UNIVERSITY OF KWAZULU NATAL

SCHOOL OF ELECTRICAL AND INFORMATION TECHNOLOGY

TECHNO-ECONOMIC IMPACT OF SINGLE FEEDER – MULTIPLE MICROGRIDS ON POWER UTILITY COMPANIES

BERNARD NGUEJI MUANDA

Dissertation

Submitted in partial fulfilment of the requirement for the Degree

Master of Science in Electrical Engineering, College of Agriculture, Engineering and Science, University of Kwazulu-Natal

Supervisor: Professor Akshay Kumar Saha

DECLARATION - PLAGIARISM

I, BERNARD NGUEJI MUANDA declare that

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2. This thesis has not been submitted for any degree or examination at any other university.

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26 NOVEMBER 2019

ACKNOWLEDGEMENT

In God I trust. He’s been there, carried me throughout my life, in all circumstances and will always be there for me. To him be the glory.

I would like to acknowledge and thank Professor Akshay Kumar for his willingness to supervise and constructive guidance throughout the compilation of this dissertation. His assistance is highly appreciated.

To my Wife Bijou Mubikay Muanda, my son Bill Ngueji Muanda and my Daughter Belle Nsungi Muanda, you are and you will always be my source of inspiration. Thank you for your understanding and support during the course of my studies.

ABSTRACT

Increase in the cost of conventional electrical energy and the decrease in the cost of solar renewable energy could be the catalyst for the adoption of microgrids in South Africa. To this effect, Urban Secure Complexes and Business Parks are well suited for the establishment of microgrids but their establishment can be successful only when they offer competitive and reliable energy while backed up in by the legal regulatory framework. The use of microgrid in parallel with an existing electrical grid could affect the Electricity Network Service Provider (ENSP) both technically and financially. The technical impact depends on the strength of ENSP's at the point of common coupling while the financial impact depends on the loss of energy revenue replaced by energy sources within the microgrid. This research considers residential scale microgrids with high penetration of Photovoltaic power plants (PVPP) and Battery Energy Storage Systems (BESS). Considering the capital of establishing a microgrid and the ENSP's energy tariffs, the research establishes how favourable are the South African market to the establishment of microgrids, how they technically impact a distribution feeder and how they affect the ENSP financially. The research is based on a single feeder supplying six Urban Secure Complexes (residential load), each converted into a microgrid with dispersed PV generation. The residential loads are based on existing establishments in Midrand but the economic modelling considers the tariff from a major ENSP in Johannesburg, Cape Town and Durban. The network model is developed in PowerFactory® while the economic model is developed in Excel. The research will demonstrate the technical and financial impact of establishing such microgrids on the ENSP. The technical impact assessment is focused on ensuring a healthy operation between for the combined microgrid and ENSP grid while connected. The financial impact will focus on the viability and feasibility of the microgrids while demonstrating the revenue losses for the ENSP. Once implemented, the impact of microgrid benefits both the consumer and the ENSP when allowed to operate in collaboration. Consumer save through reduced electricity bills while the ENSP benefits from the reduced maintenance, deferred CAPEX and energy at competitive prices.

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LIST OF ABBREVIATIONS

BESS	:	Battery Electrical Storage System
BOP	:	Balance of Plant
CAPEX	:	Capital Expenditure
CCG	:	Combined Cycle Gas
CCVSI	:	Current Controlled Voltage Source Inverter
CHP	:	Combined Heat and Power
CIU	:	Customer Interface Unit
CSP	:	Constant Set Point
DB	:	Distribution Board
DER-CAM	:	Distributed Energy Resources Customer Adoption Model
DG	:	Distributed Generation
DoD	:	Depth of Discharge
EMS	:	Energy Management System
ENSP	:	Electrical Network Service Provider
ESS	:	Energy Storage Systems
EV	:	Electric Vehicle
FAT	:	Factory Acceptance Test
HV	:	High Voltage
ICT	:	Information and Communication Technology
IEA	:	International Energy Agency
IPP	:	Independent Power Producer
IRENA	:	International Renewable Energy Agency
IRP	:	Integrated Resource Plan
kVA	:	kilo Volt-Ampere
kW	:	kilo Watt
LDC	:	Line Drop Compensation
LV	:	Low Voltage
MCC	:	Microgrid Central Controller
MV	:	Medium Voltage
MW	:	Megawatt
NERSA	:	National Energy Regulator of South Africa
NMD	:	Notified Maximum Demand
OPEX	:	Operating Expenditure
PCC	:	Point of Common Coupling

PF : Power Factor
PLC : Power Line Carrier
POC : Point of Connection
PPA : Power Purchase Agreement
PV : Photovoltaic
RE : Renewable Energy
REFIT : Renewable Energy Feed-In Tariff
RTDS : Real Time Digital Simulator
SABS : South African Bureau of Standards
SAGC-RPP : South African Grid Code for Renewable Power Plants
SANS : South African National Standards
SAPVIA : The South African Photovoltaic Industry Association
V2G : Vehicle to Grid
VCVSI Voltage Controlled Voltage Source Inverter
VRE : Variable Renewable Energy

1 INTRODUCTION

1.1 Introduction

All over the world, the demand for electrical power is forever increasing in developed, developing and even under-developed countries as shown in Figure 1-1. This is fuelled by the industrial expansion and/or the population growth [1]. Satisfying this demand while ensuring the supply reliability and availability requires the upgrade and, in some instances, the expansion of the existing electrical networks' power stations, transmission and distribution lines and the associated infrastructure required to produce and transmit power from generation stations to load centres.

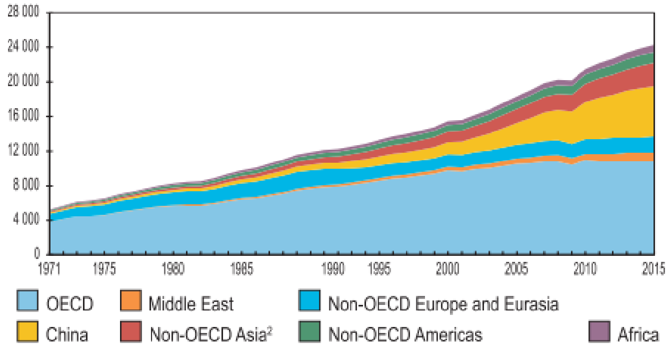


Figure 1-1: World electricity generation by region [1]

The expansion and upgrading of electrical infrastructure require significant Capital Expenditure (CAPEX). These might also lead to increased Operating Expenditure (OPEX), hence a significant capital outlay requirement for the concerned Electrical Network Service Provider (ENSP). In the Africa, most of network service providers are state owned and do not have sufficient financial power to carry out large-scale project on the generation, transmission, or distribution plant [2]. They rely mostly on borrowed funds from local or international financial markets [3], [4]. These funds repaid over a defined period but they attract significant interest and erode the Power utility's much-needed profit margin to use for further network expansions or upgrades. This leads to a vicious circle of debts, poor and unreliable networks. One of many ways of reducing the borrowing circle is to raise cash in the form of tariffs but that implies raising the cost of electricity by increasing the tariffs.

In the last decade, the cost of electricity in South Africa has increased considerably and has even surpassed the inflation over the same period [5]. On the basis of recent application to the National Energy Regulator of South Africa (NERSA) for tariff increase by Eskom (the biggest South African power utility), it is herein envisioned that trend for electrify tariff increase will continue for the near future. Eskom being the single biggest role player in the market and a bulk energy distributer to most of the utility companies in South Africa, any of its successful tariff increase application will trigger the same effect for all its municipal customers empowered to distribute electricity. In the absence of funding or subsidies from the government, utility providers such as municipalities have no choice but to pass on any increase onto the end consumers. For this reason, it is essential to understand that residential consumers will be the most affected and they will experience decreased their disposable income and possibly quality of life.

A traditional electricity network operation also referred to as “vertically integrated” consists of generation, transmission, and distribution of power to the consumers. Electrical energy is generated in bulk at one or more power stations. It is transmitted over long distances to load centres and finally distribution to the consumers. While the location of load centres is dictated by factors beyond the scope of this research, the location of power stations is dictated by the availability of fuel or primary source of energy such as coal, hydro, gas, wind, tidal, etc. for which reserves is often in located far from load centres. In recent years, concerns have been raised regarding the traditional electricity grids, from its power generation sources, transmission lines to the reliability of supply to consumers [6].

The dependency of power generation on fuel raises concern on the fossil fuel reserves that researchers are concerned about the fast depletion and impact of their usage on the environment. From power transmission’s perspective, energy losses are incurred along the transmission lines, more so when the load centre is far from the sources. Losses on the transmission line are also accounted for in the consumer tariff and are therefore paid for by the end consumer. Finally, the loss of some component can lead to power outage for a large number of consumers, therefore affecting the electricity supply reliability. This could happen regardless of the level of redundancy built into electrical network, which in most cases is radial for residential consumers.

In recent years, new development in electricity generation technology have made it possible for residential electricity consumer to generate electricity using small-scale generators (micro-sources) designed for connection and operation in Low Voltage (LV) networks. These micro-sources are characterised by their close proximity to the consumer and their varying location within the same network in contrast to the bulk generation from vertically integrated networks. For this reason, they are referend to as “Dispersed” or “Distributed” Generators (DG).

A DG can be used as stand-alone (autonomous operation) or can be connected to an existing network (synchronised). When synchronised, it is possible for power to be exchanged between the consumer and the utility grid. They allow the consumer to draw power from the grid when the DG power is insufficient to meet the local demand or export when the opposite is true. In this scenario, the consumers can also now produce electricity. Hence the use terminology “Consumers” to describe a consumer that has any form of local generation or DG.

DGs use different technologies as primary sources of energy. These technologies are broadly grouped into two categories listed as fossil fuel and Renewable Energy Sources (RPP). Fossil fuel based residential DG are small fuel generators. In contrast, the most prominent RPP sources include hydro, geothermal, solar and wind. The International Energy Agency (IEA) reports that solar photovoltaic technology (PV) and wind energy have retained the highest growth rate than any other form of electricity generation over the last decade [1]. In particular, PV plants are the DG technology of choice amongst consumers, especially those in residential areas where the rooftop PV is also reported to dominate the landscape for residential electricity consumers in Africa [7]. Most DGs are capable of supplying the residential load with no assistance from the grid but under for some DG, the utility grid has to be connected to provide support to the microgrid when and where needed.

Recent literature shows that the connection of a DG to the utility's grid disrupts the established way of generating, transmitting, and distributing electricity to the consumers. The ability to exchange power between any DG and the utility's network makes it possible for power to flow in both directions and creates challenges for the existing grid, mostly for Solar and wind based RPP.

Challenges associated with the solar and wind RPP are mainly linked to the variability and intermittence of the primary energy [8]. These primary energy sources vary with atmospheric conditions and cannot be determined or predicted with high certainty. The variations in input energy create fluctuations in the output power for which the deficit or surplus needs has to be accommodated by the utility. An alternative to managing the flow of power between the utility grid and the RPP is to use a Battery Energy Storage System (BESS) for the storage of excess energy or for complementing the system in the event of a deficit from generation [9], [10].

In the case where the consumer is allowed to feed excess energy to the grid, the tariffs seem structured in favour of the ENSP but this can be minimised if excess energy is shared with non-consumer neighbouring consumers. One way of achieving sharing excess or deficit of energy at consumer levels is by using microgrids.

Considering the rising cost of conventional electrical energy and the trend observed around the world showing that solar PV energy is leading the way for residential consumers is also the fastest growing electricity production technology, it is worth analysing the merit of such system in the South African context where forming a microgrid is likely to succeed due to the spatial town planning of residential areas.

In the case of an RPP connected to the utility grid, the exchange of power (when feed-in is allowed) between them allow the utility to provide the deficit or absorb the excess from the consumer. In stand-alone operating the consumer has to ensure their own load-generation balance. To compensate for this output fluctuation solar and wind DGs can operate in parallel with a Battery Energy Storage System (BESS) that can act as a buffer to absorb or provide any imbalance between the consumer's generation and consumption.

When connected to the utility's grid, an increase penetration of PV and BESS in the energy mix will decrease the pressure for the utility to build more infrastructure. Penetration of the technology will continue to grow especially when considering its declining cost, along with those of Battery Storage Systems [7].

PV and BESS technologies, allow for the shaping of the generating solution with the generator and storage containers stating from small sizes, defining individual use to bigger sizes akin to conventional power stations, offering DG electricity generation scalability. Both PV and BESS technologies have evolved remarkably, showing a level of maturity that is contributing to the reduction in cost. Their level of adaptability has allowed for their increased adoption in the residential and commercial environment, whereby consumers own and operate them

As the penetration of DG increases, the established Low Voltage Networks, or the grid, it becomes possible to form community-based microgrids capable of operating in an island or grid-connected modes and benefiting the consumers and possibly the Network Service Provider (utility).

1.2 Background of the study

The demand for electricity drives the network expansion and the cost of electricity for the consumer. Electrical energy consumers can avoid higher cost of electricity is by considering alternative energy sources while using the ENSP’ grid to manage the excess of deficit with respect to the load supplied. For each consumer, there should be merits in connecting all DG to form a single microgrid. The following section discuss the cause of electricity demand, alternative energy and the use of microgrid to tackle the increasing demand for electricity in urban areas

Rapid industrialisation, population growth, urbanisation and improved energy access are driving the global rise of electrical demand [11]. The South Africa electricity market exhibits the same trend. The 2016 census released by Statistics South Africa shows in Figure 1-2 an average annual population growth for the three biggest provinces of which Gauteng Province ranked the highest at 2% (or 225 000 people) per annum. In terms of towns, Johannesburg and Tshwane metropolitan municipalities recorded a population increase of 12% between 2011 and 2016 compared the remaining district municipalities with the Gauteng province [12]. This shows that the highest population growth remains concentrated in major town and therefore it is expected for this increase to put further pressure on the existing infrastructure, including those for the provision of electricity in order to meet the demands of the increasing population.

In South Africa, the electrical network topology remains largely vertical where power plants are located far from the consumers. Regardless, electricity remains more accessible in urban settlements, because of the proximity of the consumers to the electricity grid. The population growth in the urban area contributes to higher electricity demand and therefore additional pressure on the existing utility’s infrastructure. The impact of this pressure can be experiences across multiple cities where load shedding and protection tripping are frequent in the distribution networks [13].

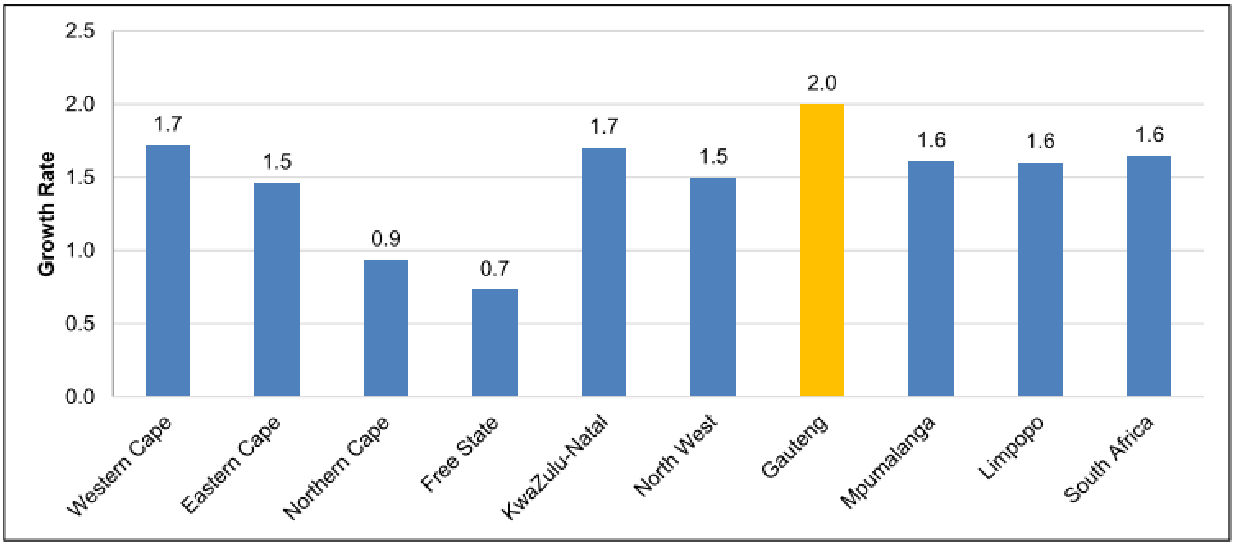


Figure 1-2: South Africa average population growth between 2011 and 2016

In order for the utility to provide quality services in line with their conditions of distribution licenses issued by the National Energy Regulator of South Africa (NERSA), utilities under pressure need to upgrade, expand and/or build new infrastructure. This requires significant Capital and Operating Expenditure (CAPEX and OPEX) which, if not subsidised, can only be recovered through increase in tariff passed on to the consumers. Network upgrades and expansion requirements drive electricity price up, more so when the generation plants and consumers are far apart [5]. Utilities are left with no choice than to increase electricity tariffs to avoid the network decay or complete collapse. Raising electricity tariffs has significant social ramification for the society at large, let alone consumers from poor communities. They could also lead to financial challenges for utilities because of the possible lower revenue collection.

1.2.1 Alternative electricity supply sources

On the backdrop of increasing electricity cost, it is convenient for most consumers to consider alternative sources of electrical energy, especially for residential consumers. In this breadth, Solar systems such as Photovoltaic (PV) are more practical and have become more affordable [11]. They are compact, scalable and capable of connecting to LV networks, and even next to the consumers and therefore require little or no upgrade to the existing electrical infrastructure.

Global trends show a preference for PV technology by residential and commercial consumers. In some instances, the PV plants are used in conjunction with BESS to create off-grid or stand-alone electrical systems also referred to as microgrids. Considering the declining cost of PV and BESS systems on global market, it is worthwhile to consider their adoption by South African residential consumers in an effort to counter the increase in electricity tariffs. Microgrid have generated interest around the world and in South Africa where researchers are looking at various type of usage ranging from powering a village or rural community [14] and [15], residential establishments [16] and a campus [17] to name a few.

Current South African regulations allow for connection of a DG (including PV) to a utility's electricity grid, subject to the utility's acceptance as dictated in the local bylaws of the jurisdiction under which the consumer is located. Permission to connect any DG can be granted by the utility under specific commercial and technical conditions.

1.2.2 The use of microgrids

Considering each consumer in isolation, a single consumer is faced with the challenge of complying with local bylaw which could allow or not, in full or in part, the connection of a DG to the utility's grid. Furthermore, it is even possible for the utility to dictate the type of DG to be connected to its electrical network. For instance, let us analyse the following two scenarios:

(1) Where a city that does not allow the connection of a DG to its utility's network: the consumers has to operate off-grid or separate his electrical load for supply from different sources, one being the grid and the other being the DG. This configuration attracts more costs, for example it could require splitting the distribution and installing a changeover mechanism to switch between the utility grid and the DG when required.

(2) A city allows DG connections but no feed-in: the consumer faces the possibility of curtailing the local generation under high generation – low load conditions or needs to install sufficiently sized BESS to store the excess energy. While curtailing the energy is a loss of revenue, the installation of BESS increased the Balance of Plant (BOP) of the alternative energy of the consumer and could make the project more expensive and less attractive to the consumer.

(3) Further to case (2), a city allows export of excess power on condition that the consumer becomes a net energy consumer over the billing period: once more, the consumer needs a BESS albeit smaller than that of (2). Regardless, this still represents additional cost for the BOP to the consumer that could make the DG less attractive. Additionally, the cost of unit energy exported to the utility's grid is less than that of the energy imported from it; therefore, the net energy is more likely to favour of the utility.

Considering the above scenarios, there is merit for each potential consumer for a small-scale power pool or "microgrid". It this way, it is possible for each contributing DG to export its excess or import its deficit capacity from within the microgrid. This arrangement could be beneficial in terms of export tariff whereby excess energy is first consumed by the microgrid consumers experiencing a deficit of power and secondly exported to the utility grid only when there is a net deficit of power across the whole microgrid. The export of power from the microgrid to the utility network can be further reduced by including BESS into the installation. Besides providing storage for the excess power, the BESS could also contribute to the microgrid resilience and enhance the availability of power to the consumers in the case of the utility grid's failure.

