] have been assumed to operate at 7 amps due to low household breaker sizing and inverter costings. This simulation design, though very conservative, leads to defining the required design for households. The criteria of the PV, battery and inverter that have been utilized in this study are considered as a base design which can be improved upon implementation.

5.3 BESS alone

Considering BESS without any external generating source would require that its charging is supported by the electrical grid. Analysis in [47] shows that there isn't any reduction in the total daily energy supplied by the Utility, hence the only benefit that can be achieved would be for the Utilities' peak load shaving. This arrangement shows no customer benefit and does not result in any energy saving for the Power Utility either. For a consumer with a BESS installation only, a likely benefit is to run on charge cycles during periods of low load and inject at periods of high utility demand especially if tariffs are based on time of use.

5.4 RTPV alone

Analysis has been considered for each residential customer having 200W (watts) of installed RTPV capacity, an overview of this connection can be seen in Figure 15 below. It is assumed that if the power generated by the RTPV would exceed their instantaneous demand then the excess power would feed into the electrical grid.

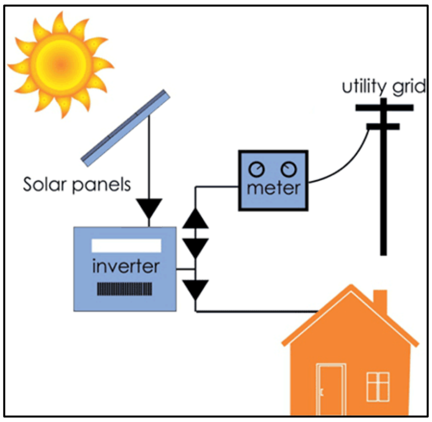

Figure 15 Conventional RTPV installation [48]

Figure 16 shows the comparison of RTPV and the network normal power curves. It can be seen that during daylight hours RTPV dispatches power; hence the reduction of power can be seen when compared to the network normal curve.

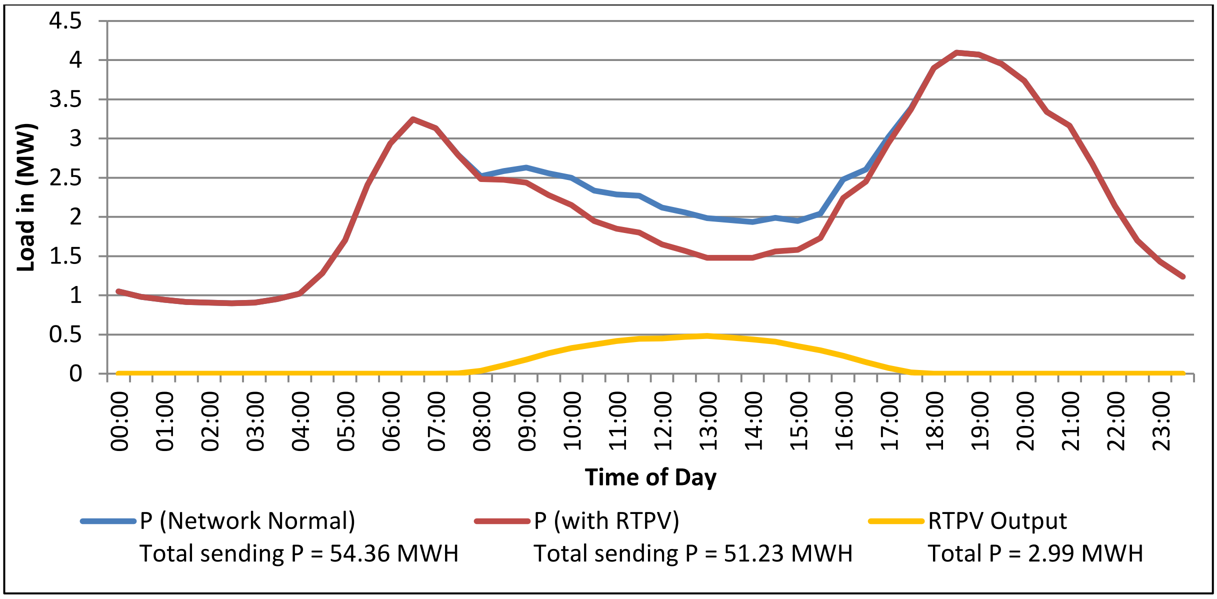

Figure 16 Active power of NB36 with 200W RTPV penetration, considered for a winter weekday

From this analysis, it is seen that the Utility loses 5.76% in revenue resulting from an overall reduction in dispatched power. While the supplied power to the customer from the utility is reduced by 5.8%, referring to data in Figure 21. Hence the benefit to the customer is credited to the RTPV injection.

The disadvantage when considering RTPV alone is that it feeds only during daylight hours, there is no effect to the networks morning and evening peaks period; the peak violations mainly exist during the evening peak time. This leaves the question of what will be the influence of RTPV combined with BESS.

5.5 RTPV with BESS

Considering the same RTPV installed capacity of 200W per residential home. In addition to this, it is assumed that each home is equipped with a battery which has 600W of dispatchable power; an overview of this connection is seen in Figure 17. This inclusion of BESS is limited only by its charge and discharge rate. Based on the available power generated by a 200W RTPV source, it was then assumed that the battery would reasonably charge and discharge at less than 7 amps.

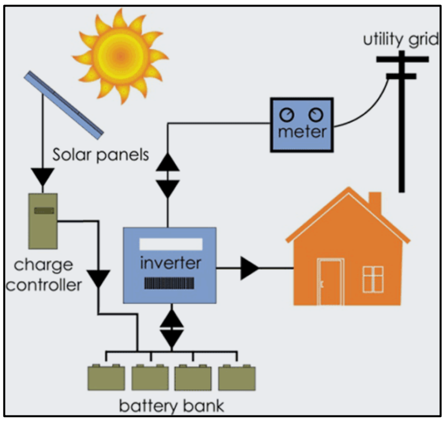

Figure 17 RTPV with Battery Storage [49]

Figure 18 shows the comparison of RTPV with and without BESS. During daylight hours 80W of power is allowed to charge the battery while the remaining power supplies the customer or overflows onto the electrical grid. During the evening peak period, the same 80W is dispatched from the stored energy over a period of 7.5 hours.