Furthermore, BESS size could be more optimised when used in a microgrid as centralised storage as opposed to individual BESS for each consumer.

Operating as a microgrid could provide a way to overcome some of the restrictions imposed by utility companies while also providing a mean to reduce the impact of electrical energy tariff increase to its consumers [18], [19] [20]. Furthermore, it reduces the pressure on the utility's grid, provides a relief and defers the extent of the required network strengthening but creates a loss of revenue for the ENSP.

1.3 Problem Statement

Grouping DGs within a defined area called a microgrid with the aim of controlling both generation and loading can improve the efficiency, reliability, and financial benefit for the consumers and utility. A microgrid could offers many opportunities while also facing challenges. Forming a microgrid requires defined boundaries of electricity supply and clearly defined Points of Common Coupling (PCC) to the utility's distribution grid.

The transition from individual DG's focused policies to a microgrid requires the economic studies to establish any financial incentive for the use of PV and BESS in a microgrid as well and the techno-economic impact on the utility. It is also equally important to identify gaps in the existing regulations and bylaws in order to propose methods for easing the establishment of such microgrids in community groups. In this respect, Urban Security Complexes have clearly defined boundaries and PCC therefore, represents the best case for study of microgrid penetration in South Africa.

Although many business and residential groupings have adopted the use of common PV plants, their financial and technical details are not disclosed. It is therefore difficult to assess on one hand the merit of such microgrid for the benefit of future decision-making and on the other hand its true impact on existing utility companies. This research aim to provide a basis upon which techno-economic decisions can be based. Although it is specific to residential electrical energy consumers in South Africa, the concept is also applicable to remote rural communities, commercial and industrial parks as long as the consumers are confined within a defined boundary and PCC regardless of the country. The issues that the author aims to tackle include:

- **The perceived lack of drive for Microgrid:** operating stand-alone DG is not economically nor practically efficient. By grouping multiple DG into a microgrid, it is possible to make efficient use of the resources, improve the system reliability, possibly providing financial benefit to consumers and/or producers located within the boundary of the Microgrid. However, microgrids are not yet fully embraced in practice in Africa where its potential is significant. Hence the need to investigate by research.

- **The existing regulatory barriers to Microgrids:** South African regulatory framework addresses DG connection to LV networks but does not address the issue of microgrid in an explicit manner. There is a provision for the penetration of Renewable Energy Sources, with the emphasis on individual Distributed Generators and not for a collective of DGs such as a microgrid. Therefore, there is a need to identify all gaps in the existing regulatory framework and propose changes to allow for the use of microgrids.

- **Compliance to the Grid Code for Renewable Power Plant (SAGC-RPP):** considering the microgrid as a virtual power plant, there is no procedure for its evaluation or status in the existing grid code. Therefore, there is a need to amend the existing SAGC-RPP to allow for an efficient establishment and use of microgrids.

- **Financial viability and impact:** considering rising cost of electricity from traditional sources and the declining cost of PV and BESS, it is possible to achieve financial viability from using a Microgrid with high PV penetration and BESS. However, it remains to establish if microgrids can fully fill the gap while remaining financially competitive.

By analysing the above-mentioned aspects, it is possible to determine the techno-economic merits of establishing a PV and BESS based microgrid in South Africa. Various studies carried out in South Africa focus on the feasibility of a single microgrid but the collaboration between multiple microgrids is not addressed. Therefore, there is no indication on what impact the collaboration of microgrids could have on the ENSP.

1.4 Hypothesis

Currently, residential electricity consumers with own generation through DG have no legal mechanism to pass on the excess energy to other consumers but via the utility grid. Although electricity cost is regulated by NERSA in South Africa, there is no end in sight for electricity cost increases experienced over the past decade. One way of reducing the vulnerability to electricity tariff increase is for consumers to take advantage of the decreasing cost of PV and BESS systems and use them in a microgrid environment to offset the utility bill or to stay completely off it. Such move could see the significant loss of revenue collection for the power grid.

Considering historic cost of electricity tariffs in SA and the decreasing cost of PV and BESS systems, there shall be a point at which the PV/BESS system becomes financially viable compared to the cost of energy from the utility. A microgrid can be established with a high penetration of PV and BESS when the cost of utility electricity becomes considerably high or when the cost of PV and BESS decreases significantly. This can be possible only when coupled with changes to the current regulations and bylaws.

Further economic benefits could be achieved by the consumers by enabling collaborations between microgrids. The simplest way to achieve such collaboration is to consider microgrids supplied from the same feeder in order to avoid any wheeling via the utility's grid. With favourable techno-economic conditions and the regulatory framework for the consumers, the establishment of microgrids in urban security complexes could benefit both the consumers and utility companies.

1.5 Research questions

Various efforts to show the relevance of PV and BESS as alternative energy source in a residential microgrid environment led to the research questions below. They cover the economic, technical and regulatory aspect with respect to the grid integration and pricing mechanisms that allow the establishment of microgrids in residential environment. Although the research questions are primarily applicable to the collaborative environment for urban and gated security complexes in South Africa, they can expand to commercial office parks, industrial zones, and rural communities.

(1) Are the existing regulatory framework and various bylaws favouring the establishment of Microgrids in urban SA? If not, what are the regulatory changes needed to ease the adoption and establishment of electrical microgrid into urban security complexes in SA?

(2) What could be the trigger points for mass adoption of microgrid in the South African shared residential and commercial consumer space?

(3) Considering various connection electrical network topologies and electrical energy tariff regimes in urban South Africa, what could be the financial impact of a full blow microgrid adoption in the shared residential and commercial consumer spaces on the electrical power utility companies?

1.6 Justification

Although the concept of microgrid in "Urban Secure Complexes" and "Business Parks" environment is gaining popularity, the technical and financial details are seldom available in the public domain. The proposed research's objectives are to provide insight into what is required to build cost effective and environmentally friendly microgrids in favourable groupings such as "Urban Secure Complexes" and to analyse their technical and financial impact on utility companies' operations and revenue collection. The outcome of this research could provide clarity on factors affecting the establishment of microgrid in shared residential and commercial spaces, requirements for the establishment of successful microgrids to achieve parity with traditional grids, best practices for the adoption and optimal use of renewable energy sources in microgrid, particularly photovoltaic. Finally, the research could provide answers on the financially effect of microgrids penetration in residential and commercial areas on established ENSP and shape their future.

At the end of the research, it could benefit consumers, body corporates, managing agents, property developers, power utility companies and policy makers. Consumers could have a financial justification for supporting and adhering to a microgrid and its broad environmental benefits. They could also have a clear view on the benefits of the local generation within one or more microgrids, particularly the potential shield against curtailment and the associated financial implications.

Body corporates, managing agents, property developers could benefit from this research as a decision-making tool when exploring ways of reducing exposure to electricity tariff increases by the utility. Furthermore, it could provide them with an understanding of challenges on reducing the exposure of consumers to tariff increase by the utility while providing energy at a lower cost;

For electrical network service providers (ENSP), this research could provide an understanding of the techno-economic impact of multiple PV and BESS based microgrids on its distribution grid. It could act as a basis of financial analysis, to provide valuable input for comparison between the deferred infrastructure and the loss of revenue due to the use of microgrids by consumers. Finally, this research could also provide a platform for technical and financial evaluation into the benefit of microgrids for struggling municipalities that have no generation capacity and are fully dependant on major utility companies such as Eskom.

For the governments, this research could provide an input to estimate the potential to accelerate RPP penetration and drive South Africa towards renewable electrical energy, thereby allowing it to meet carbon emission commitments. It could also provide key contributions to the national energy policy direction to its effort to contribute to a safer environment through a clear policy direction.

Most of this research outcome can be applied to any type of load (residential, commercial or industrial) located anywhere, including rural areas, as long as the generation and supply area as well as the ENSP’s tariff regime are well defined. Finally, this research results will be applicable to many African countries that are currently experiencing electricity supply challenges in urban and rural area due to an acute lack of funding and aging infrastructures.

1.7 Scope of the research

The scope of this research is limited to a single urban security complex that is currently supplied from a single PCC to the utility’s grid. All DG’s are PV and the BESS is centralised. The research is based on the South African regulatory framework in conjunction with the best practices recommended by the IEEE, IEC and SABS to provide the best guidance into the evaluation of microgrid in South Africa.

The estimated cost and economic benefit to establish a microgrid will be analysed and discussed while taking into consideration past and present tariff as well as the cost of other material that form the balance of the plant for the microgrid.

Limitations the research scope includes the assumption that all houses in the complex forming the microgrid have the same Life Standard Measure and share a similar load profile. Moreover, it is considered that:

(1) Heating and cooling are not part of the microgrid;

(2) Technical evaluation is limited to steady state analysis;

(3) The utility's network is modelled as an infinite source at the PCC.

1.8 Deliverables

Deliverables of this research will include the research documentation in the form of a dissertation and two conference papers with the following tentative titles:

- Paper 1: Single-feeder supplied microgrids collaboration: opportunities and challenges in the South African context.
- Paper 2: Financial analysis of a single-feeder microgrid collaboration on power utility companies in South Africa.

1.9 Thesis outline

The following section gives a brief overview of the envisaged thesis structure.

Chapter 1 provides an introduction, background to the study, problem statement and the hypothesis based on which the whole research is carried out.

Chapter 2 provides information on electricity market analysis, alternative energy sources, and the concept of microgrid including its control and operation. Examples of microgrids throughout the world are also summarised to provide a view of their proliferation.

Chapter 3 provides the research methodology used to derive and analyse the results. The results are based on a techno-economic analysis of hypothetical microgrids for which the location is moved and tested across the three South African biggest cities.

Chapter 4 provides information on the conception and validation of the technical model from which the techno-economic evaluations are carried out.

Chapter 5 gives information on the technical and financial results of the microgrid in standalone and in cooperative mode. The results are analysed in detail and then summarised to provide conclusion on the concept of cooperation amongst microgrids.

Chapter 6 gives the conclusion based on the results obtained and provide leads for future research into collaboration between microgrids and their impact on power utility companies.

2 LITERATURE REVIEW

2.1 Introduction

This section provides a summary on to global electricity access, provides alternative sources of electrical energy and discusses the associated reliability.

2.1.1 Access to electricity supply

Almost a quarter of the world population is located far from electricity grids and therefore has no access to electricity [11]. The majority of those without access to electricity lives in Africa and Asia [21].

According to the US Energy Information, global electricity demand in rising due to the ever increasing need for development [1],[22]. Historic data analysed in [5] and the electricity demand forecast in [23] as shown in Figure 2-1 confirms the worldwide trend across residential, industrial, commercial and transportation sectors while Figure 2-2 confirm the growth trend in South Africa.

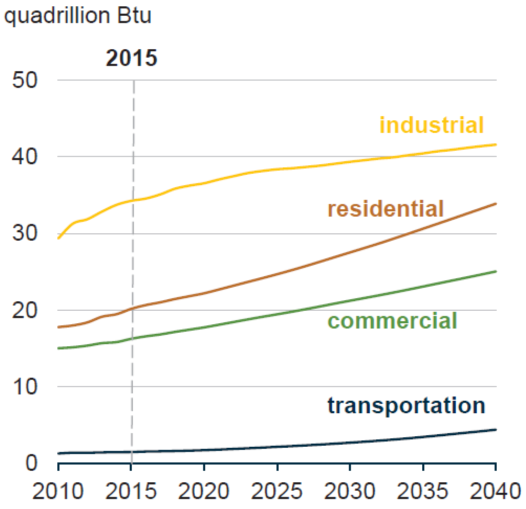


Figure 2-1: World electricity use by sector [22]

In traditional and vertically integrated networks, power generation is located in specific areas selected based on the availability of fuel. For this reason, power generation plants are not always close to load centres. Consequently, they transfer the energy from power plants to consumers requires considerable transmission and distribution infrastructure.

The challenge for access to electricity is somewhat different between the urban and rural consumers. In urban settlements, electricity is accessible due to close proximity to the electricity grid. The availability of grid in urban area is spurred by industries and commercial interest. In contrast, rural consumers' electricity consumption is somewhat lower and there is often an insufficiency of electrical infrastructure for economic reasons. It follows that the location of rural community is far from existing infrastructure. In both cases, the ever-increasing electrical demand requires for upgraded and new transmission and distribution infrastructure for the utility to provide quality and reliable electricity supply.

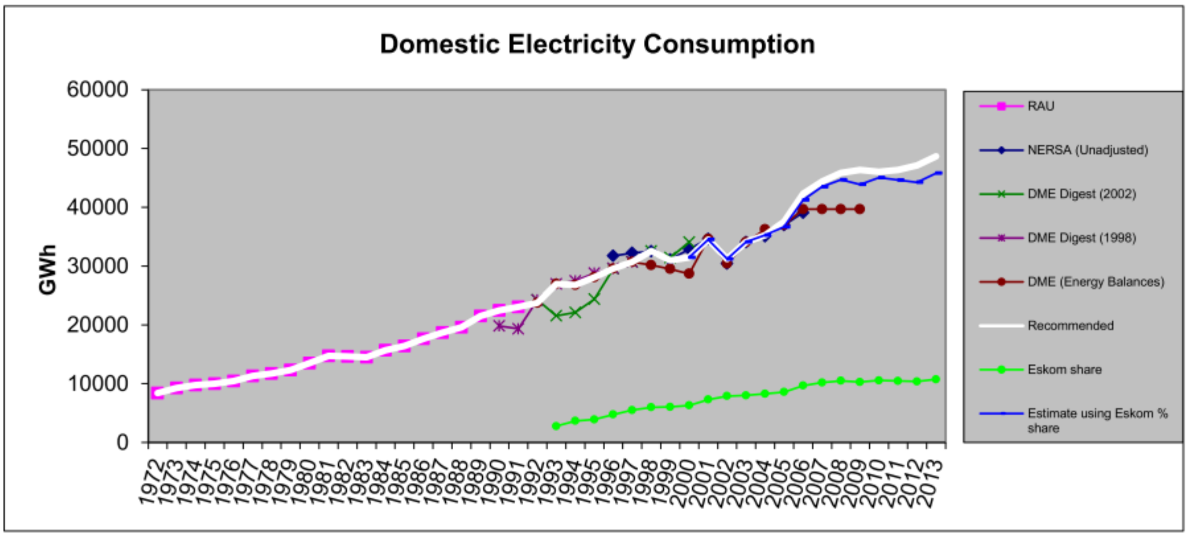


Figure 2-2: Residential electricity consumption in South Africa [23]

As electricity demand grows, the infrastructure requires timely upgrades that require not only significant Capital Expenditure (CAPEX) but also operating and maintenance cost. For a utility to undertake such projects there is a need for financial justification. Unless the costs of upgrade and new infrastructure are subsidised, the utility will recover them from the consumers by tariff increase [5]. In some cases, expensive tariff makes projects less viable for the utility and unaffordable for the consumers, especially where poor communities are concerned. This could be the reason for the lower electrification rate in Africa.

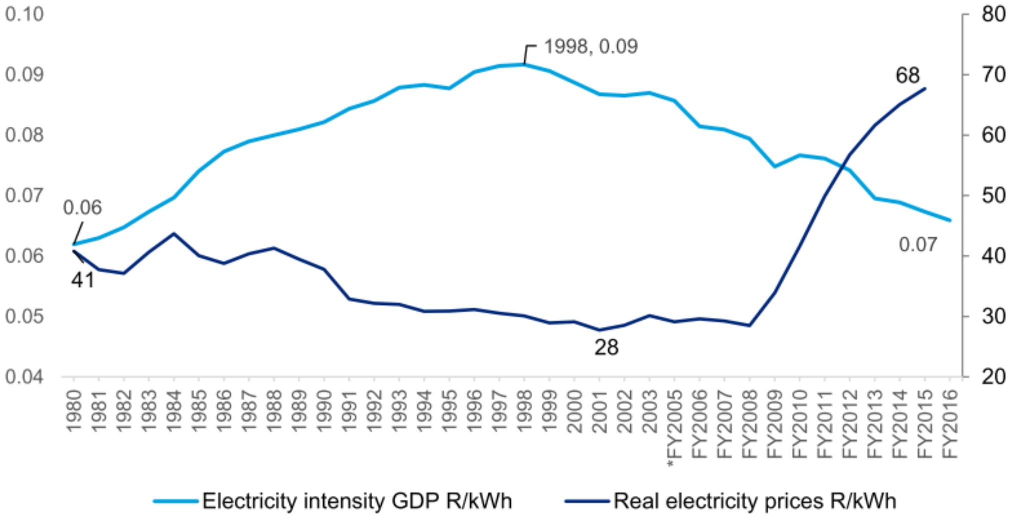


Figure 2-3:Cost of electricity in South Africa [5]

In South Africa, the electricity cost has been rising continuously on a yearly basis over the last decade as shown in Figure 2-3. The increase is driven by the cost of infrastructure expansion, new build for power stations, transmission and distribution infrastructure [5]. Some research predict that the real increase conventional electrical energy cost in South Africa could be as much as 200% compared only 74% inflation in the economy for the same period between 2007 and 2017 [24].

The trend of electricity cost increase is not showing any sign of relenting. This is supported by the frequent application by Eskom to increase the cost of electricity. This goes to shows that consumer will be under more pressure and, based on the experience of the last decade; it is safe to assume that the upward trend in electricity cost is set to continue, at least for the near future. As the cost of conventional electrical energy continues to increase, consumers are turning more to alternative sources of energy.

2.1.2 Alternative electricity supply sources

In situations where transmission and distribution lines are close to consumers, it is likely that the cost of supplying grid-based electricity is less than the cost of alternative off-grid options. Beyond a certain distance, where the cost of grid extensions becomes prohibitive, stand-alone systems and mini-grids offer cheaper energy and hence a cost advantages [11]. However, it is likely that the benefit of decreasing prices of PV could also see off-grid generation option becoming affordable in the near future.

Global trends in renewable energy indicate a significant increase in the use of PV systems and this is attributed to the rising cost of electrical energy from traditional sources, the PV technology maturity offering more reliable systems at affordable cost, the mass production and the environmental benefits [1],[11]. It is also likely that the benefit of decreasing PV prices could accelerate the grid parity between the main source and the PV plant.

Against this backdrop, it is more than ever likely that consumers could adopt DG based alternative electricity generation. The close location of DG to the consumers and the diversity of its sources provide it with a major advantage over bulk electricity generation. They require less or no upgrades to existing transmission and distribution infrastructure, incur less technical losses and offer the supply reliability [25]. Furthermore, the DG ability to host RPP further enhances its preference because of lower carbon emission, thereby contributing to protecting the environment.

Although the use of a DG can reduce the electricity consumption bill for the consumer, their usage is not financially optimal when considered to operate as the main source of electricity for a single consumer. Considering the forecast of in PV and wind energy making for the forecast highest RPP penetration of 2.8% per annum between 2015 and 2040 [22], the declining PV cost and achievable financial viability, there is a strong case to argue for more microgrids with high PV penetration to become common in South Africa.

The South African regulations allow for DG connection to the national grid but subject to the bylaw of each municipality and the conditions set by the local Network Service Provider (utility). By law, any DG requires registration with the utility and NERSA. However, DGs with a generation capacity greater than 1 MW are required to obtain a generation license permit [18],[19].

Grid-connected DG have the advantage of benefiting from the utility network that absorbs its excess power or provide the deficit whenever there is not balance between the load and generation. Where the utility prohibits or limits export into its network, regulations do not allow a DG to supply any excess energy to other consumers connected to the same grid via the utility network without prior arrangement. A DG is efficient when operated in parallel with an Energy Storage System (ESS) to store energy during excess and release it during deficit. This implies that the DG's ESS size should store as much energy as possible or curtail its output when its generation is greater than its load. In this configuration, balancing between generation and demand is possible but challenging when the DG source is intermittent such as solar or wind. However, the addition of ESS increases the cost of overall supply system [26],[27].