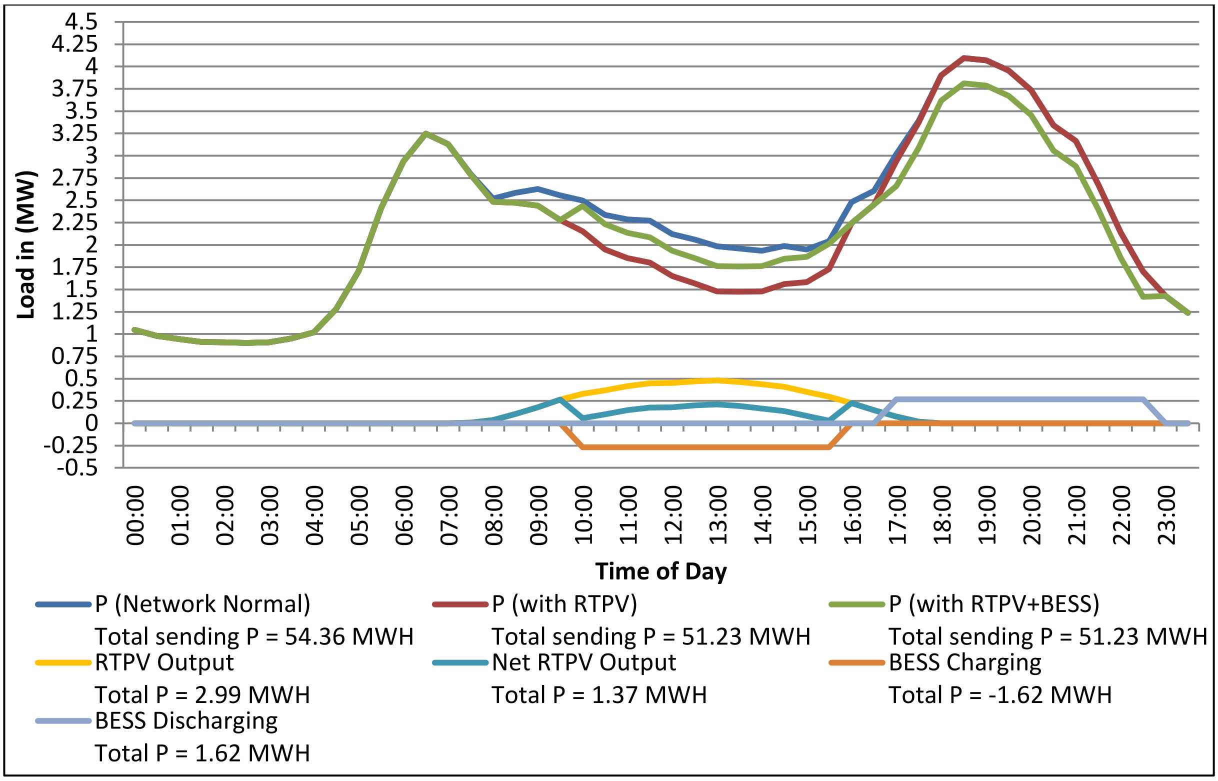

Figure 18 Active power of NB36 with 200W RTPV penetration and BESS, considered for a winter weekday

As demonstrated in Figure 18, RTPV including BESS can be seen to benefit both the Utility and Customer. The Utility benefits by the reduced voltage regulation and thermal violations which are experienced during the evening peak, and the Customer benefits by an overall reduction in power consumed.

From this analysis, it is seen that the Utility loses 5.76% in revenue. While the customer’s power consumption, referring to data in Figure 21, is reduced by 5.8%.

Further investigation of Figure 18 shows a negligible difference of power consumed if the customer has RTPV alone or including BESS.

5.6 Varied levels of BESS

While the results from the above analysis speak of how the Utility and Customers are affected, there still raises the fundamental concern related to the constraints experienced on NB36. At normal, when the load is peaking, it's found that the minimum Voltage is 92.7% and the network is thermally loaded to 102%.

The analysis shows that if customers provide backfeeding, from their stored energy, during peak times, it will reduce the constraints on the network. Analysis has considered the backfeeding of 80W, following the discussion above, and 250W for each residential customer.

Figure 19 reflects the effect of the voltage along the backbone of NB36, also showing the ability of BESS to dispatch power at 80W and 250W. It can be seen that with an increasing ability of the BESS to dispatch power, it alleviates the voltage constraint by <1% at 80W, and 2.1% at 250W.

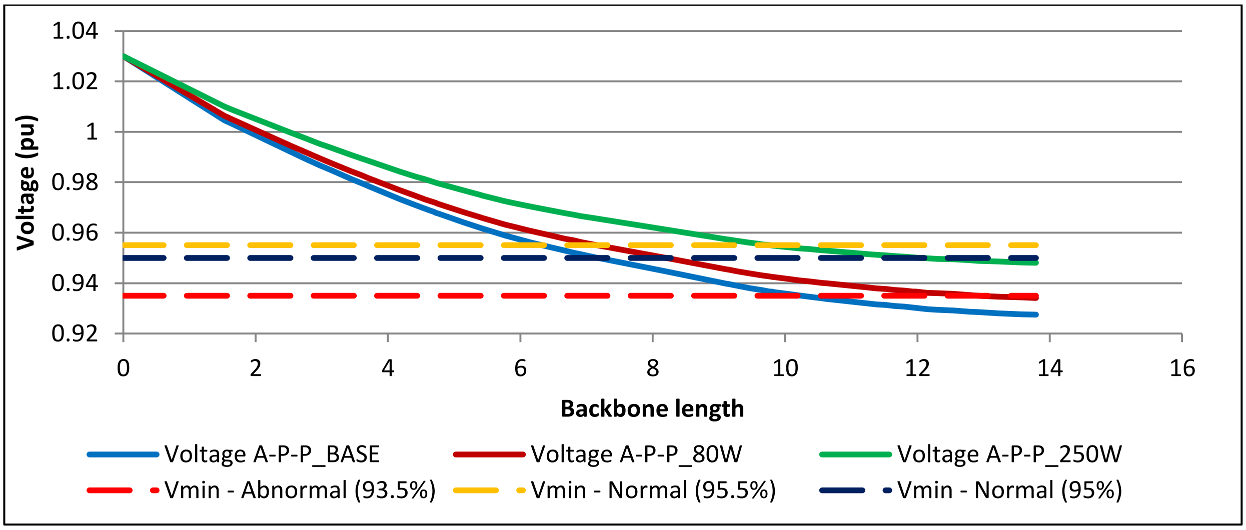

Figure 19 NB36 Minimum voltage at peak (winter weekday - 18:30)

Figure 20 shows that the normal network condition exceeds the rating of the conductor at peak loading.

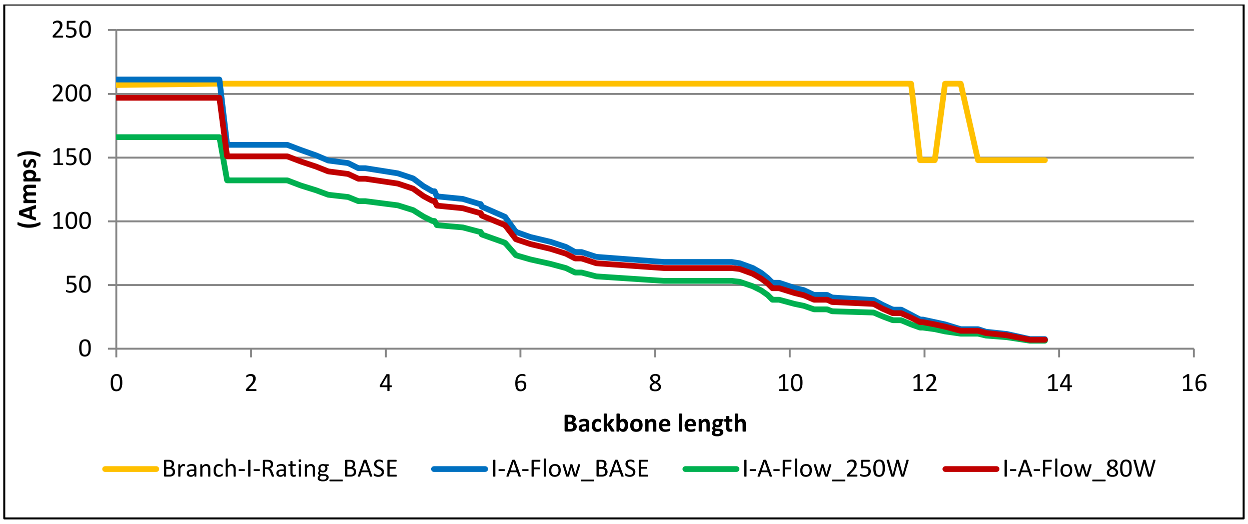

Figure 20 NB36 Thermal rating vs Load current

With BESS dispatching power we see that the thermal constraint is reduced from 102% to 94% when 80W of power is dispatched, and improved further when 250W is dispatched to 79.8%.