Grouping DGs within a defined area with control for both generation and load can improve the efficiency, reliability and financial benefit for the consumers and the utility. For instance, instead of curtailing the DG output, other consumers within the microgrid can use the excess energy. Moreover, instead of dealing with the excess energy on an individual consumer basis, the utility will deal with a single the Point of Common Coupling for all consumers in the microgrid. Furthermore, it is possible to operate a group of DG as an island within a defined area. Such operation ensures that all consumers within the area have access to electricity even on the loss of a supply from the utility. A grouping of this type constitutes a microgrid and offers many opportunities while facing challenges. Therefore, in order for a microgrid to be successful, it is imperative to overcome its technical and non-technical challenges, regardless of its operating mode.

Forming a microgrid requires defined boundaries of electricity supply and a defined Point of Common Coupling (PCC) to the utility's distribution grid. In this respect, Urban Security Complexes have clearly defined boundaries and PCC. Therefore, they constitute a perfect test environment for microgrid in SA.

2.1.3 Electricity supply reliability

Apart from the cost of electricity, the reliance on the distribution grid is such that disturbances in the distribution grid can lead to the loss of supply to vast area thereby inconveniencing residential and businesses consumers alike. Such disturbance does not relate only to faults on the systems or natural disaster but could also include event such as the lack of generation capacity leading to frequent load shedding as experienced in South Africa in 2008 and lately in 2019 [28].

One remedy to reduce the exposure to electricity price increases and improve the reliability of supply could be the use of microgrid [29],[30],[31]. A microgrid can use central or Distributed Generation (DG) sources embedded within its network to supply its consumers. On loss of the utility, a DG is capable of supplying one or more consumers for a defined period as determined by the microgrid objective at its design stage.

The objectives of a microgrid include amongst others the reduction of monthly bills from the utility, the provision of backup supply in the absence of the utility grid, the ability to generate electricity for export into the utility for financial gain, zero consumption, off-grid operations, environmental, etc. Each objective is distinct and affects its generation and BESS design capacity. In some instances, more objectives can lead to further requirement concerning the operation and control of the microgrid.

2.2 Distributed Generation and microgrids

Distributed Energy Resources (DER) are form the backbone of microgrids. This section covers their concept, design and operation in the South African context. Furthermore, their efficient use and the subsequent application in a microgrids is explored.

2.2.1 Distributed Generation concept

DG refers to electricity generation function carried out by a variety of grid-connected smaller generation plant or Energy Storage referred to as Distributed Energy Resources (DER). Their primary energy can be fuel based, chemical or renewable. The use of each type depends primarily on the availability of fuel or renewable energy source [32]. While some DGs use fossil fuels, others rely on natural resources such as the sun or wind.

DG technologies such as Solar Photovoltaic (PV) are scalable. They are available from smaller sizes suitable for usage in LV network to bigger sizes akin to conventional power station to produce bulk power. The scalability of PV systems further enhance their affordability, especially for small power users [33].

Environmental concerns and the poor efficiency of power generation from fossil fuel, strong opposition to nuclear power and new technology maturity are driving the adoption of Renewable Energy Resources (RPP) by many consumers [31]. Depending on their type and sizes, RPP supply residential, commercial and industrial for which PV is the most common for residential consumers [34]. It is therefore expected for the trend to continue throughout the world for the near future.

In contrast to conventional power plants and major power plants, the main characteristic of small micro-sources (DG) of electricity is their close proximity to the consumer. A standalone DG requires careful balance between its load and its generation. Given that electricity must be available when needed, it is difficult to maintain balance between the microgrid load and generation when an intermittent energy source such as solar or wind is used. This task is even more challenging when intermittent sources are employed for supply of variable loads and can be eased only when the microgrid generation and the storage are oversized. However, oversizing of generation or storage equipment is not always the best solution. It could render the system expensive and less efficient in terms of output/fuel ratio [29].

One way of improving the efficiency of DG is to participate in a collaborative or cooperative initiative such as a community based microgrids, more so as the DER penetration increases in distribution networks. Even though a single DG is able to provide energy to the consumer, a microgrid augments the capacity and offers customers an increased reliability, energy efficiency and resilience, cost reduction, less transmission losses and a reduction in CO_2 emission [29],[30],[31].

As a generation source, a PV system needs to meet the demand at all times. The intermittency of its energy source and the load variability implies a likelihood of load-generation unbalance. To resolve a generation deficit, it is possible to manage the consumer load through Demand Side Response (DSR) consisting or load reduction or load shifting. Alternatively, the consumer needs to import energy from other energy sources. For generation excess, it is possible to use BESS or curtailment the generation to balance the system. When using the ESS, the system has to revert to generation curtailment if the BESS is charged to its allowed maximum capacity. Alternatively, the consumer needs to export the excess energy elsewhere [35].

The alternative methods indicated in the previous paragraph for balancing the PV's load and generation are achievable through connection to the utility grid or sharing a network with other consumers through at Point of Common Coupling. Through this collaboration with the utility or other network consumers, it is possible to export the excess energy to the utility grid or to share it with other consumers experiencing a load-generation deficit at the same time that the excess production is occurring. Conversely, it is possible to import the energy deficit from other consumer's over-generating plants or the utility grid [36].

Although exchange of energy between the PV's consumer and the utility or other consumers is a foregone conclusion in SA, it is worth to explore the existing regulation and policies to ascertain their benefit for the consumers. The following section looks at the case of a single (one consumer owned) DGs system installed on radial feeders.

2.2.2 Design and operational constraints of DG in SA

In South Africa, consumers can own and operate a DG on condition to abide by the Electricity Act, the Grid Code for Renewable Power Plants (GC-RPP), NRS 097-2-3:2014 and local bylaws; all of which some important are herein provided.

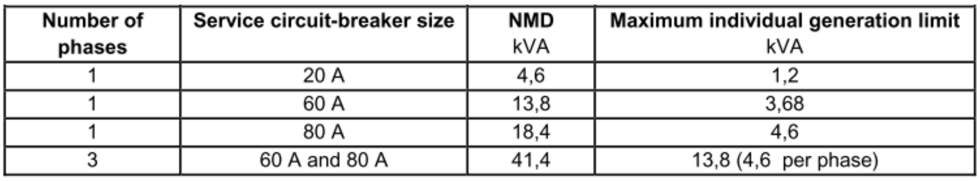
For a license-free operation of a DG is limited to 1 MW maximum generation capacity. Furthermore, unless in possession of a distribution license, a DG's owner is not allowed to wheel its excess energy to other consumers but through selling power back to the national grid (if and where allowed) at the utility defined and NERSA approved rate [18], [19].

In shared LV network [20], a DG's maximum generator capacity is limited to 25% of the consumers Notified Maximum Demand, up to 20 kVA. If its maximum generator capacity is higher than 4.6 kVA, it has to be balanced across phases and therefore the connection to a network has use three-phase technology. The total share of DGs limit is 25% of the MV/LV transformer size, already the penetration is limited. The combined DGs maximum generator capacity cannot exceed 15% of the MV feeder peak load.

In a dedicated LV network, a DG's the maximum generator capacity is limited to 75% of the consumers Notified Maximum Demand, up to 20 kVA. A DG's maximum generator capacity higher that 4.6 kVA has to be balanced across phases. A single-phase supply DG maximum generator capacity cannot exceed 13.8 kVA. Combined DGs maximum generator capacity cannot exceed 15% of the MV feeder peak load, once more limiting the penetration of DG [20].

According to [20], the circuit breaker's size determines the NMD of residential consumer and by extensions the resulting generator capacity for a shared network are presented in Table 2-1.

Table 2-1: Maximum individual generation limits in shared LV feeder [20]



Number of phases	**Service circuit-breaker size**	**NMD** kVA	**Maximum individual generation limit** kVA
1	20 A	4,6	1,2
1	60 A	13,8	3,68
1	80 A	18,4	4,6
3	60 A and 80 A	41,4	13,8 (4,6 per phase)

2.2.3 Possible intervention for efficient use of DG

From the above main conditions, (3) which is applied by utility restricts the maximum DG's generation limit allowed in (1) by a significant margin. Considering the declining PVPP cost, these provisions are limiting consumers to benefit as long as the utility has more oversight and control of the LV network. Relaxing these restrictions on the consumers with DG's can result in more benefit such as insulating them from tariff increases, improved reliability in the event of a utility grid's blackout and load shedding. For instance, such power could include: the use the maximum generation capacity of condition (1) subject to the network strength. The injection of any DG's excess generation capacity into a residential pool whereby those consumers with a net load-generation deficit can draw energy directly from the pool as show in Figure 2-4. For a greater impact, this concept can be extended to multiple microgrid, especially when connected to a radial line;

Consumers owned DGs could operate in this manner only when grouped within a "Microgrid" while enjoying the support of the regulatory framework covering embedded generation. In spite of many opportunities offered by the use of microgrid, the African continent in general and SA in particular are yet to benefit from concept of microgrid as illustrated in the existing regulatory framework in which the focus in on independently operated DG and where there is no formal reference to a microgrid. Yet the continent has one of the lowest electrification rate in the world [21].

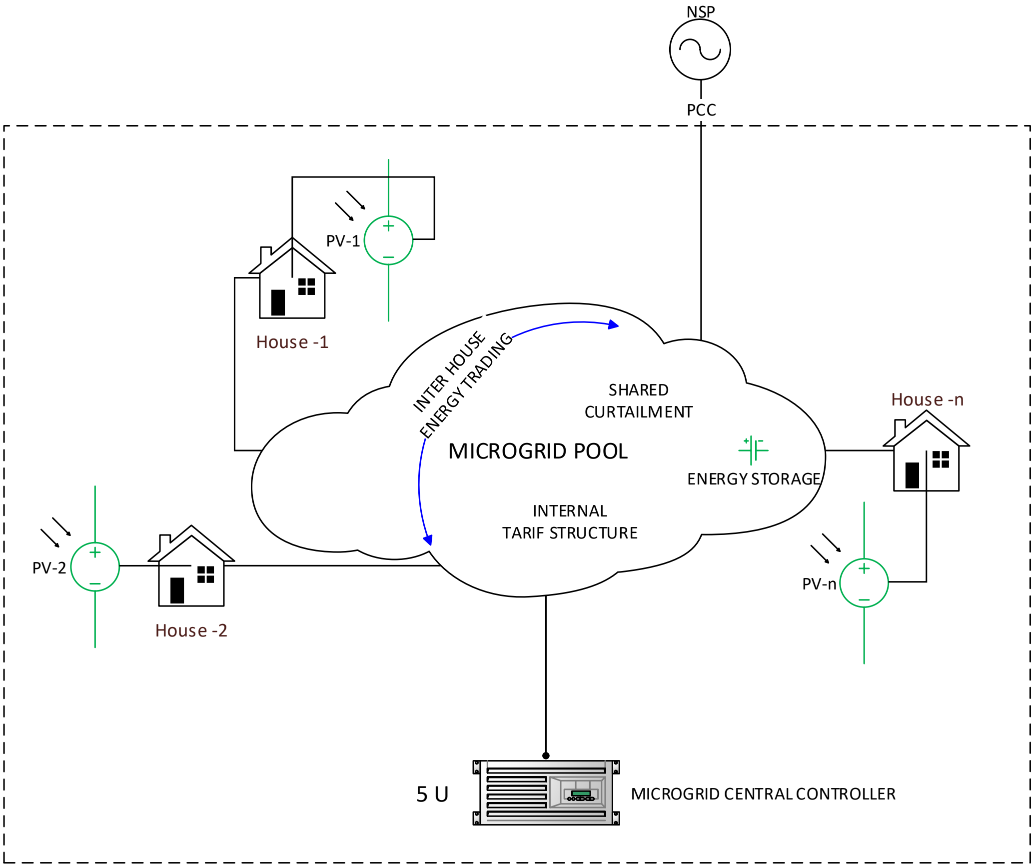


Figure 2-4: Microgrid concept

2.2.4 Use of DG in microgrid

From the utility’s perspective, a microgrid behaves like a single generator injecting power into its grid or a load drawing from its grid, depending on the power flow direction. In both scenarios, the microgrid needs to adhere to the standards and regulation regarding the power quality (within its boundaries) and connection to a utility’s grid. However, as a generating plant, a microgrid needs to adhere to the standards and regulations that at present cover only individual generators and not a collective of DG as found in microgrids. For instance, a single DG can be categorised in a specific class according to [18] but when combined as a microgrid, there is an increase in maximum generation capacity resulting from the sum of all DG capacities as viewed from the point of common connection.

As an individually operated DG, any individual curtailment, regardless of the cause seems unfair but in a microgrid environment, it is possible to share equitably even under such circumstances. To benefit from this collective gain, microgrid owners/operators have to consider and adopt an ownership and sharing models.

2.3 Choice of residential DG technology

Given the number of DG technology in the market, clarifying the type of suitable technology is important for residential area. This section explores the available technologies and their drivers as well as configurations of a solar plant on the backdrop of its global success and rapid rise.

Various DG are available on the market and some rely on fossil fuel while others rely on renewable energy. According to IRENA report [11], renewable energy sources experienced the highest growth in 2015 and in the same year, the combined solar and wind power contribution surpassed the hydropower. While the bulk of solar capacity is centralised for most countries, reports indicate that rooftop PV installation are also increasing. For instance, China has experience a threefold increase from 2017 [37]. This implies that the roof top PV plant are popular DG for residential and commercial consumers.

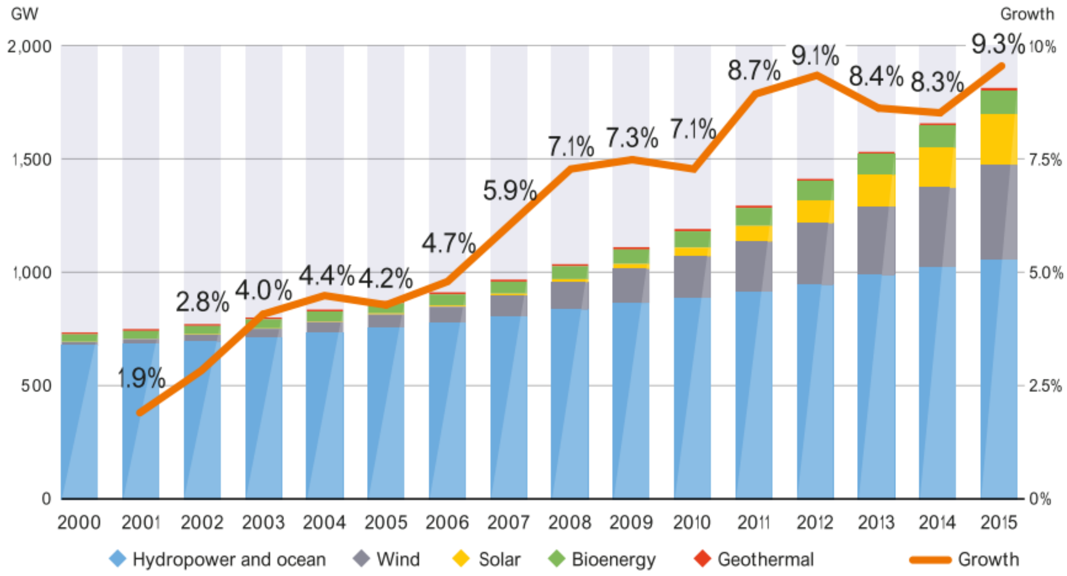


Figure 2-5: Renewable power capacity and annual growth rate, 200-2015 [11]

2.3.1 Solar PV power plant drivers

In the absence of clear policies and incentives, the increase of conventional electrical energy cost from the utility is the biggest driving force behind the rise in solar PV systems for residential consumer. For instance, Figure 2-6 shows the average cost of installing PV system in residential area for Germany, Tunisia and South Africa [7]. There is a clear indication that the installation cost is declining.

The need to balance seamlessly the consumer load and generation requires residential PV systems to be grid connected. Although connecting the PV system to the grid bring the convenience to the residential consumers, not all utility companies allow grid connection of any DG. Where concession exists for connection to the grid, it is often on individual capacity and not as a collective, let alone the collaboration between microgrids.

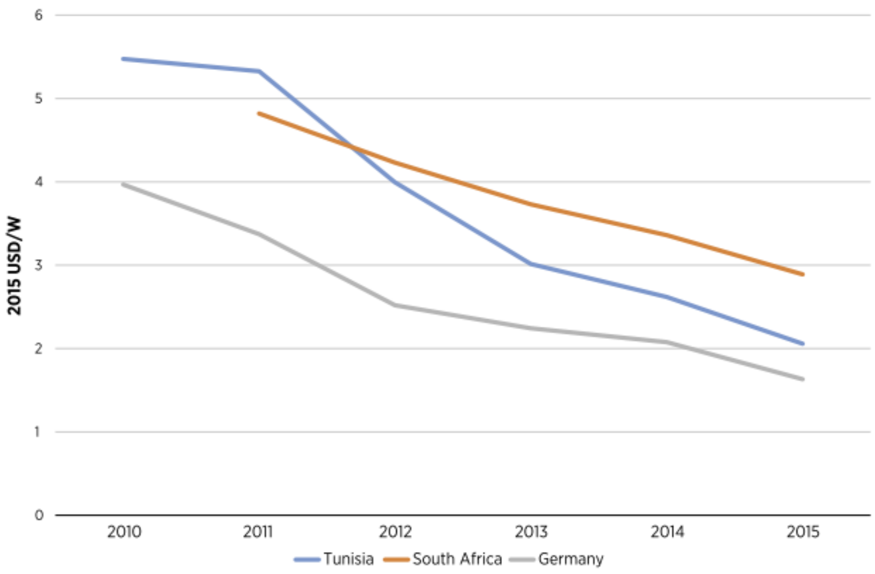


Figure 2-6: Average total installed cost of residential solar PV systems 2010-2015 [7]

2.3.2 Photovoltaic power plant configurations

PVPP convert solar energy from the sun into electrical energy. PV panels convert incident energy from solar irradiation into electrical energy but in Direct Current (DC). The harvested energy can be supplied directly to DC powered equipment or converted into Alternating Current (AC) using a DC/AC inverter for supplying AC equipment [38].

Principal PVPP topologies are shown in Figure 2-7. They vary from stand-alone or autonomous plants to grid-connected plants. Stand-alone systems cannot operate without the support of Energy Storage Systems (ESS) while grid-tied systems can function with or without ESS. PV panels are mounted on frame regardless of their location (roof top, ground, or building integrated) and the support frames can be fixed or automatically adjustable for sun tracking and for maximising solar energy harvesting optimisation [39].

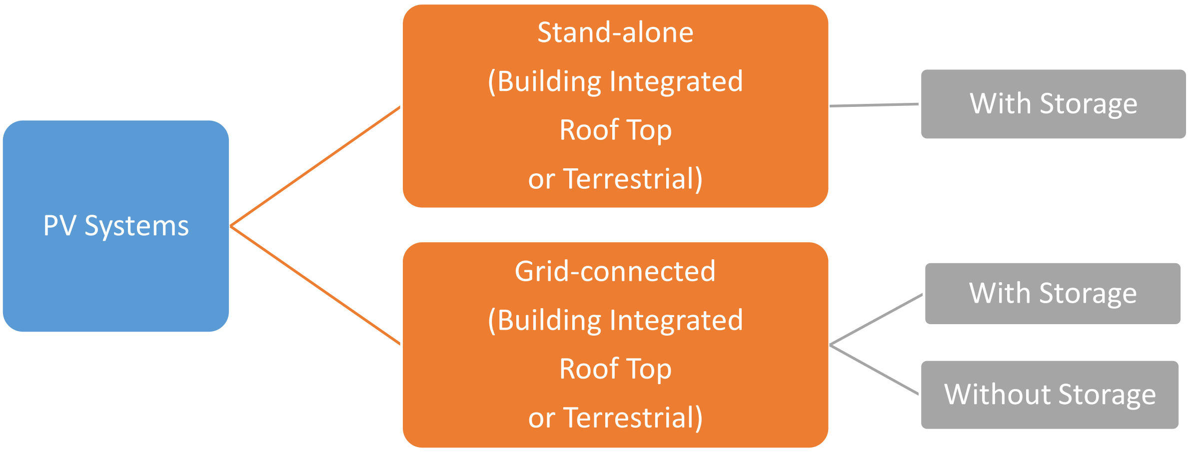


Figure 2-7: Types and configuration of PV plant [39]

Energy produced by a PVPP depends on the solar irradiation level that is mostly variable and difficult to forecast of certainty. For instance, on cloudy days the power produced by a PVPP can be only a fraction of its rated power while at night there the plant cannot produce. The varying nature of the solar energy makes it difficult for power to be available instantaneously when needed. Although this can be achieved by BESS, using BESS in grid-tied PV system is not wide spread due to resulting higher cost that of other power generation systems [40].