5.7 Power dispatched, consumed and its effect on technical losses

Figure 21 shows the network sending power, consumed power (including with RTPV, and RTPV+BESS). The difference between the sending power and consumed power is attributed to the technical losses resulting from transmitting power down the network.

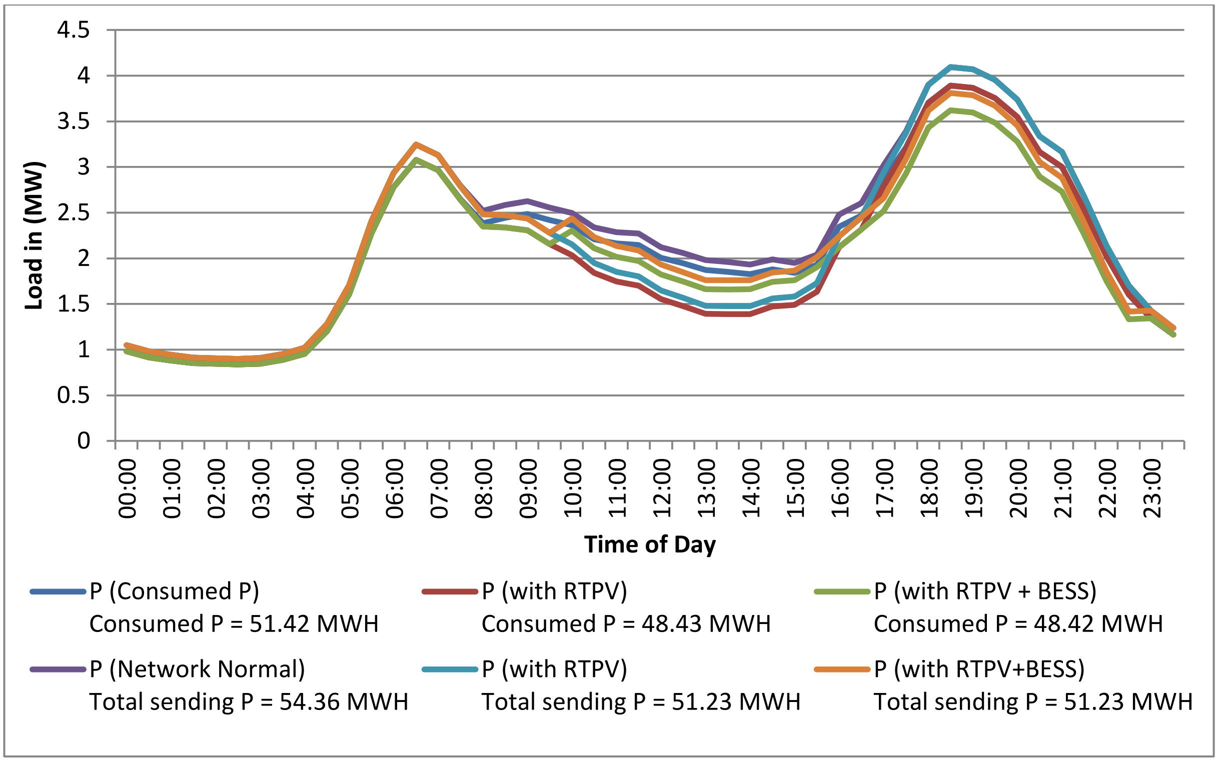

Figure 21 Sending active power, Power consumed by customers and P losses, considered for a winter weekday

Technical losses are calculated as a percentage of the total load of the feeder including both no-load and load losses. The results from the analysis help to obtain a view of the network losses; this can be used as a basis for historic trending and benchmarking and can be used as one of the triggers for network strengthening. Therefore this statistic also aids the conditioning of the priority ranking criteria. DER's may have a significant effect on network losses. A generator can lower or increase losses, depending on its location and the network configuration[15].

The technical losses vary slightly between the different options analysed:

- Network sending power vs Consumed power (Network normal) = 5.41%
- Network sending power vs Consumed power (with RTPV) = 5.47%
- Network sending power vs Consumed power (With RTPV+BESS) = 5.49%

5.8 Summary

BESS only: This option does not benefit the customer, as the batteries require grid connection to charge and discharge, not to mention efficiency losses. If discharging the stored energy occurs during peak periods, this can benefit the utility by reducing the peak violations. Therefore it is recommended that a tariff/time-of-use incentive is introduced to motivate customers for BESS only installations.

RTPV only: This is an excellent way for a customer to reduce his overall electrical utility bill; unfortunately the utility is negatively affected by the reduced sale of electricity.

RTPV+BESS: The results show that with the addition of RTPV including BESS the utility still loses revenue; however with the addition of BESS, Utilities have the ability to reduce technical violations during peak periods. Installing BESS, in this manner, shows no benefit to the customer. Therefore it is recommended that a tariff/time-of-use incentive is introduced to motivate customers for RTPV+BESS installations.

Varied levels of BESS: Though RTPV inclusive of BESS reduces the violations on the network; it can be seen from Figure 19 and Figure 20 that voltage and thermal violations persist for this specific network. Therefore it is necessary to consider an increased installation of BESS. 250W of dispatchable power offered the most appropriate quantity of power to alleviate the violations.

The effect on technical power losses: seen in Figure 21, shows a constant 5.41%-5.49% of technical power losses for each of the above considerations. This demonstrates that technical losses are similarly proportioned to its source sending power when conducting analysis on the various installation types relating to RTPV/BESS. While these amounts are typical and expected for a reticulation network - losses will defer due to topology, loading and design of networks.

Chapter 6 Conclusion and Recommendations

6.1 Challenges for the power utility:

The extent of challenges that Utilities and Municipalities would encounter when considering large scale installations of RTPV would be related to primarily; availability and visibility of data.

Current standards do not address the practical design solutions needed for all variations within customer installations and expectancy from RTPV's. This leaves an open door for non-standard customer installations which will lead to undesirable impacts on the source and shared utility power systems.

Visibility and compliance of electricity supply regulations are required at the point of supply which is conditioned to be met at the point of supply and not the point of generator connection which is embedded in the customer's installation. Therefore smart metering systems with predefined charge and discharge times/durations need to accompany RTPV installations. The extent of currently employed metering technology must be evaluated to accommodate for this operational scenarios.

The cost for an electrical system, whether or not a customer is partially or moving completely off-grid, will still be attributed to the Utility to ensure the security of supply. Therefore this study advises Utilities to lead this segment of small scale embedded generation.

An electrical system covers vast geographical areas and the installation/maintenance of RTPV's requires skilled staff. While this initially will be a hindrance, Utilities can engage with suppliers to carry out maintenance/repairs during initial warranty periods.

Data visibility is imperative for power system analysis. Both topologic and metered data needs to be available and validated. This according to [50], needs to be validated every two years. Utilities must ensure staff adequacies for data acquisition and analysis. There is a lack of data validity for non-telemetered devices, such as unknown tap positioning of retic transformers, conductor or cable which has been replaced with different ratings/types. This is challenging when configuring simulation models. For this study analysis was given to the network classification that was predominately found with residential type loads, which has been identified as C2 TZ2 type. This study, therefore, adopted a common sending voltage regulation set point of 1.03pu applied at reticulation buses. The voltage limit allowable for a normal condition is 95.5% and for abnormal conditions are 93.5. From an operations view, abnormal limits is the benchmark to adhere to, while network planners work with the normal limit of 95.5%.