Alternatively, PVPP are tied into the ENSP's grid with varying degree of objectives but most importantly to allow for the balance between the PVPP and its load to be compensated for by the ENSP [41]. In the context of this research, PVPP used assume Building Integrated Roof Top configuration with and without storage facility and connected to the ENSP's grid.

2.4 Regulatory conditions for connecting DG to ENSP

Technically, the implementation and connection of a DG to the ENSP network is no longer technically challenging. However, there is a need for greater organisation and standard in the way microgrid and their DG are treated. This section explores such requirement for a DG connected to any of the South African utility network on the basis of the grid code published by the National Energy Regulator of South Africa (NERSA).

2.4.1 Classification of RPP

Notwithstanding the requirements for the connection to the ENSP, the South African Grid Code for Renewable Power Plant provides the criteria for the connection of all RPP sizes. In South Africa, the grid code for renewable energy categorizes all RPP into categories based on their Maximum Export Capacity's [18].

Category A: 0-1 MVA of rated power and connected to the LV network and broken down into sub-categories A1, A2 and A3. DGs in sub-category A1 have a Maximum Export Capacity of 0 -13.8 kVA. They able to connect to the ENSP's grid through a single-phase supply system. This is the most common connection of RPP to the ENSP for residential consumers, owing to their inherited or existing connection. It is in this category that most residential consumer RPP would be classified.

DGs in Sub-category A2 are those rated from 13.8 to 100 kVA. They typically connect to LV but in three-phase system. Lastly, sub-category A3 DGs are rated 100 kVA to 1 MVA. They typically connect to the ENSP's grid in three-phase configuration but at MV level. This category represents the maximum export capacity allowed without the requirement for a generating license.

Other categories of DG's defined in the South African grid code are Category B rated from 1 MVA to 20 MVA and Category C rated from 20 MVA and higher but this research focuses only on category A DG's, particularly PV solar type.

In the South African grid code, the requirements for connection of RPP to the ENSP are generally less stringent in category A but more severe for category C where the plants are expected to contribute to the ENSP stability. In line with the research aim of building more microgrids connected to the ENSP, it is assumed that the plant size for each would be limited to sub-category A3 to reduce administrative burden associated with obtaining a generating license.

2.4.2 Technical requirements for a category A3 RPP

The connection of any RPP to an ENSP in South Africa is regulated by the grid code. In essence an RPP needs to meet a set of minimum requirements set in the grid code before it is granted connection to the ENSP. The minimum conditions are imposed to protect both the RPP and the ENSP. They relate to key network parameters related to the frequency, voltage power quality, protection and their associated controls. Further conditions could be required by each ENSP on the basis of the strength of their network. The following section is based on the South African Grid Code for Renewable Energy Power Plant [18].

2.4.2.1 Tolerance to frequency deviation

Under normal operating conditions when an RPP is providing power to the consumers, the network is steady and the RPP small output variation dictated by the load or prime energy sources have no impact on the ENSP stability. However, a sudden decoupling of multiple RPP from the ENSP due for instance to a fault in the ENSP could lead to significant frequency and voltage deviations, both linked to the change in active and reactive power flow between the RPP and the ENSP. Category A RPP connected to an ENSP are required to withstand frequency and voltage deviations at the connection power for all operating conditions including abnormal ones [18].

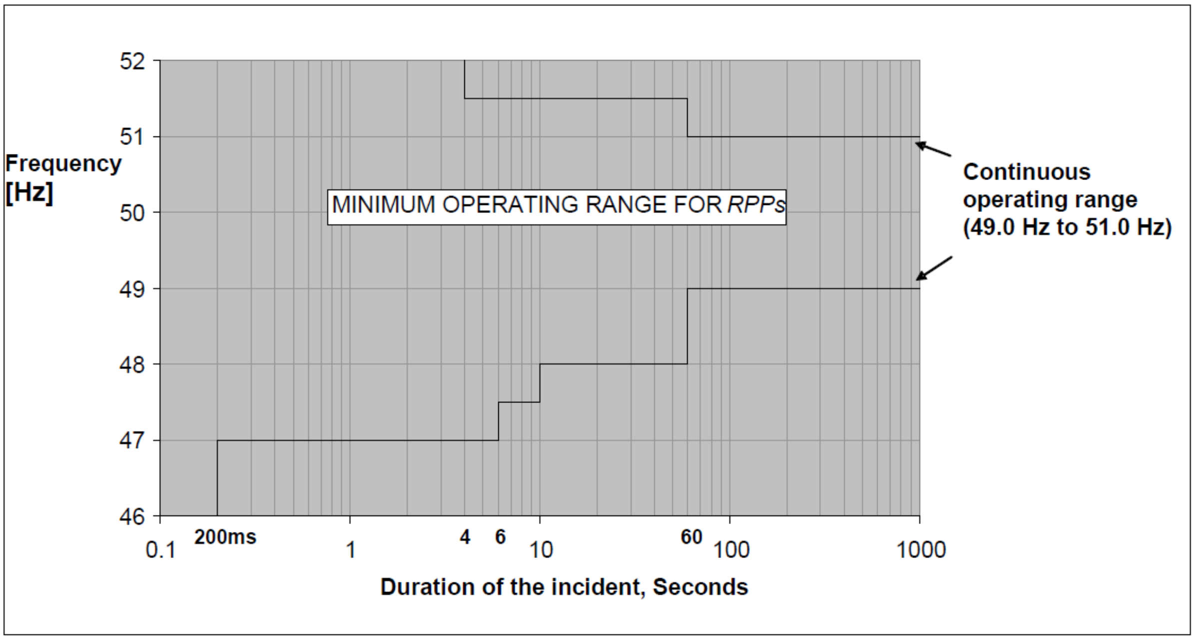


Figure 2-8: Minimum frequency operating range of a RPP (during a system frequency disturbance) [18]

The RPP is required to remain continuously in operation for frequencies between 49 Hz and 51 Hz. Outside of this window, the RPP is bound to operate for frequency changes of up to 1.5 Hz per second but is allowed to disconnect if the frequency exceeds the limits and durations shown in Figure 2-8.

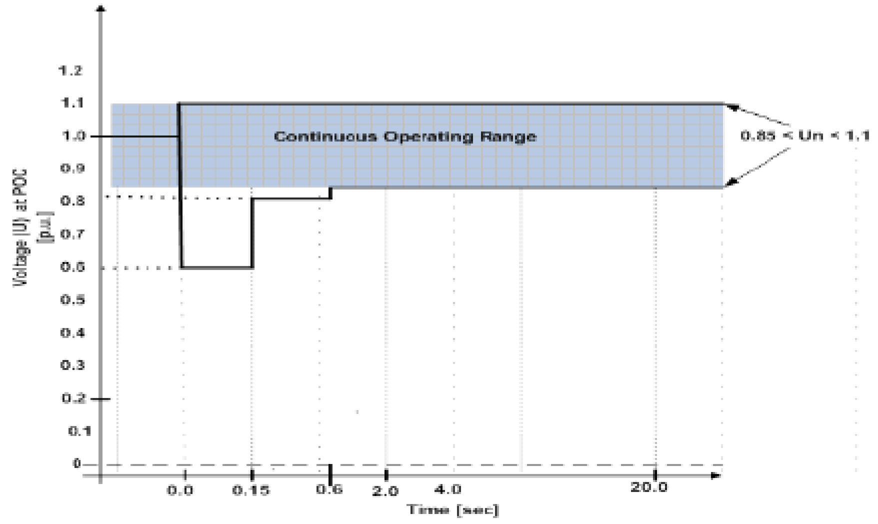


Figure 2-9: Voltage Ride Through Capability for the RPPs of Category A1 and A2 [18]

The requirement calls for the RPP to withstand voltage rise of up to ten percent rise or fifteen percent drop in the nominal voltage for an indefinite period. For deviations outside of this window, the RPP is allowed to disconnect depending on the duration of the voltage excursion as illustrated in Figure 2-9 and Figure 2-10.

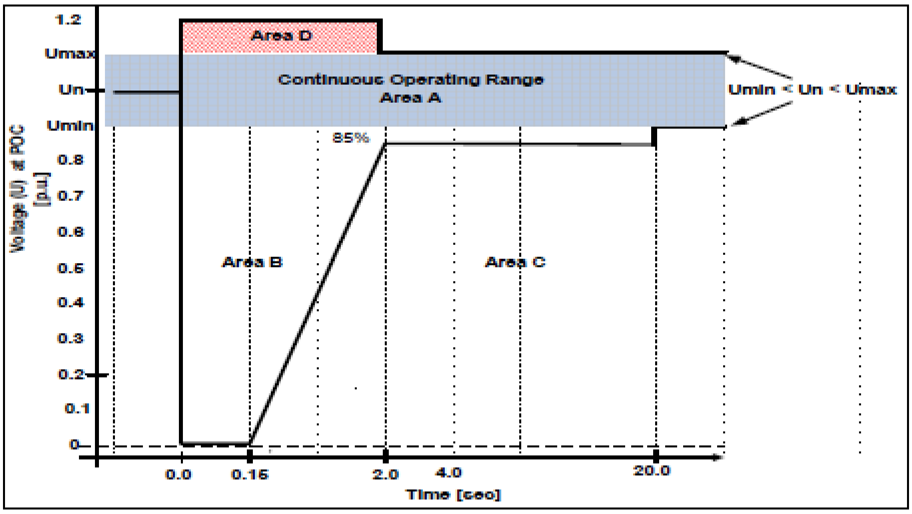


Figure 2-10: Voltage Ride through Capability for the RPPs of Category A3, B and C [18]

A comparison of the voltage withstand capability across Category A shows that the for smaller RPP in sub-categories A1 and A2 the requirement to remain connected are not as stringent as those for A3 amongst which the voltage ride through is required during sever over-voltages and under-voltage conditions.

After disconnection, the RPP is allowed to connect and re-synchronise with the ENSP only sixty second after the disconnection when the voltage is within -15% to 10% of the nominal voltage and the frequency is between 49 Hz and 50.2 Hz. This condition can be achieved without communication between the RPP and the ENSP [18].

2.4.2.2 Frequency response

The unbalance between generation and load lead to frequency deviations. Excess generation leads to higher frequency while the converse is true when the load exceeds the generation. RPP are small in nature and are not used for base load function that is reserved to base generating units located in the ENSP. However, in high frequency conditions, Category A RPP are required to reduce their respective outputs when the frequency exceeds 50.5 Hz or disconnect from the ENSP if the frequency exceeds 51.5 Hz in order to reduce the active power in the system to reduce the frequency within the normal limits [18].

During the frequency excursion between 50.5 Hz but below 51.5 Hz, the RPP is required to reduce its output to 25% of its output before the over-frequency condition as illustrated in Figure 2-11. This adjustment happens under dynamic conditions and if the system frequency is not brought under control, the RPP is allowed to disconnect when the maximum frequency is exceeded [18].

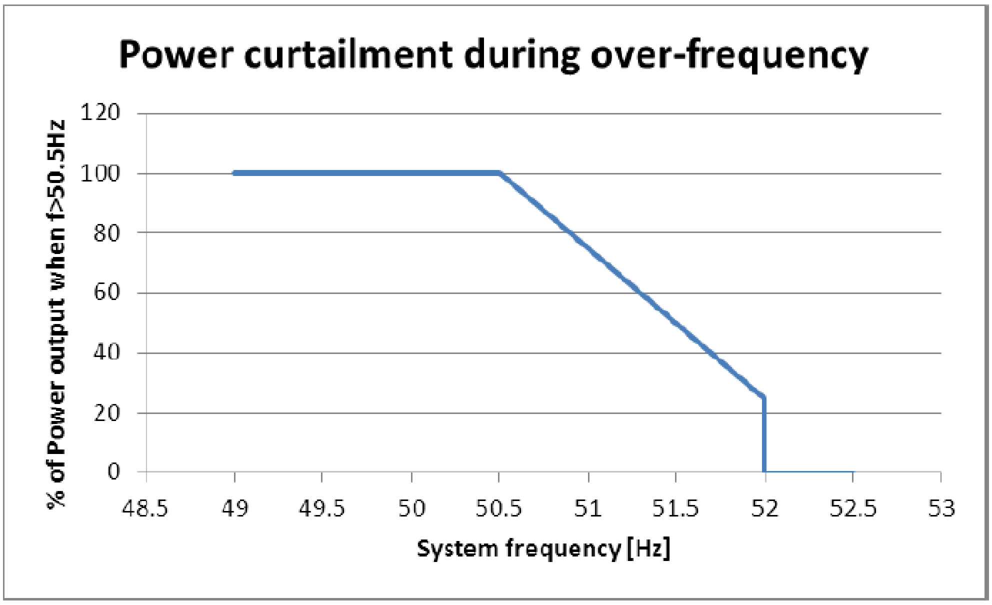


Figure 2-11: Required power frequency reduction during over-frequency for RPPs [18]

Once more, the RPP control can be achieved without the need for communication between itself and the ENSP’s operator but for reduction based on instruction from the SO, sub-category A3 and higher rated RPP are required to communication with the SO or ENSP and to have active power functions to accomplish such requirement.

2.4.2.3 Reactive power capabilities

Further to withstanding the voltage ride through during faults, category A RPP are required to support the network voltage by providing reactive power support. In sub-category A1 and A2 the RPP is required to maintain its power factor not lower than 0.98 leading or lagging for any real power output. For sub-category A3 RPPs, more reactive power can be drawn or injected into the ENSP provided that the power factor is maintained at 0.95 leading or lagging and shall be available when the plant is producing at 20% or more of its rated capacity. In this way the RPP supports the ENSP with voltage control [18].

The limitation of reactive power between the ENSP and RPP ensures that reactive power is not injected or drawn from the ENSP more than necessary. Furthermore, this limitation reduces the pressure for the ENSP to provide for ancillary services. Unless otherwise specified by the ENSP or Systems' Operator (SO), the grid code specifies a unity power factor for Category A RP by default. On this basis, there is no requirement for communication between the RPPs and ENSP for the purpose of exchanging information related to the control of reactive power, voltage or power factor as the case with other RPP categories [18].

2.4.2.4 Power quality

RPP are also required to ensure that they meet the power quality standards for which the most important is to comply with harmonic levels as defined in the NSR 048 [18]. The proof for such compliance lies at Factory Acceptance Test (FAT) provided by the manufacturer.

2.4.2.5 Protection and fault level

The major requirement from the grid code is for the RPP to be equipped with islanding detection to shut down its operation within two second after a successful detection. According to the ENSP, an RPP cannot land and island with any part of its part048 [18]. This is essential in ensuring the safety of the ENSP's workers operating, maintaining or repairing the affected part of the network against accidental energisation leading to electrocution [42].

2.4.2.6 Active power constraint, Control function requirement and RPP Availability and visibility

On the basis of the previous requirement from the grid code, active power constraints, control function, availability and visibility of RPP from the ENSP is applicable for bigger generation capacity classified in sub-category A3, category B and higher. Therefore, they fall beyond the scope of this research electrocution [18].

2.5 Impact of DG on the ENSP

In traditional network, current or power flows from the source to the load. The resulting voltage drop across the feeder makes the voltage at each load connection point lower than the source voltage. The connection of new sources near the load has several impacts on the way the network traditionally operated. For instance, when there is excess generation, there current flow can reverse and flow from the load connection point towards the source. The reversal of power flow can cause instances where the voltage at the load is higher than the voltage at the original source located upstream of the network [43]. Mitigation technics to resolve this voltage rise include the use of energy storage systems or active power curtailing to reduce the amount of power injected back into the grid and reactive power compensation [43]. Further techniques to control the voltage include the use of transformer tap changer operation [44], [45], [46].

Further to the voltage rise that is most prominent with DGs, further impact on the network include harmonics and DC injections caused by power electronics employed in the power conversion process, particularly with solar [47]. In the certain cases where the power transfer infrastructure is not upgraded, a high DG penetration can lead to an increase in system losses and overloads [48]. In the case of intermittent primary source, voltage dips could also be experienced [49].

2.6 Advantages of grouping DG

In light of the preceding, it is possible to implement PVPP based DG for each consumer. However, grouping them could eliminate the challenges and provide more advantages. For instance, an individually owned PVPP could trip due to overvoltage caused by injection of energy into the ENSP by other PVPP located upstream of the feeder. In this case, the objective of the individual DG is forfeited and could not be met if the condition persists for longer period and is repeated more often. It cannot share electricity with other consumers but send any excess to the ENSP's grid, subject to technical requirements and tariff as published and amended from time to time [19]. Unless backed with a significant BESS, it is not resilient in the event of ENSP's grid unavailability [50].

When grouped, PVPP have the ability to control the voltage through reactive power is enhanced. The lack of generating capacity (for instance due to maintenance, repairs, etc.) from one PVPP can be compensated by other PVPP in the same grouping through collaboration and sharing of the same LV network. Therefore, consumer benefits from the system's resilience and availability. Ancillary services can be centralised and the better tariffs can be negotiated for imports from the ENSP's grid [9], [51];

Although individual DG such as PVPP are allowed to connect to ENSP's low voltage networks, there is no provision in the current grid code to accommodate their grouping. Where such grouping is envisaged, the most adapted vehicle could be through grouping such as microgrid [52]. This combination of multiple DG within a microgrid can be viewed as a virtual plant with its internal load. Only excess or deficit of energy will cause the exchange of power between the microgrid and the ENSP [17], [53].

2.7 Microgrid Concepts

The U.S. Department of Energy microgrid Exchange Group defines a microgrid as "*a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid*". CIGRÉ C6.22 Working Group defines a Microgrid as "*an electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded"* [54].

The concept of microgrid (microgrid) is not new; it existed in the beginning of power systems whereby local generation supplied an interconnected area at Low Voltage (LV) level in the late 19th century [55]. However, rapid development lead to the need for bulk generation, transmission and distribution. The distribution grid became common and regulations evolved with a strong emphasis on electricity grids covering larger areas.

In modern days, consumer owned DG are widely in use but in most cases for supplying only the owner alone. For instance, diesel generators are widely used as standby power sources for essential services and in some instances; they operate in conjunction with Uninterrupted Power Supply (UPS) to provide power to critical loads at as financial institutions, healthcare facilities, etc. On the back of technology maturity and decreasing cost, DG systems are now widely used in residential, commercial and industrial properties, mainly rooftop PV but mostly as standalone source to supply a limited load with the support of BESS [7].

A simple microgrid topology comprises DER generating the power, the load consuming the power and one central controller to manage the generation resources and the load. Like distribution networks, microgrid can use different topologies based on the type (AC or DC), voltage level, contingency, environmental and other considerations. The operation of a microgrid can be either standalone (autonomous or islanded) or grid-connected [56].

Establishing a microgrid require the evaluation of three major components. One should consider the Economic, Technical and Environmental impact in order to arrive to a meaningful conclusion. All three components have some degree of interdependency as indicated in Figure 2-12. For Instance, power losses, system reliability in the network and incentive schemes designed to encourage the use of RPP all have an economic impact on the microgrid [48].

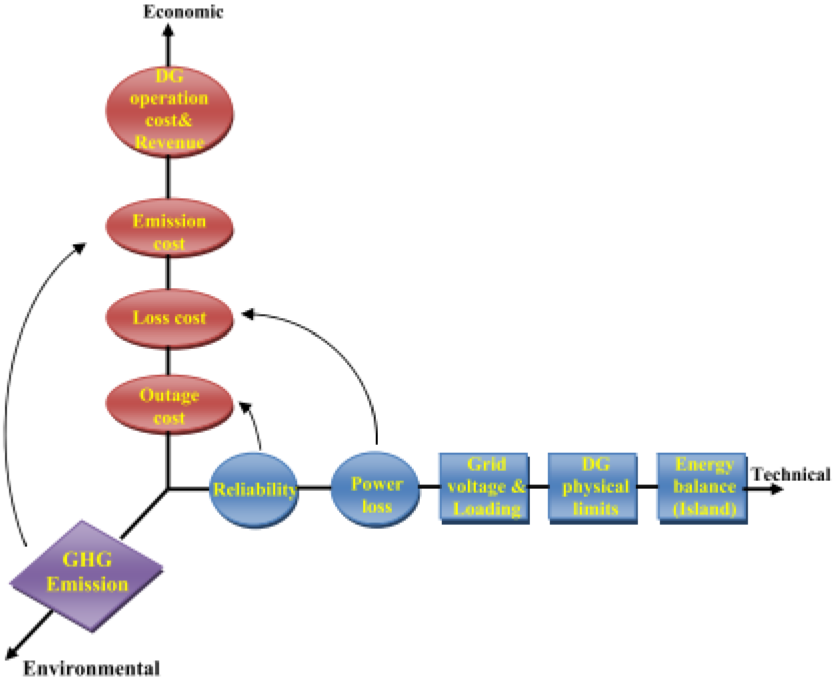


Figure 2-12: Main microgrid considerations [48]

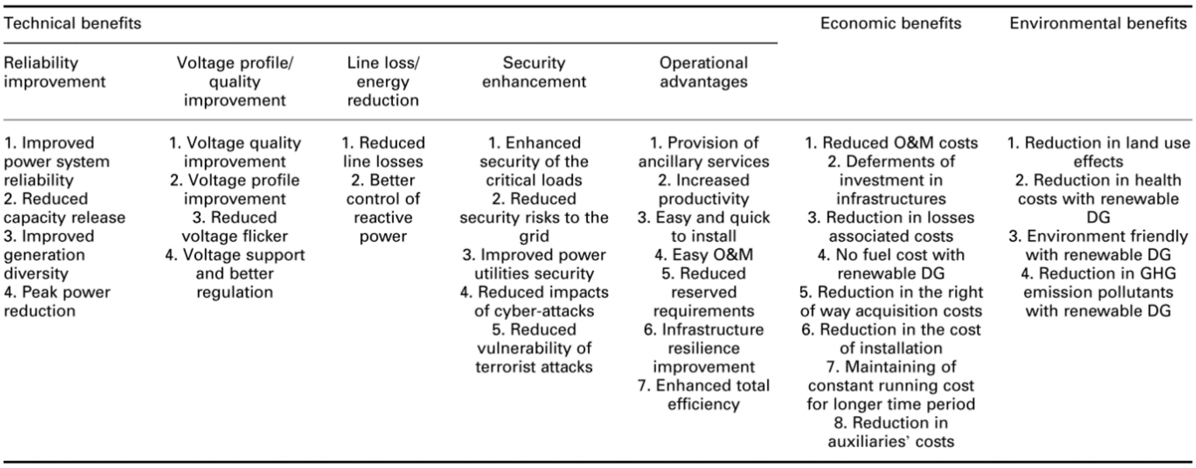
Regardless of its operating mode, microgrids offer benefit and opportunities but their operations also create challenges for the LV network as described in [57],[58],[59], [53] and [60] where the most common challenge is voltage rise.

2.7.1 Benefits of adopting a Microgrid

The benefits of using a microgrid are described in detail in Table 2-2.The use of a microgrid can benefit the consumer and utility by improving reliability and voltage profile, line loss reduction, operational flexibility, economic and environmental benefits [30]. For instance, the establishment of a microgrid provides relief for the ENSP by reducing the load on its network. Consequently, the current is reduced, resulting in the reduction in power flow (both active and reactive) from the utility’s grid and therefore a reduction in the energy losses, voltage drops and ultimately the voltage profile improvement along the concerned feeder. In many ways, these advantages are shared by the microgrid (its consumers by extension) and the ENSP.

Apart from the technical, there are considerable financial advantages that can be derived from the use of microgrid. For instance, the cost of operation and maintenance the ENSP is reduced. The investment in infrastructure and the need for servitude can be deferred in for the ENSP, thereby providing a financial relief on the cash flow or allowing for capex shifting to other projects. For DG’s using renewable energy such as solar or wind, there is no associated fuel cost and carbon emission is reduced.

Table 2-2: Benefits of distributed generation [60]



Technical benefits					Economic benefits	Environmental benefits
Reliability improvement	Voltage profile/ quality improvement	Line loss/ energy reduction	Security enhancement	Operational advantages		
1. Improved power system reliability 2. Reduced capacity release 3. Improved generation diversity 4. Peak power reduction	1. Voltage quality improvement 2. Voltage profile improvement 3. Reduced voltage flicker 4. Voltage support and better regulation	1. Reduced line losses 2. Better control of reactive power	1. Enhanced security of the critical loads 2. Reduced security risks to the grid 3. Improved power utilities security 4. Reduced impacts of cyber-attacks 5. Reduced vulnerability of terrorist attacks	1. Provision of ancillary services 2. Increased productivity 3. Easy and quick to install 4. Easy O&M 5. Reduced reserved requirements 6. Infrastructure resilience improvement 7. Enhanced total efficiency	1. Reduced O&M costs 2. Deferments of investment in infrastructures 3. Reduction in losses associated costs 4. No fuel cost with renewable DG 5. Reduction in the right of way acquisition costs 6. Reduction in the cost of installation 7. Maintaining of constant running cost for longer time period 8. Reduction in auxiliaries' costs	1. Reduction in land use effects 2. Reduction in health costs with renewable DG 3. Environment friendly with renewable DG 4. Reduction in GHG emission pollutants with renewable DG

A PVPP based microgrid can benefit from all the advantages of DG as discussed above. These advantages can be multiple if more microgrid are considered and configured to collaborate. In such case, the aggregated impact of one or multiple microgrid could be significant for the power utility when viewed from the ENSP's connection point.

2.7.2 Opportunities offered by Microgrid

Various researches have concluded that the use of microgrid presents opportunities for the microgrid consumers, the ENSP and the broad society at large. These range from the decrease in the use of fossil fuel, improving the penetration of RPP, providing opportunities for rural electrification and the potential for job creation.

For generation that rely on fuel such as coal, diesel, etc. the use of DER contributes to the generation mix and thereby creates opportunities to reduce the use fuel and dependence of generation thereon [29]. However, in the South African context, it is seldom to find a fossil fuel-based DG used in by residential consumers. Moreover, environmental concerns such as noise makes it less attractive for residential usage, let alone in community-oriented establishments such as complexes.

The availability of DER in small scale allows for its connection to LV network without much re-design works. For countries with abundant solar and wind energy resources such as South Africa, adopting microgrid will certainly enable the use or RPP and increase the penetration level, thereby acting as enabler for high penetration of RPP [29], [57].

The electrification of remote rural area requires transmission and distribution infrastructure for which the cost is likely to outstrip the benefit due to the high capital required and less revenue from electricity sale. In the case a microgrid could be the cheaper option with rural electrification [29],[61]. Although it is fair to assume that microgrid will enable for rural electrification, it is equally important to ascertain the cost thereto. For countries without subsidies from government, it is not possible for rural areas where unemployment is prevailing to afford electricity at any cost. On this basis, the use of microgrid could come to a huge cost that would render it unaffordable for rural population already struggling with the basic needs.

For urban establishments, the installation of more DG near the consumers could reduce the amount of power transferred from generation to consumers. From the ENSP perspective, additional generation from embedded generation reduce the pressure on its generation and transmission infrastructure and in turn, upgrading or extension of the existing network on the basis of increased load can be deferred [29], [60]. As much as this is an advantage to the ENSP, it is equally important to observe that the benefit of microgrid consumers could come to the expense of reduced revenue collection and increase employee to MW ratio for the ENSP. This raises the need to balance between the loss of revenue and the gain of deferred capital for infrastructure build program.

Since microgrids are a reduced version of mainstream ENSP’s grid that comprise generation, transmission mediums, point of connection, controllers, etc., there will be case of operation and maintaining its infrastructure. Furthermore, the demand for DG such as PVPP could create a potential market for manufacturing in emerging countries such as South Africa, hence the opportunities for job creation [29].

A community-based microgrid can operate as an entity with non-utility status in order to maintain its independence from some regulatory requirements. For instance, the South African NRS 097-2 limits the amount a DG can inject into the LV network [20]. In a microgrid environment, it is possible to challenge this provision and add more RPP generation capacity. For example, a cooperative environment such as an Urban Security Complex can install more micro-sources with the view to be self-sufficient, sell excess capacity, store excess and use excess energy when needed, etc.

For remote rural communities or facilities such as army bases, distribution networks require the construction of a line and possibly substations for electrification. The use of an islanded microgrid in this environment can negate or lessen the need for infrastructure between the distribution network and the consumers, thereby contributing to the deferment of network expansion capital expenditure [29]. This demonstrates that the opportunities offered are not only for the consumer but also for the distribution grid. Finally, the exchange of power between consumers within the microgrid is free of utility engagement and less exposed to electricity tariffs increased.

Overall, opportunities offered by microgrid have raised awareness, led to more researches on the subject and encouraged more tests. Noticeable projects for rural electrification include in Isle of Eigg - Scotland (Supply to 90 residents), Huatacondo – Chile (Supply to a community of 150 residents) and Kythnos Island in Greece to mention a few but more projects undertaken across the world are provided in Table 2-3 [62]. Some of the microgrid listed therein are capable of operating both operation modes (island or grid-tied). The list of projects is non-exhaustive but provides a reference of projects from which a microgrid research and campaign can use as reference.

Table 2-3: Summary of significant microgrid tested and still under test

Microgrid Name & Location	Description	Installed Capacity	Operating Mode
Fort Carson Colorado, USA	Military base with a total area of 550 km3.	• 1 MWp PV, • 3MW Diesel generator, • EV with V2G capability. • Plans are in place to include wind, ground source heat pumps, biomass up to 100MW.	Grid connected, Islanded
Mesa del Sol New Mexico, USA	Mixed commercial-residential handed to the University of New Mexico.	• 50 kWp PV, • 80 kW fuel cell, • 240 kW natural gas generator, • Lead acid battery bank of unspecified capacity, • Hot and cold thermal storage of unspecified capacity.	Grid connected, Islanded
Santa Rita Jail	Prison of 4000 inmates with a surface area of 50 hectare.	• 1.5 MWp PV, • 1 MW fuel cell, • Unspecified Diesel, • 2 MW lithium ion battery	Grid connected, Islanded
Sendai, Fukushi, Japan	Supply to Tuhuku Fukushi University	• 50 kWp PV, • 350 kW natural gas fired generator set • Unspecified "modest" battery storage.	Grid connected, Islanded
Huatacondo, Chile	Supply to a community of 150 residents.	• 22 kWp PV, • 1 MW fuel cell, • 150 kW diesel generator, • 170 kWh battery storage • Energy Management System	Islanded
Borrego Springs; California, USA	Supply to a community of 2800 customer residential community.	• 700 kWp PV, • 1.8 MW diesel generator, • 1500 kWh battery storage • 6x8 kWh energy storage units • 125 residential home area's electrical network	Grid connected, Islanded
Fort Collins USA	Supply to commercial and industrial consumers	• 345 kWp PV, • 5 kW fuel cell, • 700 kW CHP, • 2720 kW of backup diesel generators, • Private 790 kW biogas and 200 kW PV (from the brewery), • 60 kW micro-turbines.	Grid connected, Islanded
Isle of Eigg Scotland	Supply to 90 residents	• 322 kWp PV, • 1 MW fuel cell, • 100 kW diesel generator, • 1170kW hydro power • 24 kW wind turbines	Islanded

Illinois Institute of Technology USA	Supply to an educational facility	• Unspecified PV power planned, • Unspecified wind turbines, • 2x4 MW CCG, • 500 kWh battery.	Grid connected, Islanded
UCSD USA	Supply to an educational facility	• 13.5 MW gas turbine, • 3 MW steam turbine, • 1.2 MW solar-cell	Grid connected, Islanded
Hachinohe Japan	Supply to an industrial zone	• 60 kW PV, • Unspecified small wind turbines, • 100 kW lead-acid battery bank • 170 kW biogas.	
Kythnos Island Greece	Supply to an island	• 10 + 2 kW PV, • 5 kW diesel generator, • 53 + 32 kWh battery bank.	Islanded
Mannheim-Wallstadt Germany	Supply to 1200 inhabitant and commercial units in an ecological estate	• 4.7 kW fuel cell • 3.8 kW solar PV system • 1.2 kW flywheel storage unit • Two CHP units rated at 9 kW and 5.5 kW (electrical)	Grid connected, Islanded
Hangzhou Dianzi University China	Supply to an educational facility	• 120 kWp PV, • 150 kW diesel generator & fuel cell, • 50 kWh battery storage	Grid connected, Islanded

2.7.3 Challenges faced by microgrids

As microgrids provide benefits and opportunity for consumers and ENSP, their operation and integration does not go without challenges. Establishing a microgrid is bound to technical and non-technical challenges. Technical challenges relate mainly to the operation, control and protection of the microgrid regardless of its operation in standalone or islanded mode.

When a microgrid is connected to the ENSP grid, it is possible for power to flow from the ENSP to the microgrid or vice-versa. The direction change depends on the balance between load and generation within the micro-gird. Whereas traditional power flow from the ENSP grid into the microgrid has no impact on the microgrid, the reverse power flow can lead to voltage rise, loss of protection coordination and in some instances increase the losses in the distribution network [30],[63],[13].

In a PVPP dominated microgrid there is a considerable number of DC/AC inverter. Unlike rotating machines, this equipment contributes less to the fault level due to low inertia. The resulting fault level contributions are lower and can lead to loss of sensitivity for protection devices, especially when the microgrid changes its operational status from grid-connected to stand-alone operation mode [13]. Low inertia is also a concern in a microgrid and can lead to significant frequency deviation especially in networks with a high PV penetration

[29],[58],[64]. Furthermore. poor dynamic stability resulting from the interaction between micro-generator within the microgrid are also cited as cause of local oscillations because of generation and load dynamics [64].

Due to intermittent output caused by variable prime energy, power quality presents a challenge in microgrids with high penetration of RPP. Without support from the grid, it is challenging to provide and maintain the balance between the generation and loads. The unbalance between generation and load could lead to frequency and voltage fluctuations. The use of storage systems can reduce or eliminate the fluctuation by maintaining a good balance when providing the deficit of energy or storing the excess [29],[30].

The conversion from DC to AC is a process that creates harmonics albeit insignificant in modern inverters. The interaction of capacitive and inductive property of some network equipment and inverter harmonic injections could raise power quality issues exasperated in the presence of resonance conditions at the PCC. Although this is a concern, the problem can be solved by the use of harmonic filters at the POC but it would imply an increase in the Balance of Plant [59].

ENSP have also voiced concerns on islanding and safety of maintenance workers. As source of power, DG are seldom controlled by the ENSP or visible to it. In the event of loss of the tie line between the microgrid and the ENSP grid, there is a concern that the islanded DG could still energise part of the utility network. In such instance there is a high risk for repair or maintenance crew to accidentally come in contact with live parts of the network and thereby risk of electrocution [65].

Another major concern for microgrid is that of power restoration, Capacity and Reserve Margin following a blackout. Some types of microgrids may requires a black start in the case of emergency. However, this research is concerned only with PVPP as source of energy but regardless of the type, the microgrid capacity and reserve management need to ensure a match between generation and load, particularly when designed for stand-alone operations [65].

Although the most common challenges faced by a microgrid are of technical nature, there are also non-technical challenges associated microgrid. For instance providing incentives like carbon credit, etc. to would be RPP users or owner of plant could see a significant spike in adopting the PVPP [66].

The ownership model needs to be addressed, risk carrier and responsibility matrix need to be clearly defined for the microgrid to be successful. For instance, the model needs to be clear enough in separating the collective ownership to the consumers. This will dictate how the pricing for energy consumed from the energy pool formed by the microgrid. The cost of electricity is such environment need careful consideration to make it attractive to other consumers located in the same microgrid.

Lastly, the existing regulatory frameworks are designed with DG in mind and are not adapted for microgrids. These need to be changed to provide a legal status to microgrids. Such changes would ensure that microgrids are clearly defined from a physical limits and regulatory perspectives. Furthermore, the legal status could clarify or provide guidelines for the tariffs and define the interaction with ENSP.

2.7.4 Topology and concepts

Like any electricity grid or network, an electrical microgrid is composed of a source, loads and the power transfer medium. Power generation sources within a microgrid comprise non-renewable and renewable energy. Typical renewable include PV, wind, biomass, micro-turbines and Fuel Cell [32] while non-renewable sources are often fuel based. Its load can be residential, commercial, and industrial or a mix of one or more types. Furthermore, a microgrid can include an energy storage system, ancillary services to provide stability for frequency and voltage control, gas and heat system.

2.7.4.1 Types of microgrids

A microgrid can use AC, DC or both network types to distribute electricity to the consumer. An example of an AC microgrid is provided in Figure 2-13. It is connected to the distribution grid and contains PVPP, BESS, and Wind Energy Power Plant (WEPP) [29]. It has both residential and industrial customers. Although a microgrid can include many forms of energy sources, the present research is limited to the use with PV and BESS. The voltage level at which a microgrid distributes electricity and connects to the distribution grid is not defined but it should be dependent on the import or export capacity of the tie line between the microgrid and the utility's grid.

A Microgrid can have multiple DG's types with various penetration levels and can make use of BESS placed at a central point or distributed throughout the microgrid. Furthermore, a microgrid can also have ancillary services such as reactive power compensation to improve on the quality of supply [9],[48]. The main driver of DG choice of fuel is the local availability, the conversion system, the environmental and the operating cost. The cost of technology such as PV has matured and is decreasing. The operating cost of a PVPP is lower and its impact on the environment is minimal [11]. It is therefore optimistic to expect a high-level penetration of PV in future microgrid, especially for residential applications.

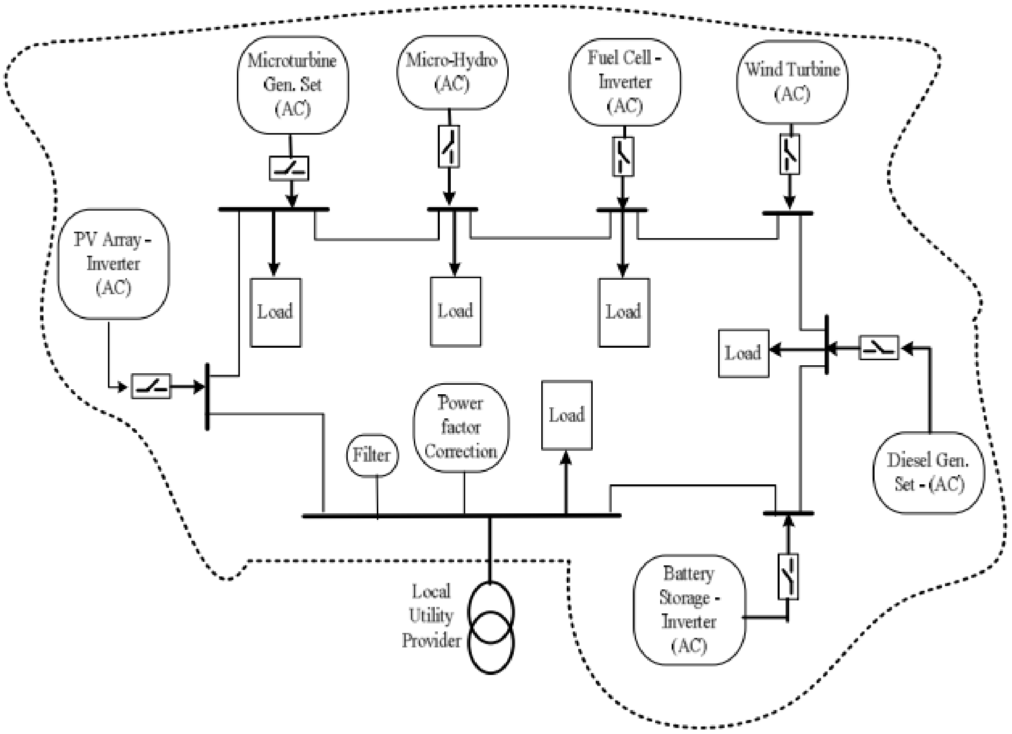


Figure 2-13: An AC based microgrid topology [29]

The most advanced microgrids are able to operate in parallel when the ENSP grid is healthy or in standby mode following an unscheduled or planned event. Through a central Energy Management System (EMS), a microgrid can dispatch power based on the demand and availability of stored energy of fuel. In this way, it is possible to control the tie line flow between the microgrid and the ENSP's grid [67],[68].