The Continuous network changes resulting from rising electrification and illegal connections discredits network analysis and requires a more frequent update of simulation models.

The structural integrity of domestic households might be of concern, should this be in question then the possibility of attached/adjacent pole-mounted panel erection should be considered.

Pre-existing RTPV installation poses a problem if they do not meet with compliance requirements, therefore a Utility needs to survey pre-existing RTPV installations and take note or correct its electrical connection to the power grid. This exercise will be cumbersome but the data obtained will validate/purify the power system analysis. While site visits are carried out, it is suggested that meter re-programming include ‘Time-of-Use’ tariffs and amendments to supply agreements can be implemented.

Currently, there is no information on the degree of households which has become “self-suppliers” due to lack of a detailed registry for small-scale embedded PV plants. There is a need for such records, especially for the supplying distributor.

The assessed voltage unbalances on three-phase networks may not exceed 2%. On networks where there is a predominance of single-phase or two-phase customers, the assessed unbalance may not exceed 3%, and customer contributions to unbalance must be limited to 1% voltage unbalance at PCC, according to [29].

6.2 Recommendations for Power Utilities' resolve for constraint networks

The immediate responsible action of Utilities would be to inform field staff of instances where ratings have been exceeded. Operations philosophy for these cases will have to be temporarily amended where decisions to stop manual field switching is considered. There is a need to create tags on control/controlling devices that operational limits have been exceeded, allowing network control to manage field operations in a safe manner.

While RTPV demonstrates genuine relief for MV networks that are experiencing violations, currently there are networks with severe violation relating to Voltage, Thermal and Technical Losses. These require immediate attention as these pose a severe threat to the power system and environment. These feeders should firstly be inspected to identify any defects and/or abnormalities. The Power Utility should stop any further customer connections on networks that experience violations until these are alleviated. A Power Utility can consider mitigating violations and relieve capacity in line with the appraisal criteria and the findings in Table 11:

6.2.1 Voltage

- Evaluate if the voltages control setpoints have been optimised on the HV/MV system to ensure suitable busbar voltages on the MV system.
- Adjust the fixed tap position of reticulation customers for voltage-sensitive customers.

- Investigate the use of voltage regulators to provide temporary relief for voltage violations.
- Phasing corrections to optimize MV phase balancing.
- Consider automatic tap changers in distribution reticulation transformers.
- Installation of shunt capacitors to support voltage.

6.2.2 Thermal

- Investigating if the load can be shifted to free up capacity by optimising networks.
- Investigate if a thermally violated network is experiencing violations as a result of lower-rated conductors/cables in small isolated locations.
- Infer-Red scans can be conducted to identify high thermally loaded equipment on networks, which can be specifically upgraded such and portion of lines, jumpers, links, etc.

6.2.3 Overcurrent

- Re-templating the line conductors so that it is tensioned to reach its full templating temperature, which is the safe allowable temperature that still maintains the statutory clearance above ground level [51].
- Short term solution, evaluate possible network reconfiguration to minimise fault levels. Engage with plant, planning and settings to determine the viability of options considering other network parameters that may change (e.g. reliability indices and settings).

6.2.4 Reliability

- Installation of automatic/remotely controlled breakers to mitigate violations during peak period.
- Carefully monitor load growth to ensure potential risks are managed.
- Pro-active evaluation of networks can help identify the nearing of violations due to growth or topology changes.

- Shorten LV-lines.
- Constructing another line/cable in addition to the existing line/cable(s).
- Upgrading or augmenting existing transformers.
- Upgrade existing equipment, replacing inadequately rated equipment with equipment of a higher fault level rating.

6.2.5 Backfeedability

- Implementing any backfeedability plans to mitigate violations.
- Implementing or put projects/refurbishment plans in place to address the violations, possibly even splitting large networks.
- Create normally open points (network splitting). Change the network configuration such that the impedance (between the generation and equipment with inadequate fault level rating) is increased and the fault level reduced.

6.2.6 Losses

- Reconfiguring the network in order to change the power flow and thereby reduce loading on constrained elements
- Consider higher cross-section/sizing for conductors

6.3 Future studies

To ensure connectivity to the grid is done in a safe manner and that customers don't get burdened with unnecessary costs, the Utility, in order to accommodate high levels of RTPV installations, needs to establish installation guidelines, clearly defining operational requirements and limits. An ESI standard in this regard would be favoured as there would be standardisation across all supply authorities. With this, a typical installation comprising of an appropriate solar panel, inverter, smart meter and battery will be standardised and comply with electrical regulations [52]. If an all-encompassing metering unit is designed and tested, then further assessments can be done to conduct harmonic analysis with high levels of RTPV penetration.

This study does not use specific technical designs but rather showcases to the ESI what the benefits are, and presents the impact of the implementation of RTPV to alleviating network constraints. Therefore it is encouraged that the ESI considers the development of a ‘smart metering unit’ which has the ability to manage supply, storage, dispatchable renewable energy for consumption, programmable for utility directives and accommodating of flexi-time of day tariffs. This unit must also have the ability to isolate from a faulted supply connection for both the safety of persons and apparatus.

Electricity being stated as an essential service is to be made available to all citizens. According to the Free Basic Electricity policy, an allocation of 50kWh per month should be provided to poor households. Further analysis of RTPV installations with 50kWh monthly capacity needs to be conducted to support the free electricity initiative by using RTPV with BESS. This directly reduces utility costs. This study has demonstrated the effects of 18kwh per installation, while this address the aim of this study to elevate technical violations, further installed capacity can be explored.

The distribution network has a limit to how much renewables can be integrated due to voltage and/or thermal constraints. The limit is often referred to as ”hosting capacity”. When the limit is reached, the integration either stops or capital grid investment needs to be made to host more connections. From this study it is observed that each network will have a unique hosting capacity, based on electrical parameters, therefore each MV network will require individual analysis [53].

From the analysis summarised in Table 14, it is found that for the various operational scenarios, it financially affects the Utility and the customer. Therefore it is desired to conduct a direct cost and benefit analysis for Utilities and Customers; however, this will need to be conducted after establishing the industry-standard equipment types. Consideration needs to be given for a proposal of customer tariff rates which includes RTPV with and without BESS. It is recommended that a Flexi tariff structure is introduced to promote the installation of BESS [54], since BESS installations don't have any financial benefit to the customer as seen in Table 14.

There is a need to further investigate power quality issues such as harmonics generated by inverters, voltage unbalance, etc. [8]. Other aspects to consider are due to PV been installed gradually at random locations within MV networks; this affects the voltage balancing/current phasing and network zoning over a period of time. There is therefore a need for further assessments into future network requirements taking into account load and generator forecasts [55].

There is no type testing or SANS approved testing houses for inverters in South Africa at the moment. In the interim, an alternative method needs to be developed to ensure that inverters which are employed operate within some defined limits in the absence of an inverter standard for households. Inverters are an important component of SSEG and their optimum performance is equally important [4]. To unlock the potential for rooftop PV in South Africa technical standards must be finalised that will inform rooftop PV [9].

6.4 Concluding remarks

It is seen that minimal amounts of RTPV penetration with BESS can eliminate technical constraints. This benefits the utility by addressing network violations and customers benefit by having their electrical bill reduced. Table 14 summarises the four implementation scenarios considered for this study.