Microgrids identities revolve around two key types namely the "customer microgrids" also known as "true microgrids" and "utility or community microgrids". A customer microgrid is self-governed, operated and connected to the distribution grid through a single point of common coupling. They are easily implemented because they employ existing technology and are bound by the same regulatory structures that that of the distribution grid [54]. In other words, a microgrid of this nature is nothing other than a private electrical network. The PCC serves as a reference point for many purposes such as metering, compliance monitoring, measurement and signalling, etc. Downstream of the PCC is literally a private domain over which restrictions are relatively loose but still need to comply with relevant regulations.

Utility Microgrid is a designated area of the existing grid. Its fundamental difference from a customer microgrid is mainly the regulatory and business model that binds it to comply with existing utility standards. This kind of microgrids represent a converted portion of the existing network in virtue of the amount of its DG penetration for the purpose of localised control [54]. Such microgrid aim is to assist the main distribution grid, for instance, it can assist the main grid with voltage regulation. Such microgrids also provide a niche for collaboration between microgrids and can be bought from the utility and managed like a private entity.

2.7.4.2 Type of DG in a microgrid

Distributed Generation types and technologies are classified according to traditional and non-traditional generators. Traditional generators have turbines and convert primary energy such as fuel or natural gas into mechanical energy from which they produce electricity. On the other hand, non-traditional generators have no turbine. Principal technologies currently in use include Combined Heat power (CHP), Fuel cells, micro-turbines, photovoltaic and small wind power systems. Their capacity range from micro (1-5 kW), small (5 kW-5 MW), Medium (5-50 MW) and large (50-300 MW) [32].

Fuel based DG are able to provide real power and reactive power except for the Fuel Cell that can provide only real power and their usage cannot extend for long periods and therefore it is possible to use them for base power [32]. Renewable energy sources such as solar and wind are intermittent, difficult to control and therefore provide an unsteady supply of energy. For that reason, the best way to use them is in conjunction with other generation energy sources to provide smoothing or base power [8].

2.7.5 Microgrid storage systems

Energy storage systems rely on storing energy from other sources and releasing it when required. On their own, they cannot produce electricity and the amount of energy they can deliver depends on their storage size. On this basis, energy storage is used mostly to complement other DG and to supply electricity only for short periods to maintain the continuity of supply.

Traditional Energy Storage Systems (ESS) were mainly pumped hydropower and battery systems. Emerging ESS include Compressed Air Energy Storage, Flywheels, Power to Gas and Super capacitors. For more than a century, pump storage technology dominated the energy storage in the power sector but that is changing as the growth of renewable energy deployment is leading to advances in other power sectors, including Battery Energy Storage Systems (BESS) [9].

A BESS is composed of one or several batteries connected in parallel and series configuration to obtain the desired current and voltage. The BESS is also composed of a monitoring and control, a power conversion system and its most important component that is the battery. Three main categories of batteries are used in BESS applications. Low temperature such as Lithium ion, Lead-acid and Nickel-Cadmium; High Temperature batteries such as Sodium Nickel Chloride, Sodium-Sulphur and Redox flow such as Vanadium, Zinc Bromine.

Battery compositions have two major characteristics. Commonly used batteries are cell-based where small cells are combined to form a battery module. Flow batteries on the other hand are composed of a tank and a central reaction unit. In the past, battery performance, safety issues, regulatory barriers and utility acceptance hindered its full integration as a mainstream option in the power sector. Since then, battery technologies have matured and have improved performance and are more reliable due to technology advances. Most importantly, the cost of battery storage is declining while recent technological progress is making batteries safer and more efficient [9]. Batteries are used in various energy supply applications, notably for storage, variable energy smoothing and fast/short-term electricity balancing in ancillary markets. Therefore, batteries can ease the integration of a significant portion of renewable energy into existing grids.

Battery versatility and market development has led to expectation for a significant deployment than in the past. For this reason, they are considered as key component for the integration of renewable energy, especially in isolated and remote areas. By incorporating power electronics and storage, intermittent RPP such as solar and wind can provide automatic adjustment for power demand balance, thus mimicking traditional power systems. In this way, batteries can be used to mitigate frequency deviation and can therefore make variable RPP more dispatchable [9].

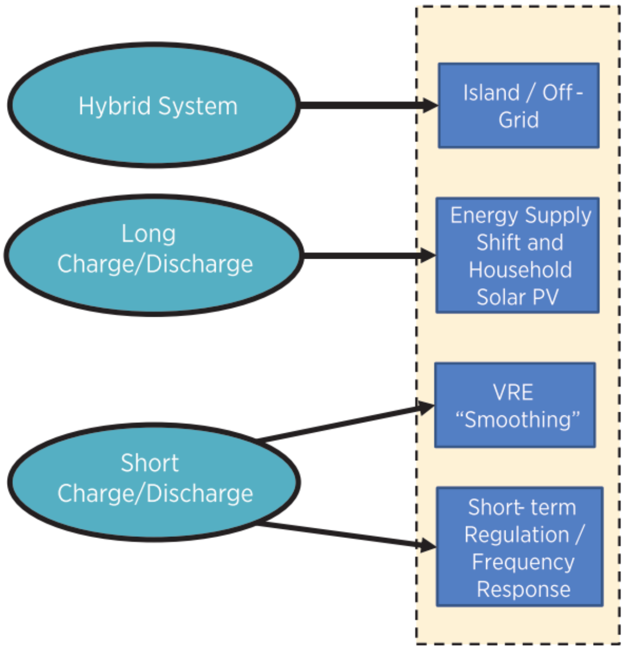


Figure 2-14: Consideration for battery selection by application [9]

Battery storages are not suitable for medium, long-term, or seasonal storage. These can be provided by compressed energy storage, power to gas, etc. However, for residential applications, batteries are the storage technology of choice because of its relatively cheaper cost when compared to other storage technologies.

A battery life is defined by the number of charge and discharge cycles it can complete before losing its performance. The number of cycles is defined for a given depth or discharge (DoD) and operating temperature. Using a battery at higher DoD would reduce its lifespan and the opposite is true. Flow batteries are not affected by DoD to the same extent as cell-based batteries. To optimise the life of a battery, a monitoring and control system can be used to unable the control of charging and discharging while taking into account the temperature of battery cells, thus avoiding its overcharging and overheating [9].

A battery produces energy in the form of direct current. Since alternating current is used for most application, it is necessary to convert the DC produced power to AC and the inverse is true for battery charging. In a microgrid environment, a BESS can be configured as distributed or centralised but, in both cases, the principle of conversion from AC to DC and vice versa remains the same. Distributed BESS tends to be smaller as they designed for a single user. They are connected to the same point as the PVPP and the load, generally at the consumer's distribution board. In contrast, centralised battery systems are bulky and need more space to accommodate the converters and batteries while their location is network dependant.

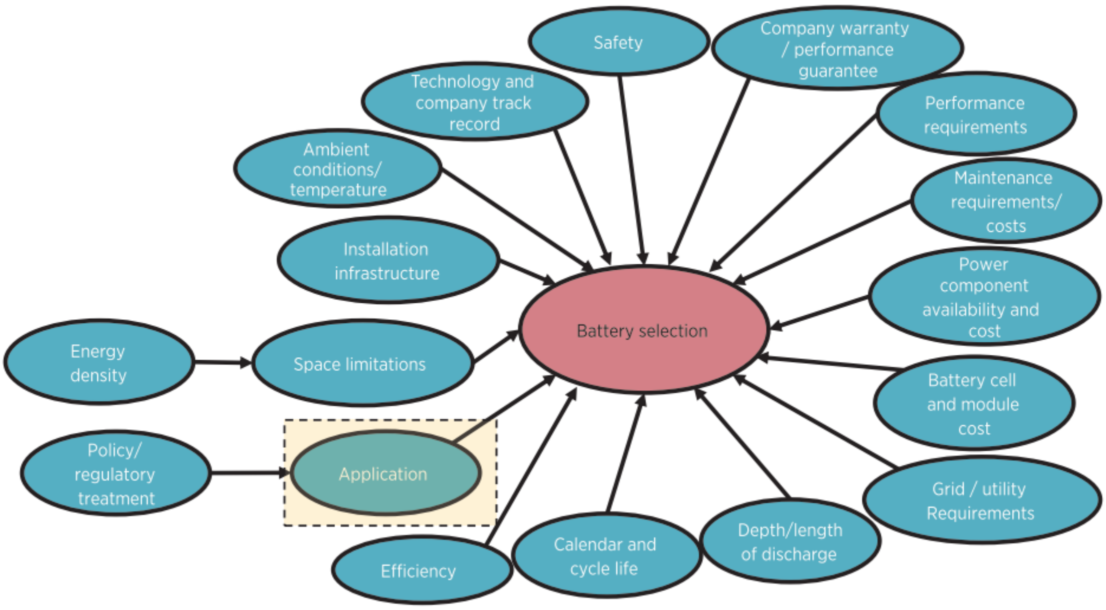


Figure 2-15: Consideration for a battery selection [9]

The selection of a battery depends on various factors and the overlap between the performances of various categories makes the selection more complex. As a guide, IRENA recommends for the battery selection to be guided by three applications types show in Figure 2-14 while proposing a list of factors to consider for battery selection as given in Figure 2-15. In the context of this research, consideration will be given to all three applications depending on the microgrid objective.

2.7.6 Operation of a Microgrid

Depending on the fuel type, a DG can operate in standby, in stand-alone (off-grid) or in load sharing when connected to a microgrid. A DG such as a diesel generator is able to function in standby, isolated or load sharing when integrated to the local network. Such DG can be used efficiently by optimally allocating power, considering the fuel availability and a coordination of generation unit mix and the load. For a better efficiency, DGs can be combined under a single control to form a microgrid that is essentially a small-scale electricity grid.

One or more microgrids can be connected to the existing network at a defined connection point from which it can be viewed as a single generator. The interconnection standard and national regulation guide the connection of a DG to an existing distribution network but does not elaborate on the microgrid connection.

When operating in off-grid mode, a microgrid has to match its electricity demand and generation to ensure that there is not deficit or excess generation. The control of such system pauses technical challenges, more so when the use of intermittent renewable energy sources such as PV are dominant. In a high PV penetration microgrid, each generator output varies depending on the prevailing weather conditions. The electrical demand is equally variable depending on the consumer behaviour. Due to the random variations in generated power and load, the probability of unbalance between load and generation is high. This random unbalance creates challenges for frequency and voltage stability in the microgrid.

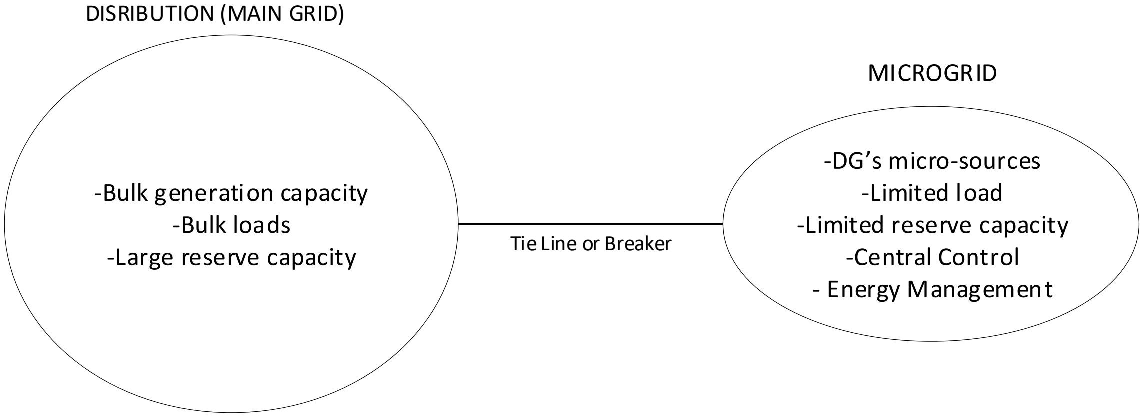


Figure 2-16: Interaction between distribution grid and microgrid

Various regulations such as the IEEE 1547.2-2018 [69] or local regulations in [18] and [20], etc. require for the DG to disconnect from the distribution network in the case of a disturbance in the distribution network. Though this requirement aims to protect, provide safety and security for the utility network, it could work against the aim of increasing the penetration of RPP. By using a microgrid, it is possible to continue supply its consumers even after the failure of the utility's grid. In this manner, consumers owning DG benefit from the availability of power, hence an improvement in the supply reliability.

Although the microgrid provides benefits to its consumers, it is faced with major challenges related to its operation mode (parallel to the grid or standalone). These challenges range from the operation, control and protection [30] as discussed in the following sections.

2.7.6.1 Grid connected operation

A grid-tied microgrid can exchange power with the utility's grid by either importing or exporting power, depending on the balance between its load and generation. However, exporting power into the distribution grid pauses challenges to the existing electrical network, mostly voltage instability in Low Voltage

Networks[70]. Addressing this challenge requires the use of reactive power compensation systems, line voltage regulators, transformer tap changers to mention a few but their effectiveness is limited [71].

Alternative methods for controlling the voltage rise and maintain its values within the regulatory limits are to reduce amount of power exported into the distribution or to store the excess energy into BESS instead of export back into the distribution grid [72],[73]. In a radial network commonly used by most utilities to supply residential consumers, the PV connected at the end of the radial feeder experiences the highest voltage rise all the times and is likely to be the first to breach the voltage limits [74]. If generation curtailment is imposed, the consumer at the end of the feeder is the first to disconnect the PV source while others located elsewhere along the feeder can remain connected. Forcing the end of the line consumer to reduce the amount of power injected could be construed as unfair due to differing treatment of other producers connected to the same feeder, specifically those upstream [75]. This begs the question of how to compensate users at the end of the feeder in direct comparison with those upstream when the network conditions demand for the disconnection to protect the network.

For a grid-connected system, the distribution grid compensates for the deficit and excess power from the microgrid. In this case, the exchange of power between the utility grid and the microgrid provide mutual benefit between them. For instance, a microgrid could provide voltage support, peak load shaving, etc., thereby eliminating the need for ancillary services for the distribution grid [31]. Conversely, connection to a utility grid provides a microgrid with reserve margins required in the event of a deficit of power from local generation. The mutual benefit between the distribution grid and the microgrid provides a mean for solving Active Power-Frequency and Reactive Power – Voltage challenges.

The main non-technical concerns in a grid-connected microgrid are the safety of maintenance personnel in both the distribution and in the microgrid. To address this challenge provision must be made for isolation between the distribution network and the microgrid at each Point of Common Coupling.

2.7.6.2 Islanded operation

In islanded operation, a microgrid has to balance between its generation sources and its load with no support from the utility grid. This implies that the frequency and the voltage levels have to be maintained at regulatory levels. Though the frequency and voltage control can be achieved with fuel based micro sources, it relatively complex in the microgrid with high penetration of intermittent RPP [76].

Where islanded operation occurs due to disturbances in the distribution system, the microgrid will face a voltage and frequency change. For that, a change in control strategy is required immediately after the islanding occurrence [77]. The control requires for the microgrid to transit from a state where it had support from the distribution grid to a state it has to control the frequency and voltage. This could happen under two major scenarios:

- Microgrid importing power from the distribution grid: the loss of the tie line or breaker leads to frequency drop in the microgrid. DG's are required to react to this condition by increasing their output to match the demand. Alternatively, load shading can be applied to bring the electricity demand within the available generation capacity. BESS could be added to the microgrid to augment the generation capacity, especially when the microgrid is characterised by a high penetration of intermittent RPP.

- Microgrid exporting to the distribution grid: the loss of the line or tie breaker results in an increase in frequency. DG's are required to adjust their output to reduce the generation to match the demand. In this case, it is possible to disconnect some micro-sources from the microgrid.

In both scenarios, the load-generation unbalance in the microgrid could lead to frequency and voltage deviations that needs correction. Without the support of the utility grid, the microgrid inertia is relatively low due to the use of micro-sources and constant output power of some DG's [64]. Coupled to the intermittency of RPP, these conditions can lead to transient and steady state stability issues for the microgrid.

From the above technical challenges of operating and microgrid, its control requires a careful management of loads and micro-sources to achieve the balance between load and generation as well as the system stability. This leads to the need for a Microgrid Central Controller (MCC) along with an Energy Management System (EMS) to achieve an efficient use of the resources. In this scenario, the design of the MCC can be such that it achieves the coordination and management of individual controllers at load, micro-source and storage unit levels [78].

2.7.7 Control of a Microgrid

A microgrid control system is essential and critical to achieving its objectives depending on which various control theories are available. Existing control method share the same objectives that consist of the regulation of voltage and frequency regardless of the operation mode. More objectives include the efficient load sharing and coordination between DGs, re-synchronisation of microgrid with the ENSP's grid after the tie-line restoration, the control of power flow between the ENSP's grid and the microgrid, the optimization of the microgrid operating cost, the handling transients and the restoration of preferred conditions when switching between operating modes. These control objectives fall broadly into three levels of control philosophy shown in Figure 2-17 as primary, secondary and tertiary. The level at which the control is applicable ranges across all microgrid components that include micro-sources control, load control and Energy Management System. Furthermore, the three control levels differ significantly according to their function and timescale [79].

The primary control is the fastest of all three control levels. It maintains the voltage and frequency stability when switching between grid-connected and island modes. Its primary control techniques include the PQ (Real and Reactive power), VPD (voltage and Power droop) and FQB (Frequency and Reactive Power Boost) achieved by use of Current Controlled Voltage Source Inverter (CCVSI) or Voltage Controlled Voltage Source Inverter (VCVSI).