This study has demonstrated what the least amount of RTPV can do to improve the technical performance of a network. An additional benefit is reducing thermal and voltage constraints which will allow more customers to be energised. Furthermore, it has been demonstrated as a deferral solution to capital projects, especially in dense areas. The ESI is encouraged to explore

RTPV and BESS, as with the price of these installations continuing to reduce [21] [12], the possibility of having more of these DER's connected to the electrical grid is imminent, especially with the South African government starting to fund renewable installations [56].

Table 14 Summary of analysis

Case study considerations:	Power Utility	Customer
1. BESS only	☑ Beneficial for load shaving	☒ No benefit
2. RTPV only	☒ Overall loss of revenue	☑ Reduced electricity expenditure
3. RTPV + BESS	☒ Overall loss of revenue	☑ Same reduction of electricity expenditure with or without BESS ☒ Unwarranted cost of BESS
4. Varied levels of BESS	☒ Overall loss of revenue ☑ Improved minimum voltages ☑ Reduce Thermal loadings	☑ Same reduction of electricity expenditure with or without BESS ☒ Cost of BESS will vary

For BESS to become feasible for the customer it is recommended that it becomes incentivised by the power utility either through a time of day tariff structure or a rebate incentive [57]. Unless BESS is incentivised, it is anticipated that it would not materialise at a residential level on a large scale.

It is envisioned that for a Power Utility to remain a significant role player in the electrical supply and demand industry, that consideration is seriously given to being at the forefront of roof-top PV installations with battery storage within their customer supplied residential homes. If an electrical industrial supplier identifies the potential of large scale supply and maintenance of RTPV to households, this will reduce a Power Utilities role thereby negatively impact them.

This study promotes a Power Utility to take the lead in the large scale roll-out of RTPV and BESS. This not only helps to reduce the burden on the power system but to also secure the future of the electricity supply industry. Having the installations implemented by the utility and/or partially incentivised opens the door to securing a maintenance tariff in customer's utility connection agreements. This can be used by the business to fund maintenance and repairs for the life of the SSEG. This is necessary as RTPV's and BESS have a +/-10 year average lifespan. A maintenance tariff will financially benefit a Utility, thereby securing its future roles as the key electrical supplier for South Africa.

Electricity is the cash cow not only for municipalities but also to a power utility. When RTPV becomes cheap and beneficial to consumers, this will affect the revenue generated from the sales of electricity. The material costs will not be a limiting factor for very much longer, considering the declining costs worldwide. Power utilities and municipalities should consider taking ownership of these segments and offer a long term payback period as an option for customers or implement a type of renting/leasing service for SSEG equipment to secure future business. This will dynamically change the electrical industry. Current plans to meet electrification demands have lengthy timelines and is often associated with the establishment of new infrastructure. RTPV and BESS can provide immediate, cost-effective and sustainable solutions as demonstrated in this thesis.

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Annexure A – Voltage appraisal analysis

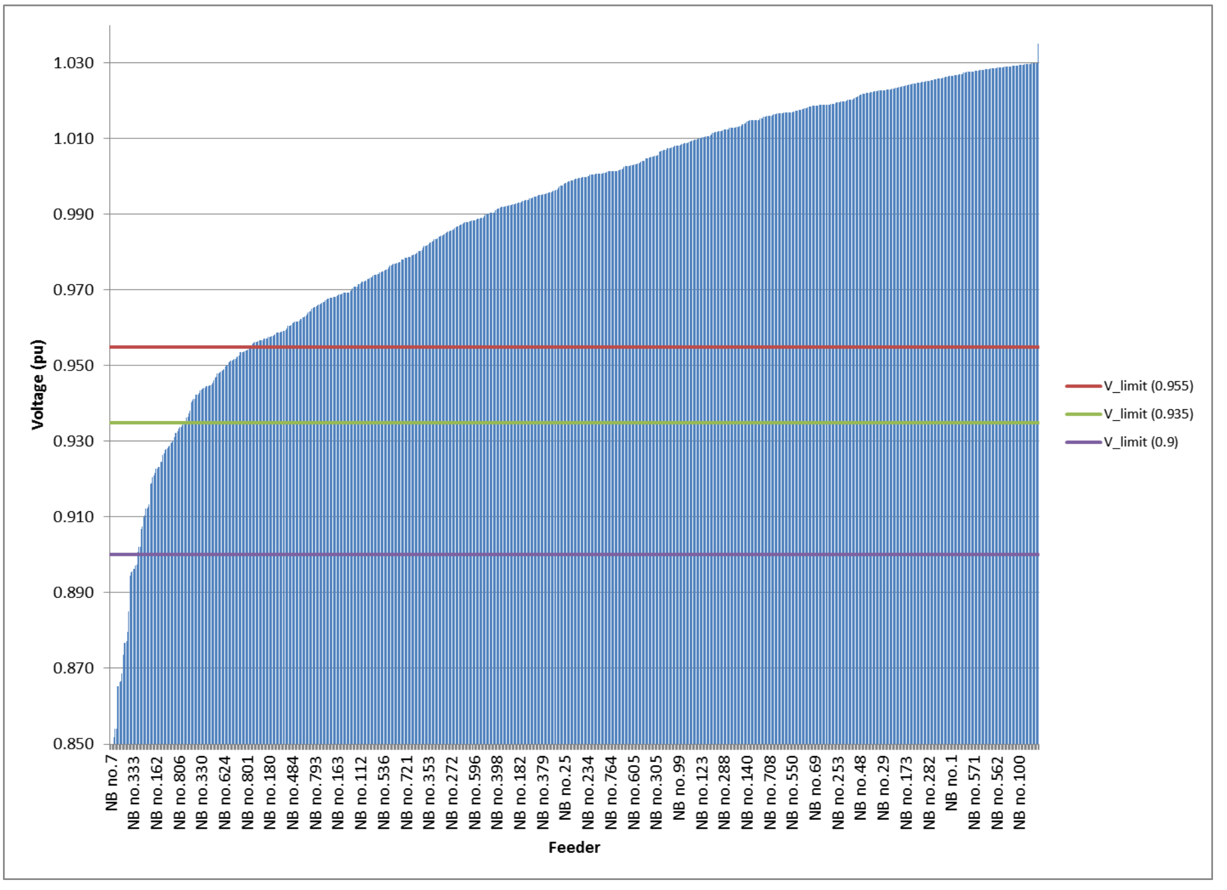

Figure 22 Voltage appraisal results (column view)

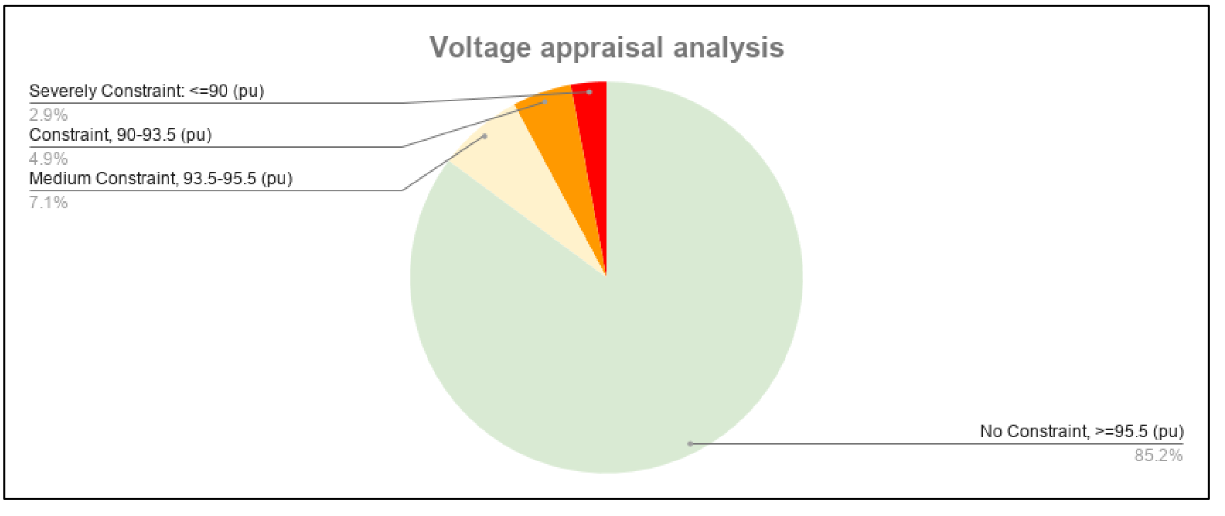

Figure 23 Voltage appraisal results (pie view)