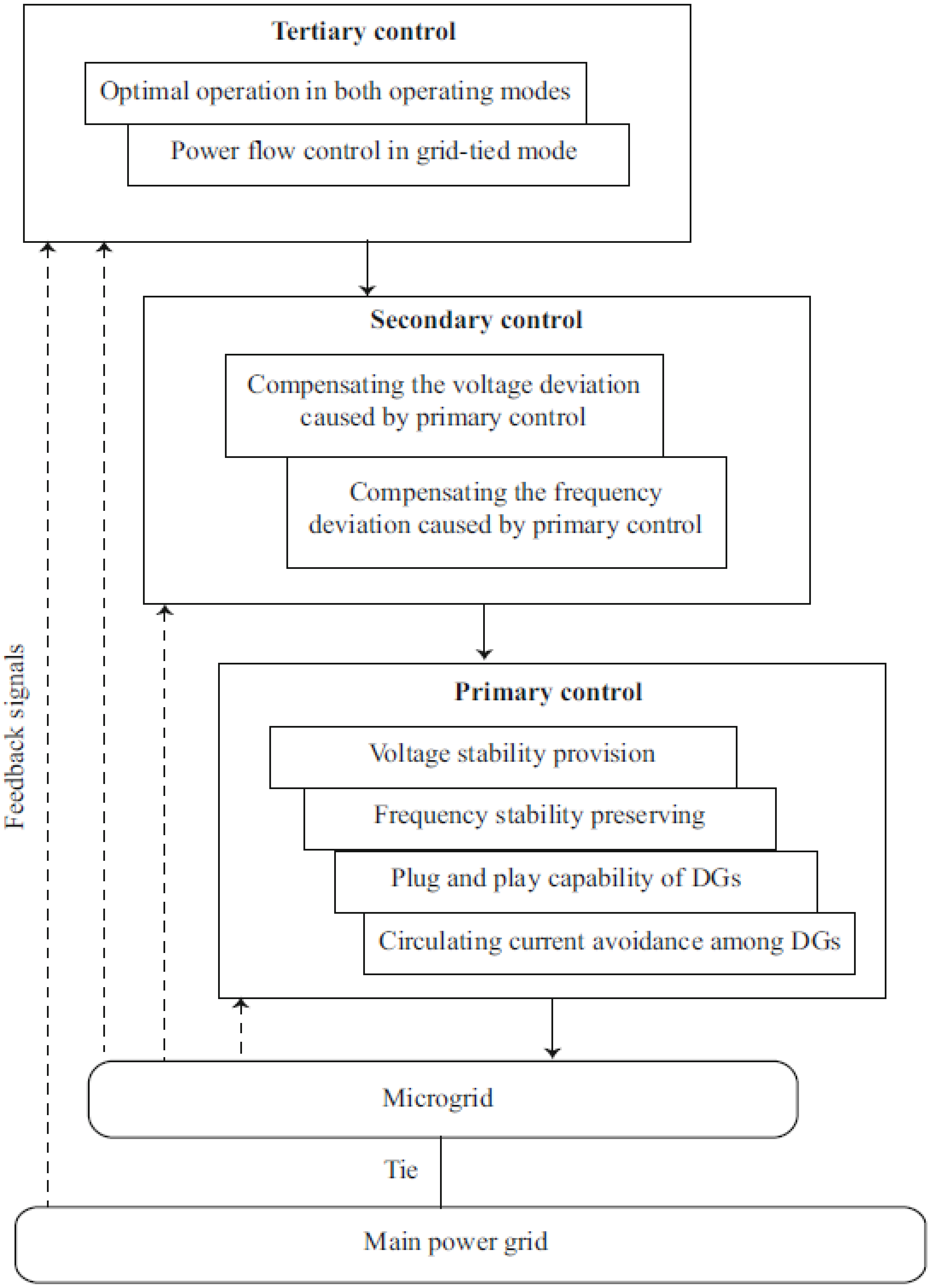


Figure 2-17: Hierarchical control levels of a microgrid [79]

The secondary control is responsible for the compensation of voltage and frequency deviations. The tertiary control is located at the highest level of the Microgrid control chain and is the slowest. It is responsible for the optimal operation in all operation modes and the power flow control between the Microgrid and the main grid. The tertiary control is mainly deployed to provide optimal operation in any microgrid operating mode. Essentially, it controls the flow of power between the utility and the microgrid. This controller can be programmed on the basis of the utility tariff such that the exchange of power is regulated to the microgrid advantage.

The above control levels provide flexibility between microgrids and the utility grid. They allow for any type of configuration and operation to be established, subject to local regulations but from a technical perspective, the use of multiple microgrids and the utility grid is possible.

2.7.8 Protection of a Microgrid

For a microgrid that can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode, changing between the two operation modes require careful consideration in relation to the protection coordination. The challenge with the protection of a microgrid lies in most cases at the PCC. For LV network, the most common form of protection uses overcurrent concept that relies on a current limit to determine overload or fault conditions on the network [80].

Overcurrent (OC) protection relays based on current sensing are popular in radial network. For the microgrid to switch from grid-connected to island mode or vice-versa, the protection relay requires a set of settings to satisfy both conditions. If the current sensing is high to accommodate high fault levels from the utility grid, this could lead to loss of sensitivity in islanded operation. In the case where the current is too lower to cater for low fault levels in island operation, it could lead to nuisance tripping in grid-connected operation. For this reason, new protection schemes are proposed. Some incorporate the traditional OC method with a high impedance protection scheme for an effective response while others proposed the use of differential protection schemes that has a disadvantage of reliance on communication link but seems more simpler than OC methods [81].

2.7.9 Regulatory and Economic Frameworks

The South African Electricity Act 4 of 2006 [19] explicitly states in clause 8 that "*No person may, without a licence issued by the Regulator in accordance with this Act- (a) operate any generation, transmission or distribution facility; import or export any electricity; or be involved in trading*". Its amendment in schedule 2 notice of 10 November 2017 grants exemption for generation facilities with a capacity lower than 1 MW for individual usage or sharing when located in the same property provided that permission is obtained from the NERSA [82]. Although the amendment provides hope for the establishment of microgrid in residential establishment, it also raised important questions regarding the legality of microgrids in the South African context.

2.7.9.1 Existing regulatory framework

NERSA has published the framework detailing requirements for the connection of renewable energy to the transmission and distribution grid [18]. Further technical requirements, both technical and non-technical are addressed in NRS097-2 that is soon to become a national standard. Both documents provide guidance regarding the operation and of connection a DG to the existing distribution network but do not cover aspects related to microgrids.

Along with the electricity act, the South African Grid Code Requirements for Renewable Power Plants (SAGC-RPP) and NRS 097 form the current regulatory framework based on which some electricity ENSP's policies promote the use of DG for residential, commercial and industrial consumers. However, these policies are leaned more on the production of electricity from a single generation facility. Although consumers are allowed to install DG's and in some instances export power into the power utility, wheeling of power for the purpose of sharing of power produced by one consumer with other consumers is not allowed, unless a use-of-system agreement is reached with the distribution company [82].

Based on the topological, operation, control and protection differences between a DG and a microgrid, it is practical to establish a microgrid with a status a generation/distribution facility. However, the microgrid must adhere to the conditions required for non-generating license and distribution license from the regulator. This include the Maximum Export Capacity capped at 1 MW, prohibition of power or energy wheeling through the national grid to other consumers and the restriction for applicable tariffs applicable to the end user not to exceed that of the licensed distribution company covering the same area from similar PCC.

These conditions set the tone for a microgrid to take over consumers that previously obtained electrical energy from the power utility. However, the second condition makes it difficult for collaboration between microgrids but the benefit of such configuration could be argued in favour of allowing such collaboration to flourish. For instance, enabling the wheeling by the microgrid owners by leasing a portion of the existing ENSP's infrastructure. Alternatively, microgrid owners could simply build new infrastructure for this purpose but it could lead to higher CAPEX.

2.7.9.2 Economics and Tariffs

The cost of traditional electrical energy from the distribution grid has significantly increased for the past decade [5],[24]. The rising cost in a sluggish economy has created challenges for many households that electricity is fast becoming unaffordable. At the same time, the cost of renewable energy generation systems is decreasing, especially solar power [7]. With solar energy in abundance in South Africa, there is a case for determining the merit of using PV in a microgrid environment, regardless of grid tied or stand-alone.

In the South Africa, PVPP are used in stand-alone mode or grid connected. A steady growth is reported but their operation is seldom interconnected as a microgrid under the existing regulatory frameworks. The key factors influencing the merits of a microgrid with high PVPP penetration and BESS are the initial capital costs, the depreciation period for major components, the feed-in tariffs for excess energy and the consumption tariffs. Economic benefits of a PVPP can be drawn only where it financially outperforms the distribution grid in a long term while providing the required reliability of supply [83].

Establishing a microgrid in a collaborative residential environment requires significant investment and to achieve that, it is important for each consumer to participate, either as a right-out consumer or consumer. Consequently, the level of participation and benefit offered in return must be attractive and fair to each consumer. To achieve this a clear and transparent mechanism that addresses and responds to financial benefit is required. The overall concept can succeed on the financial front only when the cost of acquiring electricity from the utility is higher than that offered in a microgrid environment. Such scenario can be achieved when multiple microgrids collaborate and exchange power.

2.7.9.3 Ownership Models

A microgrid environment could be such that different individuals, corporations or a mix own the generating plants. For it to be viewed as an entity, it does need not only a physical boundary but also a clear ownership model. For the Distribution Company or regulator, ownership of a microgrid is of importance for administering any regulation or standard at the connection point. For consumer/producers within the microgrid, there is a need to understand the ownership share model. These issues are looked at by D.E King research in which he proposed five different ownership models for microgrids [84].

The Utility Model in which the microgrid belongs to the distribution company that operates to reduce customer costs. This model is suitable for area remote to the established distribution grid. The cost can be justified against the capital required for the construction of transmission infrastructure, substations and transmission losses resulting from importing power from a long distance to the load centre;

The Property owner Model in which the microgrid belongs to a single owner and provides power to tenants based on a lease agreement. Although this model is simpler from an establishment point of view, it could be problematic in the South African context of urban security complexes where space is often a constraint. Furthermore, the microgrid owner needs to ensure that every other tenant within the grouping buys into the idea and incentives such as lower tariffs. The Co-operative model in which the microgrid belongs to a firm or group of individuals and serves their own need but customers are free to join and consume electricity based on the terms of a contract. The Customer-Generator Model in which the microgrid belongs to a single individual or firm that serves its own needs and any neighbour that can join under the provision of a contract. The District heating Model in which an independent firm owns the microgrid and the power is sold to multiple customers under the provision of a contract.

In the context of a collaborative environment within an Urban Security complex, the co-operative model is the most suitable because it provides the possibility for ownership by multiple individual. However, it could be made more effective by enticing all consumers within the complex to join. In this research, a modified co-operative model whereby the microgrid ownership resides in the hands of a collective of the Urban Security Complex property owners, thereby automatically admitting each Urban Security Complex property's owner as a consumer. In this hybrid model, the ownership could be for instance based on the investment of each property owner. The cost of electricity could also be tailored to reflect ownership weighting such that those that invested in the generating plant benefit more.

In spite of all the opportunities offered by a consumer owned microgrid, its establishment can be successful only when backed by favourable legislations and regulations in the local market. Microgrids need a legal status and possibly a license to operate and rival utility companies. In the current regulations, it is fair to say that microgrids are operating as utility companies without legal status.

For the successful adoption and integration between microgrids and NSPs, a greater collaboration is required between the utility, NERSA and consumers/producers. Such collaboration should be based on loosening the existing regulation to encourage more participation.

2.8 Microgrid Modelling

A microgrid can be composed of multiple sources that can be renewable, non-renewable or a combination. The present research's focus is more on solar PV sources with BESS. In these systems, the most important components of a solar PV system are the solar panels used to convert the solar irradiation into electrical energy, the inverter that converts the DC current produced by the solar panel into the AC power and finally an optional BESS that stores or released electrical energy into an AC system. The transfer of energy between AC and BESS requires AC/DC and DC/AC conversion systems to ensure that the energy can be converted from AC to DC form and stored in BESS when the production capacity is higher than the load and vice-versa when the load is higher than the local production.

The design and analysis of a microgrid requires an electrical model that cover the generating sources (in this case the PV panels), the inverters, the BESS and lastly the electrical load. The following section discusses the modelling of a PVPP that constitutes the major components of a microgrid.

Photovoltaic is a process by which the solar energy is converted into electrical energy. PV cells are semiconductors and have electrical characteristics similar to those of a diode except generates electricity when in contact with a source of light [85]. A PV panel consist of many PV cells connected in series and parallel to increase the output voltage and current.

Many models have been developed to represent electricity production from photovoltaic effect. The simplest model shown in Figure 2-18 represents an ideal solar cell for which the relationship between the output voltage and the incident light induced current is given in equation (3). Although the model provide a clear relationship between various parameter, it does not produce an accurate I-V characteristics needed for modelling of PV systems [86].

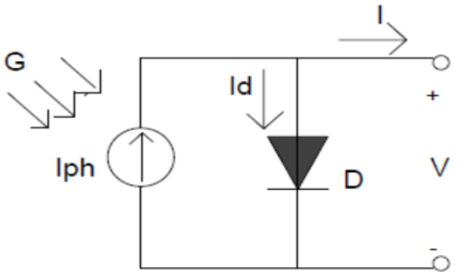


Figure 2-18: Ideal Single diode model

$$I_{pv} = I_{ph} - I_D \quad (1)$$

$$I_D = I_{sat}\left[e^{\frac{V}{n_s v_T}} - 1\right] \quad (2)$$

$$I_{pv} = I_{ph} - I_{sat}\left[e^{\frac{V}{n_s v_T}} - 1\right] \quad (3)$$

$$V_T = \frac{nkT}{q} \quad (4)$$

An improved single diode model also known as five-parameter is given in Figure 2-19 in which a series resistance (R_S) and a parallel resistance (R_P) are added to represent the effect of voltage drop, energy losses and leakage current across the solar cell. It provides simple model of a practical solar cell with a minimum error with respect to the PV cell characteristics [86]. In this model, the maximum voltage is reached under no load or open circuit condition (V_{OC}) while the maxim current (I_{SC}) is obtained under short-circuit conditions.

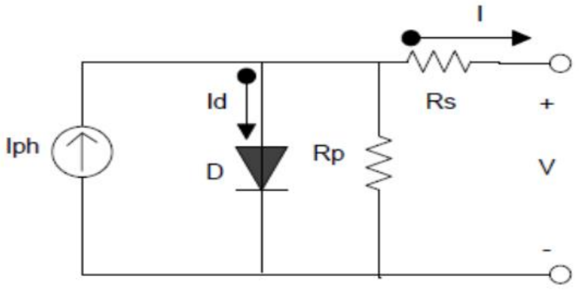


Figure 2-19: Practical Single diode model

$$I_{pv} = I_{ph} - I_{sat}\left[e^{\frac{V+IR_S}{n_s v_T}} - 1\right] - \frac{V + IR_S}{R_P} \quad (5)$$

$$I_{ph} = \left(I_{ph}\right)_{T1} + K_o\left(T - T_1\right) \quad (6)$$

$$\left(I_{ph}\right)_{T1} = \left(I_{SC}\right)\frac{G}{G_{STC}} \quad (7)$$

The current produced by the incident light is thus expressed by equation (5) where the parallel and series resistances are taken into account. Parameters included in equations (1) to (7) are defined below.

I_{ph} : Photocurrent (A) generated by incident light (A)
I_{sat} : Diode reverse bias saturation current (A)
q : Electron charge 1.6021×10^{-19} C
k : Boltzmann constant 1.3865×10^{-23} J/K
T : Operating temperature (Kelvin)
n : Diode factor ($1 \leq n \leq 2$)
G : Irradiance (W/m2)
R_s : Series resistance (Ω)

R_p : Parallel resistance (Ω)
n_s : Number of cells in series
V_{OC} : PV module open circuit voltage (V)
I_{SC} : PV module short circuit current (A)
V_{mp} : PV module voltage at maximum power (V)
I_{mp} : PV module current at maximum power (A)
I_D : Shockley diode current (A)
I : PV module current (V)
V : PV module voltage (V)
v_T : Thermal voltage equivalent
STC : Standard Test Conditions (1000W/m^2 at 25^{o}C)

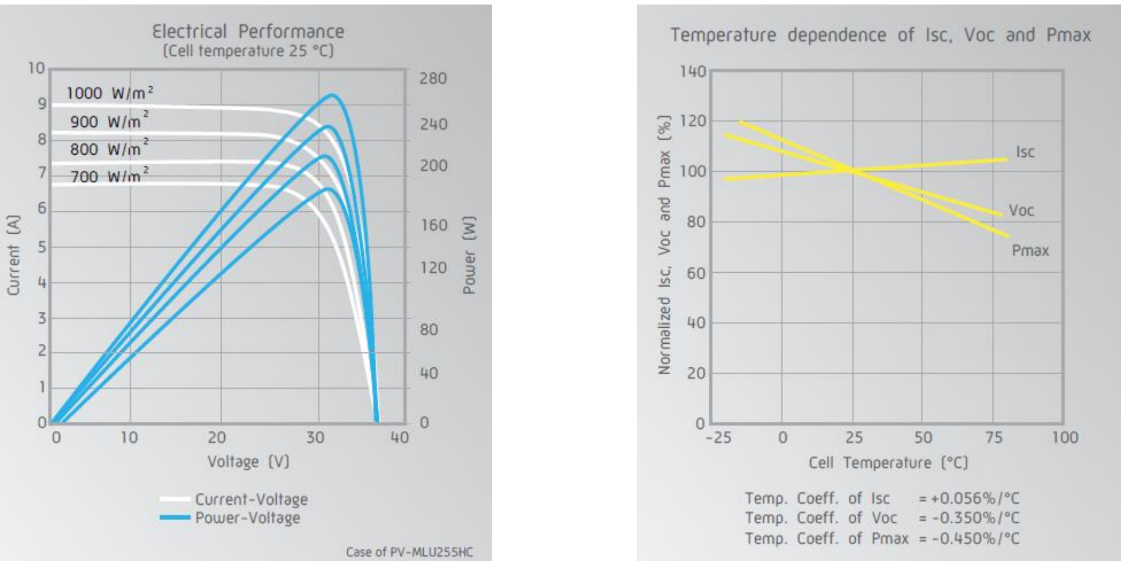


Figure 2-20: PV panel's I-V and P-V characteristics and the dependency on temperature

Equations (5)-(7) provide information about the photovoltaic process in a cell. Under normal operating conditions, a PV cell current is directly proportional to light intensity of solar irradiation and is influenced by the PV cell operating temperature. Solar irradiance has the biggest influence on the output current of a PV cell. More irradiation leads to more power while the inverse is true. For a fixed irradiation value, higher temperatures lead to less photo current and therefore less power while lower temperature lead to more output power.

Typical I-V and P-V characteristics of a PV panel are given in Figure 2-20 for Mitsubishi PV-MLU255HC 255 W solar panel. Each I-V curve corresponds to a fixed irradiation value for which there is a corresponding maximum power on the P-V curve. Furthermore, the effects of temperature are shown where the output voltage and power decrease as the operating temperature exceeds 25^{o}C. For each irradiance, it is possible to extract maximum power from a solar cell by applying Maximum Power Point Tracking (MPPT) algorithm. This is achieved using the DC/AC or DC/DC inverter [87].

2.9 Microgrid Objectives

The size of a microgrid relates to its physical boundary, its generation and consumption capacity. Whereas the Microgrid consumer behaviour influences its overall consumption of electrical energy, its generation capacity is more a function of its objective. Such objectives could be for peak load shaving, the financial incentives through reduced electricity bill and feed in tariffs, the zero net consumption from the utility grid, the supply reliability and the combination of two or more of the above [31], [51]. For each of these objectives, it is possible to determine an optimal generation size for the PV generation, storage but that objective is beyond the scope of this research.

Peak load shaving consists of increasing the local (microgrid) generation during the time of peak. For residential consumers, the peak load is likely to occur in the late evening. For a system with high PV penetration, this might not be possible owing to the output intermittency and unavailability of the PV power during the evening peaks. Therefore, the peak shaving is possible only with the use of energy storage systems.

Meaningful financial incentives are possible if the regulatory framework encourages the use of RPP through incentives such as the feed-in tariff and/or carbon credits. In this configuration, achieving the objective is highly dependent on the generating capacity of the microgrid and the applicable feed-in tariff. Its dependency on the electrical storage system is relevant only when operating in other tariff regime than flat rates. With this objective, it is even possible to buy electricity from the grid at lower prices and use or resale at higher prices if non-flat tariff such as Time of Use are applicable.

Achieving a net-zero consumption from the utility requires the internal microgrid generation to be greater than its load. Due to the intermittency of PV sources, only an optimal sizing of PVPP and BESS could make a net-zero consumption from the utility grid possible [66].

Where supply reliability is required, the microgrid must island with the load and re-synchronise to the utility upon the main grid restoration. This is possible to achieve but requires a substantial investment in BESS for which the size is highly dependent on the desired islanding autonomy. If the islanded microgrid has to supply loads for a prolonged period, it would call for a bigger BESS, which in turn could render the Microgrid financially unviable [9].

2.10 Potential for microgrids in urban environment

A typical Urban Security Complex is composed or stand-alone or cluster of houses. In most cases, its operations are looked after by a property Management Company with the “body corporate” composed of selected owner (director) tasked with the oversight. A microgrid can be easily implemented in Urban Security

Complexes owing to their spatial planning, the availability of roof space suitable for the installation of Photovoltaic solar panels and the existence of a collaborative environment such as “body corporates” formed in the interest of the property owners.

The extent of DG in South Africa is not extensively covered and the reason can be attributed to factors such as competition amongst developers and the lack of a national information repository. It is seldom to find residential consumer using any form of generation but solar PV. The use of solar PV has increased significantly but almost exclusively for individual consumption and not for distribution to other consumers. In some instances, the PV system as DG is not allowed to connect to the LV network belonging the ENSP, such is the case in South Africa with Eskom [88].