Annexure B – Thermal appraisal analysis

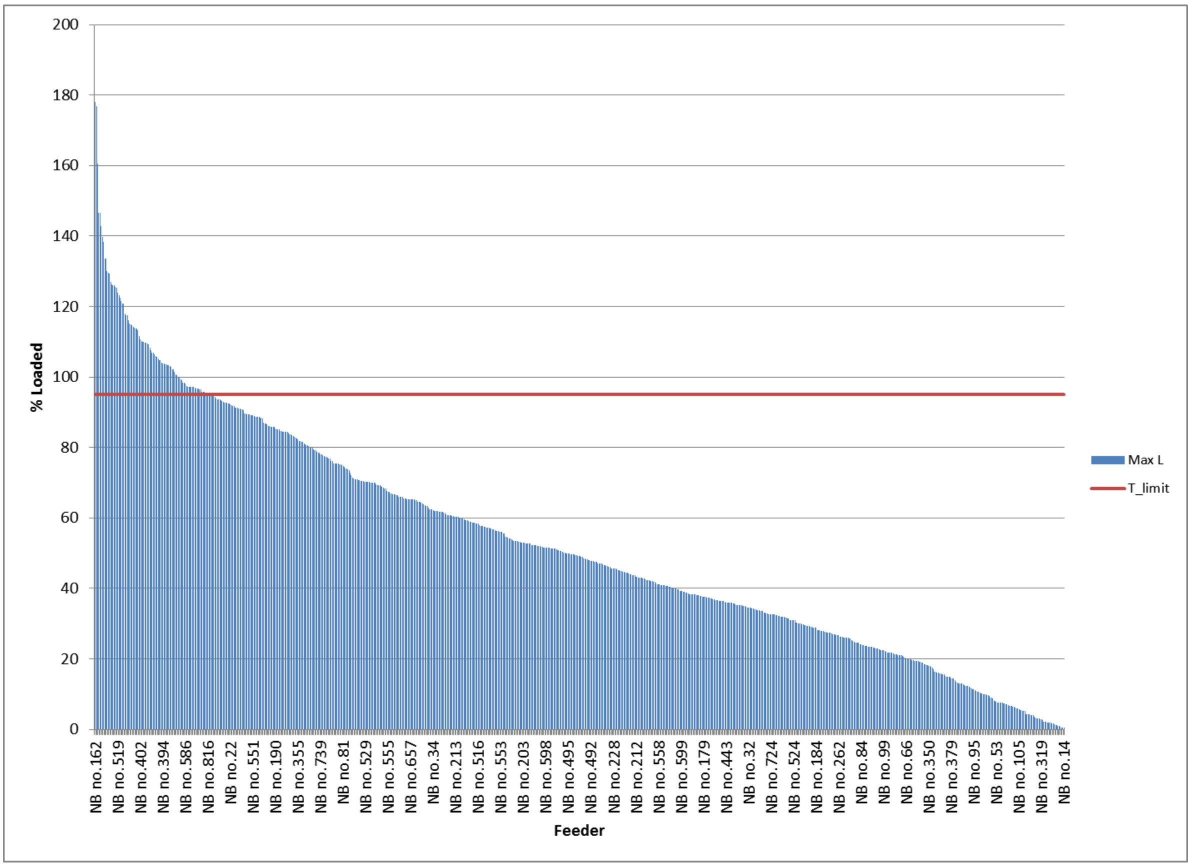

Figure 24 Thermal appraisal results (column view)

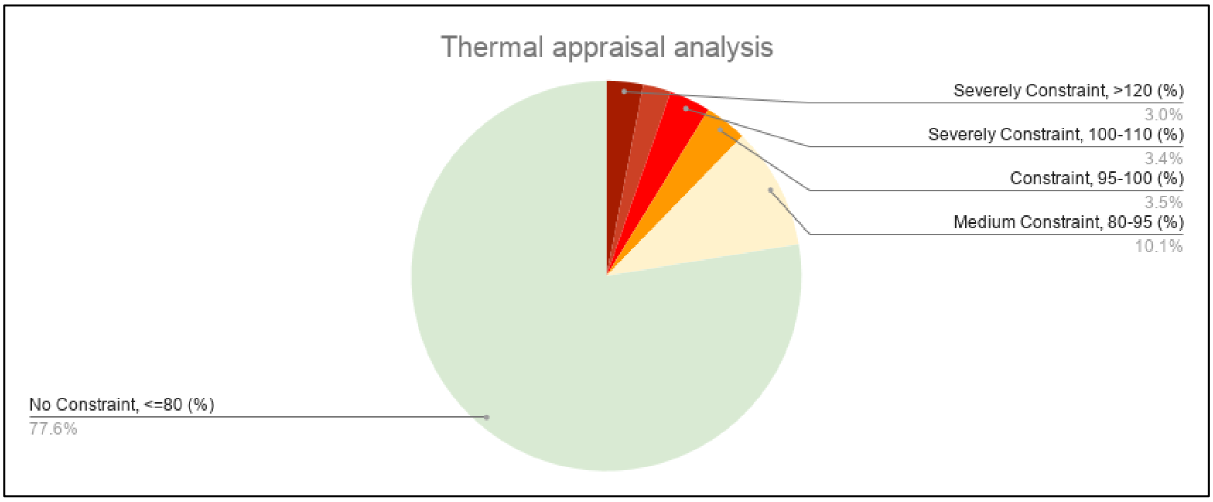

Figure 25 Thermal appraisal results (pie view)

Annexure C – Overcurrent loading appraisal analysis

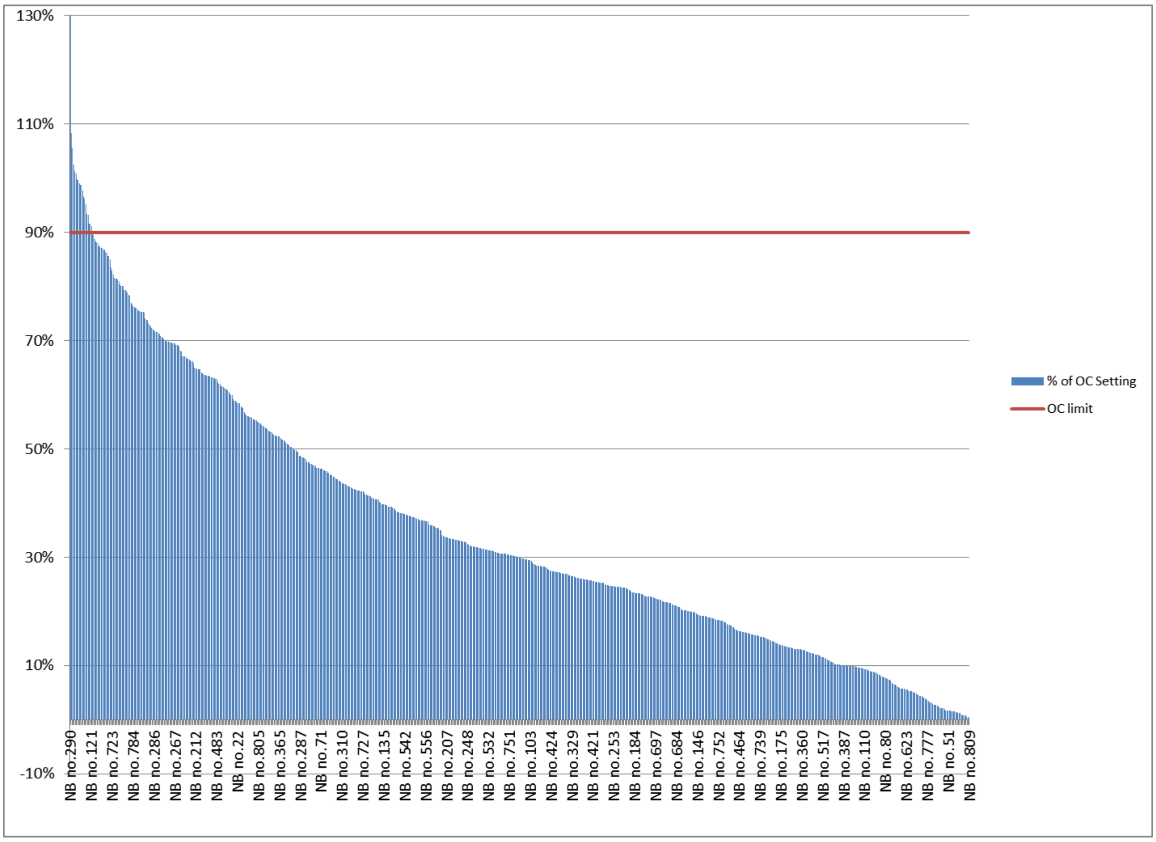

Figure 26 Percentage loading of OC setting appraisal analysis (column view)

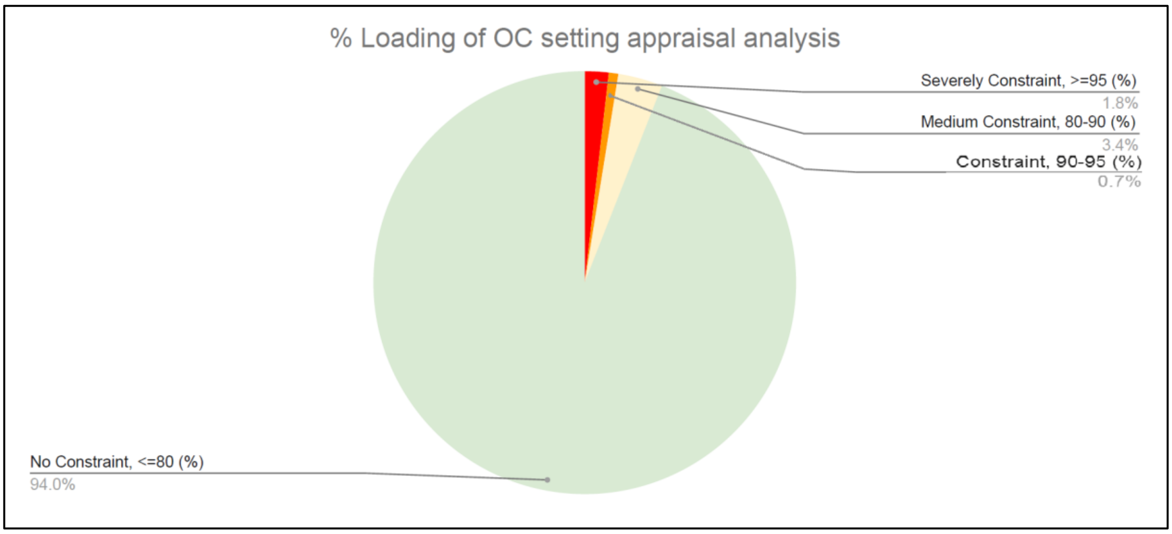

Figure 27 Percentage loading of OC setting appraisal analysis (pie view)

Annexure D – Reliability appraisal analysis

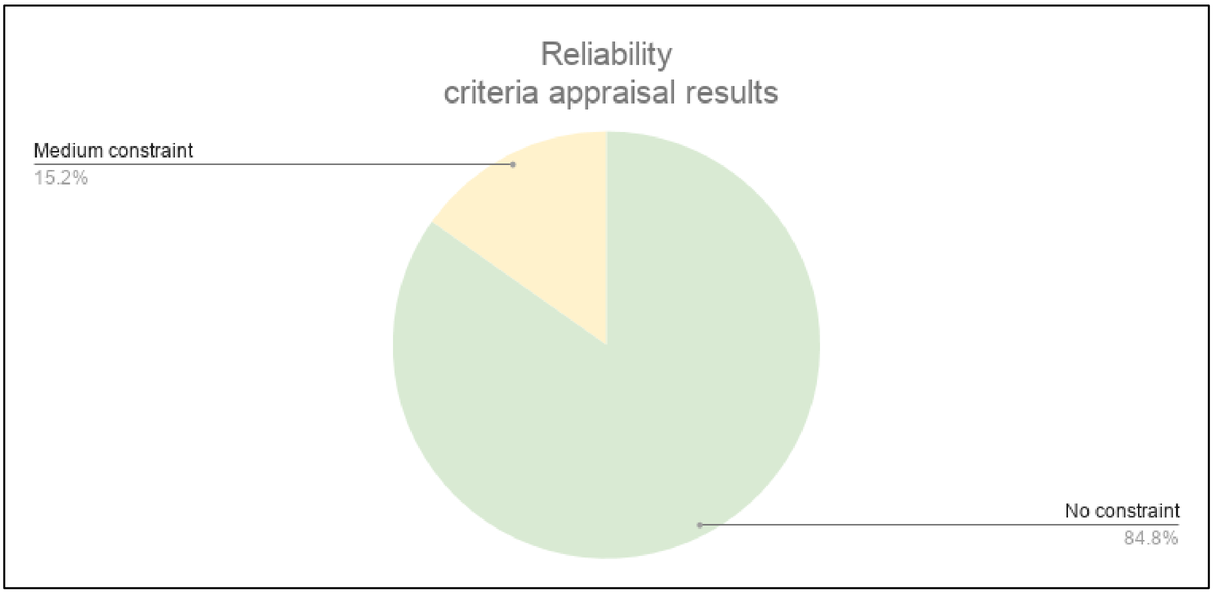

Figure 28 Reliability criteria appraisal results (pie view)

Annexure E – Backfeedability appraisal analysis

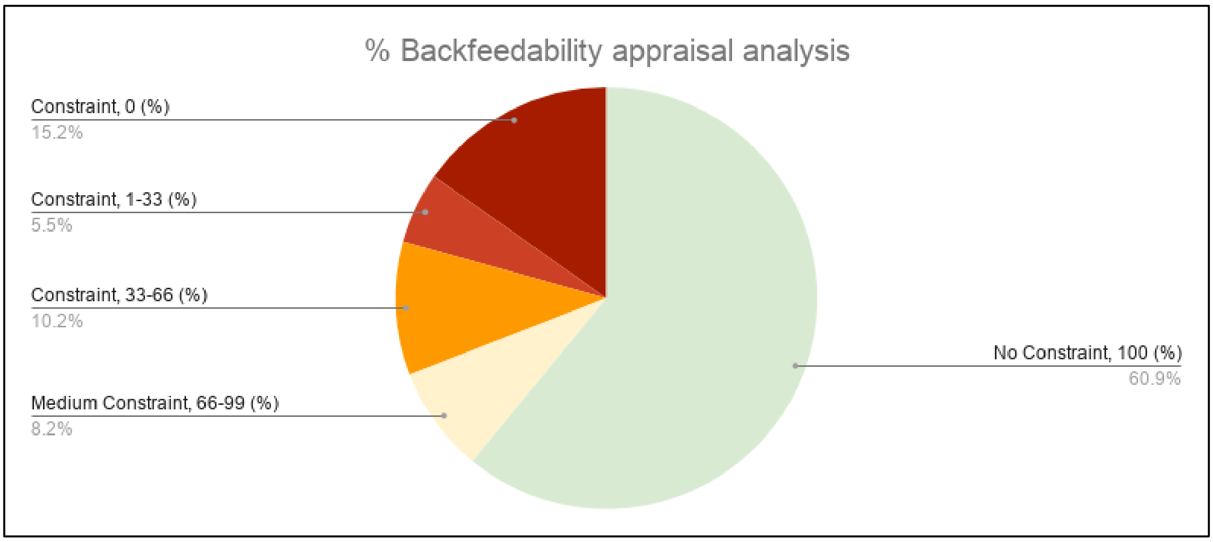

Figure 29 Percentage backfeedability appraisal analysis (pie view)

Annexure F – Losses appraisal analysis

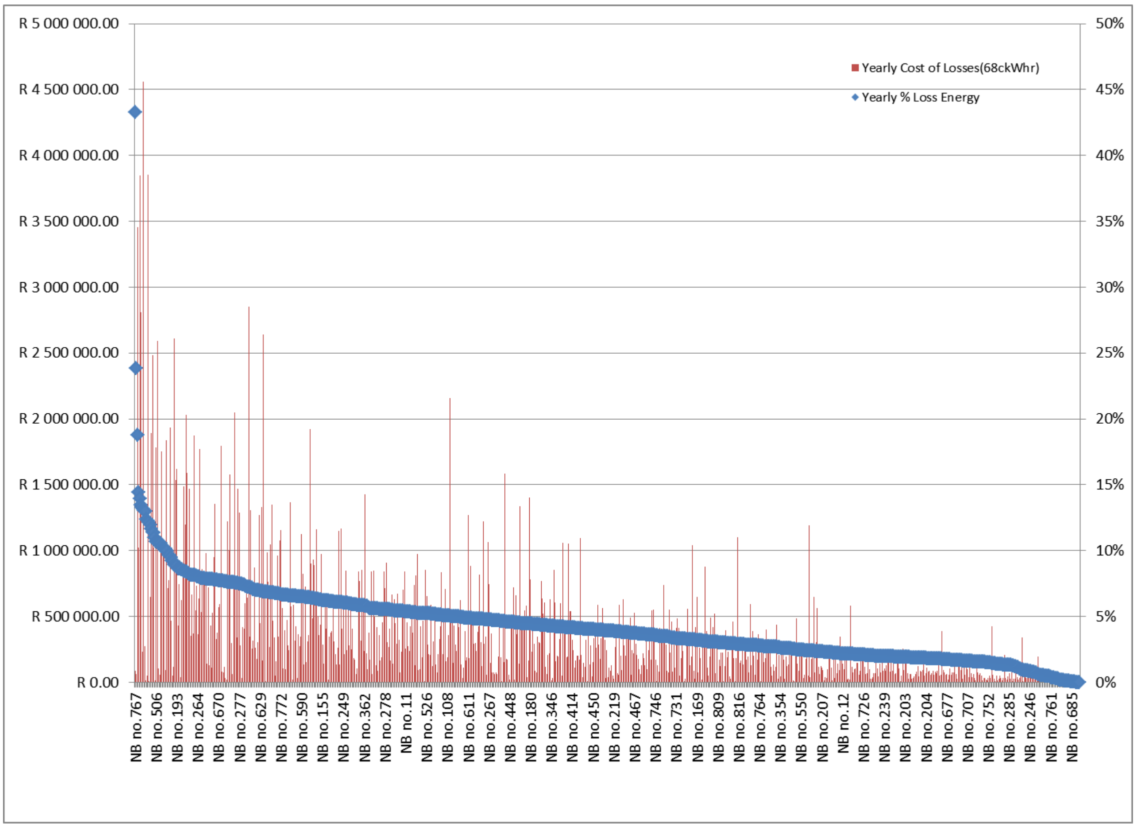

Figure 30 Percentage losses appraisal analysis (column view)

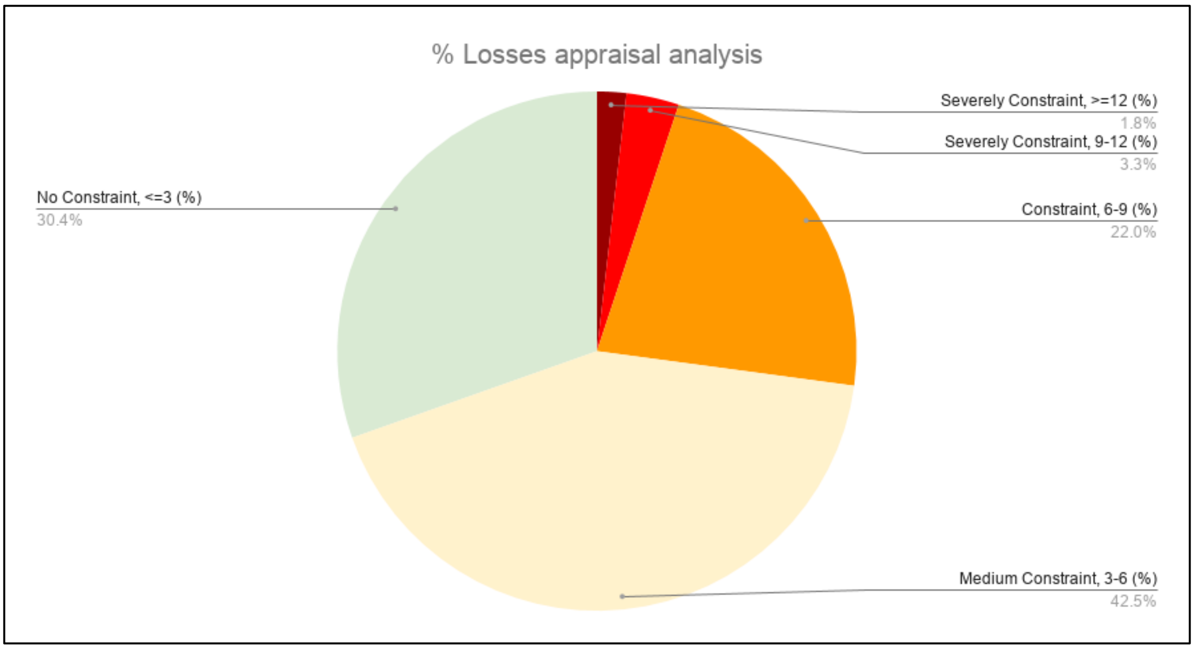

Figure 31 Percentage losses appraisal analysis (pie view)