Having realised the benefits of DG, major South African distribution licensee such as City of Cape Town, Ethekwini Municipality allow for connection to their LV network on condition to meet the requirement of NRS 097-2-3 and SAGC-RPP [89], [90]. On the financial side, feed-in tariffs offered for power exported into the distribution network is far below the cost of drawing power from the grid. Moreover, utilities such as the City of Cape Town impose further conditions whereby the net energy in a billing period must be result in a net consumption for the consumer. This implies no real monetary value is offered to the consumer producing electricity. Rather, any proceed of excess generation is used to offset the consumer’s bill. In order to take advantage of the DG penetration, a collective initiative such as microgrid is required. In such configuration, it is possible for the consumer to benefit as a collective from the use of microgrid. Furthermore, the concept can be extended to allow microgrids to collaborate by exchanging power without wheeling on the utility’s grid.

2.11 Microgrid related studies in South Africa

Despite the existence of DG, the potential benefits for the consumer and its adoption by utility such as the City of Cape Town [89], some utilities are still reluctant to adopt them. Such is the case in South African’s Eskom supplied consumers [88]. This reluctance could be the result of many challenges faced by the integration of DG and implicitly that of microgrids too.

A quick observation of the urban landscape gives a glimpse into the changing landscape whereby consumers are now open to the use of PV systems. The literature survey also points to a soaring interest in Microgrid, mostly in established business complexes and new residential complexes. Some experimental projects are at planning stage while others are operational in part or as a whole. They have differing objectives, topologies and serve various purposes as elaborated below.

Raj Chetty and Renier de Lange of Eskom developed Ficksburg Microgrid to supply a remote farming community of 14 households in the Free State by operating in off-grid mode. The microgrid consists centralised resources of 30 kW PV generation, a 90 kWh BESS, a 22 kW backup generator and a basic Demand Side Management (DSM) consisting of grouping loads into essential and non-essential parts. Main considerations for sizing Ficksburg Microgrid included only refrigeration, lighting, cellular phone charging and entertainment. The community used solar geyser to provide hot water and LPG gas for cooking instead of having them connected to their microgrid. According to the paper, this microgrid will serve as a pilot project for future massive roll out in remote communities by Eskom [15]. Despite the use of Ficksburg microgrid as testbed for massive roll out, there is no discussion on the financial viability of the model including the affordability by the community. Moreover, there is no mention on its compliance to the SAGC-RPP and no discussion on its control and monitoring.

T. Fanele Xulu et Al explored the design of a standalone PV system and battery to supply a 25 houses village in Ezikhumbeni village in Kwazulu Natal. The researcher calculated the total village load and sized the PV system to 17 kW and 4980 Ah battery [14]. The research does not indicate the distribution network for supplying power to each household; it does not mention the financial viability or affordability of the user. Moreover, there is no reference to aspects of control and load management within the PV system.

Nick Singh et Al. from Eskom Research, Testing and Development recognise that microgrid represent the future of generation and distribution. They recognize the importance of exploring microgrid in the South African context by considering the role of traditional power utility in the market following the evolution of this disruptive technology. The research shows the awareness of the South African biggest power utility to the fact that the cost of electricity from solar energy could soon become competitive in comparison with the conventional electricity. To ensure that the power utility embraces the concept of microgrid to its advantage, the authors explore data collected from another pilot project in Lynedoch, Stellenbosch in the Western Cape. The pilot project aims to supply to thirty household of different living standard measure from three to ten. The main characteristic of the microgrid was equal generation capacity based on roof top PV and a local BESS for each household [16]. Although the project aim is to explore microgrid with the view of future rollouts, the microgrid information is not available, there is no cost benefit or financial viability and no reference to adherence to the SAGC-RPP.

Clinton Carter-Brown is exploring the possibility of the most comprehensive microgrid found in the South African literature. The aim of his work was to implement a microgrid with three sources of energy (solar, wind and biogas) to Supply the CSIR campus in Lynnwood, Pretoria. The microgrid would accommodate the integration of electric vehicle and would be capable of operating in grid-connected or island mode. The aim of the project was to demonstrate the use of microgrid as future energy system based on a combination of fluctuating and non-dispatchable renewable operating in the most cost-efficient manner in the African context. On completion, the CSIR microgrid will contribute to the supply of 30GWh per annum at a base load of 3 MW peaking between 5 and 6 MW. The microgrid will implement ground mounted and roof top PV, DSM and energy efficiency while classifying electrical loads into the essential and non-essential groups. Finally, the entire CSIR microgrid will operate as a virtual power plant with no plan for any energy export. The research indicates more work is in progress with an emphasis on the financial aspect and the compliance to the SAGC-RPP [17]. Although the research mostly aligns and shares the same principles with the establishment of microgrid for Urban Security complexes, it is of commercial nature and its basis for consumption relies on commercial tariff and heavy consumption. Therefore, tis dynamics and dependencies are dissimilar to those expected in a residential microgrid.

Mike Barker [91] used DER-CAM model to find the cost-optimal configuration and capacity of DG for the Durban International Convention Centre. The microgrid comprises a 1 MW of diesel generator, 180 kW of UPS and is grid-connected. Results produced from DER-CAM gave an optimal investment considering PV, BESS and electric vehicles. The focus was more on the economic performance when adding PV systems to the energy mix than the technical requirement of the microgrid in relation to grid-connected or islanded operation mode.

3 RESEARCH METHODOLOGY

3.1 Introduction and overview

This research aims to demonstrate the suitability of the existing South African regulatory framework to support a high penetration of renewable energy into the network. Although its present form allows for the connection of distributed generators, the concept of grouping these into a microgrid is not clear.

For microgrids to be attractive to potential consumers/producers, there is the need for their techno-economic justification. Consumers are more inclined to financial incentives, for instance a reduction in the monthly electricity bills. These benefits could be made enhanced by establishing collaboration amongst microgrids, mostly for those supplied from the same feeder.

In this context, three key inputs are considered in evaluating the microgrid techno-economic viability as illustrated in Figure 3-1. They include the grid code used in part to assess the technical compliance of the microgrids; the regulations and bylaws used to assess the microgrid compliance and the required changes to encourage their adoption and the capital and operating expenditure as well as tariffs to assess the financial impact of microgrids on power utility companies.

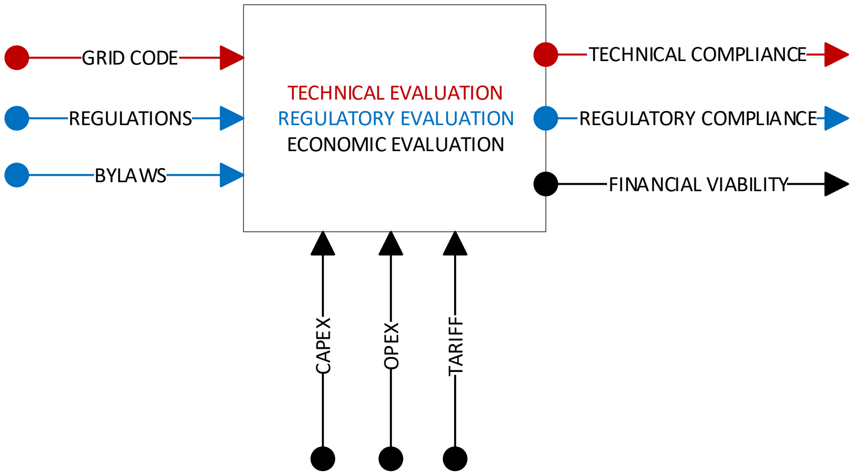


Figure 3-1: Techno-economical evaluation principles

The research focuses the requirements for the establishment of a microgrid with a high penetration of PVPP and BESS, capable of operating in either grid-connected or off-grid mode and compliant with the South African regulations in [18]-[19] and local bylaws as applicable in each municipality. The major research areas include the regulatory environment, the technical and the financial evaluation.

By evaluating a microgrid in the context of the existing regulatory frameworks (grid code and utility standards) and electricity market (various tariffs), it is possible to determine how microgrid could change the landscape of the electricity market in South Africa from both technical and economic perspective. The objective function of such a microgrid will be to achieve the minimum cost of electricity for consumers living within the microgrid boundary.

The net saving for the client and the reduced load forecast result in deferred cost of infrastructure build. This can be accumulated over the years in order to evaluate the financial impact of microgrid collaboration on the power utility companies. Since many utility companies are established in South Africa, this research considers power utility companies in three biggest South African Cities of Johannesburg, Cape Town and Durban.

With recent advances in renewable energy have seen a high proliferation of Photovoltaic technology in residential environment. Should consumers form a microgrid, its objective could be for instance, to optimise the use of internal generation of electrical power. This reduce the overall electricity bill from the power ENSP and therefore achieving savings at microgrid level implies savings for each of its consumers. At the same time, such savings would be detriment to the revenue collection of the ENSP

For this research, the microgrids studied serve only residential loads with the aim is to reduce the cost of electricity for individual consumers living within defined boundaries. Over and above the adoption of internal generation, the operation of each microgrid could be improved through adopting a common connection point to the ENSP’s grid, increasing DER assets for generation and energy storage. Furthermore, microgrids can be grouped into clusters of two or more where they can collaborate to optimise the use of the distributed resources further.

The research uses technical and financial modelling in order to establish the compliance of a microgrid with existing SAGC-RPP, the suitability of the existing SAGC-RPP to the concept of microgrid and the financial viability of the microgrid in the South African context, specifically that of Urban Security complexes. The literature review, data gathering, microgrid technical and financial modelling form the backbone of the research.

3.2 Data Gathering

Data used in this research are technical and financial. The technical data includes the electrical network single line diagrams and layouts, load and generation profiles, equipment characteristics and ratings, advisory and regulatory constraints. Data required for financial analysis include the tariff, interest rate, discount rate, historic tariff data, cost of PV system’s components, etc.

Data is collected from observations, existing test models in research journals, Original Equipment Manufacturers’ data sheets, national standards, utility standards, the SAGC-RPP, etc. Other forms of data collection have been to use standard validated model from certified software libraries such as found in DIgSILENT, ETAP, MATLAB or DER-CAM.

3.3 Research Model

The research model is based on a European LV test feeder model adapted for the supply of a residential area in South Africa’s Gauteng province. The residential area is subdivided into logical entities or microgrids connected to the same feeder at 11 kV.

3.3.1 Network Topology

Each complex is supplied from an 11/0.4 kV substation with 3-phase and neutral feeders at 400 V. LV Feeders from the substation are used to supply distribution kiosks from which each house (consumer/producer) is connected. This last mile connection between the consumer unit and the kiosk is achieved through a single-phase service cable.

In order to simplify the network to ensure that the number of nodes does not exceed the maximum allocated for a student license for the use of DIgSILENT software, each microgrid is represented by a lumped generation and a lumped load represented at the LV side of the MV/LV transformer.

3.3.2 Network Parameters

The network model consist of the MV/LV transformers described in section 3.3.1, the distribution and service cables, the PVPP and the Battery Storage. More details on the model are covered in the network model and validation in Chapter 4.

3.3.3 Static and quasi-dynamic simulations

The process of using multiple static loadflow method is time consuming when considering a resolution of 15 min per set of data. Newer technique group multiple simulation into one command with the possibility of considering feedback between time steps simulations.

For instance, this research will use quasi-dynamic function (see flow diagram is depicted in Figure 3-2) designed by DIgSILENT and offered as a module in PowerFactory™ software. The module allows the user to carry out multiple loadflow for a defined period, all at once. Unlike static loadflow that would provide the power flow and associated losses for a specific time, quasi-dynamic simulations provide time-based power flow and associated losses. These results provide more accurate values of energy trading and losses for any given period. The output of quasi-dynamic simulations provides vital information on energy trading between the utility and the microgrid and this is one of many inputs for financial analysis.

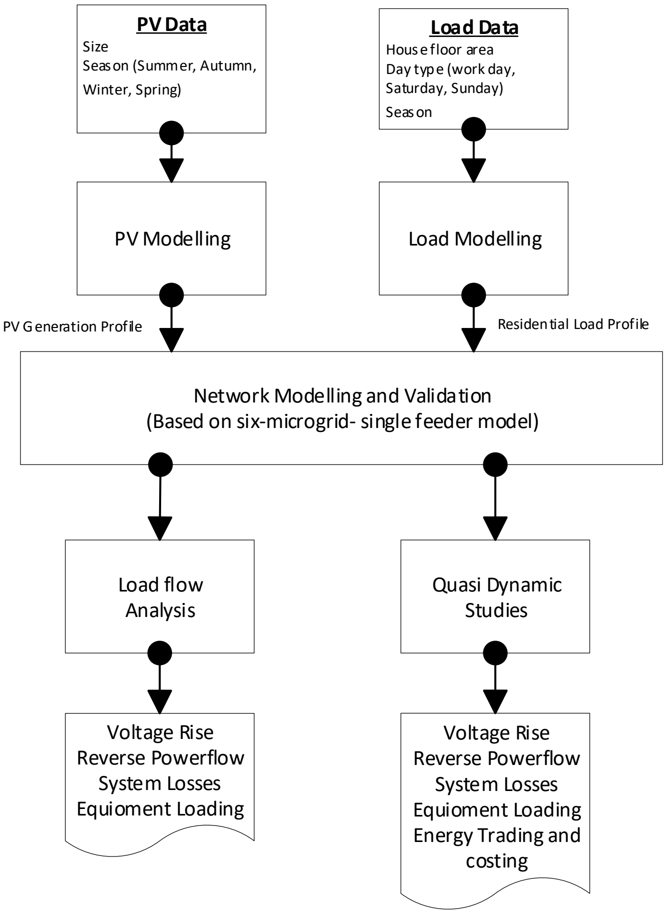


Figure 3-2: Proposed Research Methodology for technical evaluation

3.4 Case studies Analysis

The analysis of microgrids' impact on the utility grid requires the establishment of typical or common operating scenarios. To this effect, it is considered that each microgrid consumers are able to afford the installation of roof top PVPP and the balance of its plant with a capacity to meet its peak demand. For the purpose of this research, the load profile of all domestic consumers is assumed the same for any day of the week and irrelevant of the season but the solar irradiance is assumed on seasonal basis.

Under normal circumstances, a user or a group of users draw power from the utility's grid. The user's energy consumption bill is based on a define billing period. Alternatively, it is possible for some or all users to employ local embedded generation such as PVPP to offset the consumption offset the consumption from the grid or export the excess power produced into the utility grid for financial gain. In some cases, energy storage system can be used to shift the import and export pattern between the utility grid and the microgrid, also for the sake of minimising the cost of energy charged by the utility.

Although the above are likely to be the main scenarios, it is worth considering the collaboration between microgrids such that the excess energy produced from embedded PVPP from one microgrid can be consumed by other microgrids instead of sending back into the utility's grid. Just how successful this collaboration can be and its impact on the ENSP is the essence of this research. On this basis, the technical and financial impacts envisaged in this research are assessed by considering the following four case studies and their associated topologies:

- Case study 1 (Base Case): this scenario explores the status-quo whereby electrical energy is wholly purchased from the utility while no local generation or energy storage is installed in any of the participating microgrids;
- Case study 2 (Grid-tied and local generation): this scenario builds on the first but with embedded PV generation without storage facility into each of the microgrids;
- Case study 3 (Grid-tied operation with local generation and energy storage system): built on the basis of the second case study but with added energy storage system, this scenario is able to control the import and export of power between the utility grid and microgrids in response to semi-dynamic tariffs such as Time of Use (TOU);
- Case study 4 (controlled exchange with the utility's grid): this scenario assumes a collective ownership of the supply feeder with no energy storage facility. Microgrids are operating in collaboration Energy can be exchanged between microgrids to minimise energy import from the utility while maximising on the excess power generated from the microgrid.

For each case study, a technical evaluation is carried out to ensure that the network performance complies with regulatory requirements of the most stringent between South African Grid Code for Renewable Energy Power Plant and local power utilities. In the case of this research, consideration is given only to microgrids operating in grid-tied mode. Therefore, these requirements apply mainly to the voltage supply variations that must be maintained within ±5% of the nominal voltage and the network losses.

The financial evaluation considers market prices for energy consumed and feed-in tariffs for energy exported from the microgrids into the utility grid for three main South African towns of Johannesburg, Cape Town and Durban. Although Eskom supplies some of the areas in these three cities considered for this research, it is entirely ignored by assuming that only the relevant city's utility supply electricity to the residents. For ease of reference, each town's Power ENSP is herein referred to by the town name. Therefore, the three utility companies are referred to later inhere as Johannesburg, Cape Town and Durban.

3.5 Technical Analysis

The technical objective is to study the impact of multiple microgrids supplied from the same feeder on the ENSP's grid. This include monitoring the voltage, computing the energy and losses with and without the use of PVPP. The analysis tools used to achieve the objective include performing sequential loadflow or Quasi-Dynamic Simulations on the six-microgrid single feeder model developed in Chapter 4. These simulations are performed over successive time interval for a defined duration, typically a day, month or year.

The technical analysis is based on the requirement of grid code connection as laid out in SAGC-RPP. Although the requirement of the grid code covers steady state and dynamic behaviour at the point of connection, the focus this research is on voltage level, power flow and losses on the feeders. The research model is tested for voltage stability, reverse flow and losses before and after the connection of microgrids. Time step analysis focus at key time such as peak to ascertain the improvement in voltage level due to the connection of microgrids and at off-peak to ascertain the level of voltage rise in the network, particularly at the end of the feeder.

A comparison is carried out between each case and the base case to ascertain the technical performance. In this way, it would be possible to determine the technical impact of the proposed microgrid collaboration on the ENSP' grid.

3.6 Financial analysis

The financial analysis consists of assessing the electrical energy consumption of all six combined microgrids before and after the connection of PVPP, both in grid-tie operation. For each scenario, the monetary value of the energy exchanged between the microgrid and the ENSP's grid is investigated considering applicable tariff in each of the three major South African towns. The yearly energy yield, associated cost for each town and the cost of setting PVPP are used to perform revenue collection projections for subsequent years while assuming a fixed electricity cost increase and discount rate. Using Net Present Values, a comparison is performed against the base case to ascertain the merit of the proposed microgrid collaboration and its impact on the utility grid. Furthermore, an attempt is made to determine de deferred cost but not the duration thereto.

3.6.1 Tariff analysis

Tariff plays a big component of the financial analysis herein. Various tariff structures used by major electrical utility in big South African metros are used as starting point for cost analysis but later are used to calculate annual cost of electrical energy consumption for the present and future. In the latter case, historic tariff will serve as a basis for predicting future tariffs used for economic analysis.

3.6.2 Microgrid economic benefit analysis

Despite the decreasing cost of PVPP and storage systems, establishing a network remains relatively capital intensive. Such expense can be justified only where the economic benefits are transparent. In this chapter, an economic analysis is performed for the establishing a microgrid. The main consideration for the model includes the CAPEX, OPEX and the electricity tariffs for each of the town under consideration. The economic justification considers the equipment life cycle, various tariff regimes, and its objective function to determine the conditions under which a microgrid can be financially justified.

The objectives of a microgrid have a significant impact on its CAPEX, OPEX and impact on the NPS grid to which it is connected. In this context, the financial model looks are ways of minimise the cost of energy as much as possible to assess the financial impact on the ENSP.

The cost benefit considers the cost of investing in a high penetration PVPP microgrid, revenue through feed-in tariff or the cost saving resulting in the use of microgrid versus buying of electricity from the ENSP. To achieve this, the financial model takes into account the energy, tariff regimes and power flow between the microgrid and the ENSP's grid. Since NSPs use different tariff regimes, the financial modelling uses the same network topology and results under different operations but applicable to the three biggest South African town of Johannesburg, Cape Town and Durban.

A base case consisting of the electricity consumption will serve as base for comparison with the cost of each of the four objectives presented for microgrids. The cost benefit for each case covers a period of not less than the design life of a PV, taking into consideration the interest rate, operating cost, cost of replacement, maintenance cost, the utility tariffs and discount rates.

DER-CAM or excel software are used for the proposed analysis. Main inputs to the model include the topology, load profiles, tariff regime and DER options as shown in Figure 3-3. For an accurate financial modelling, where data is not available, historic tariffs are used to make projection for future tariffs. In order to arrive to a meaningful conclusion on the financial viability, various tariff structures in step 3 and various price scenarios for DER in step 6, both present and projected future.

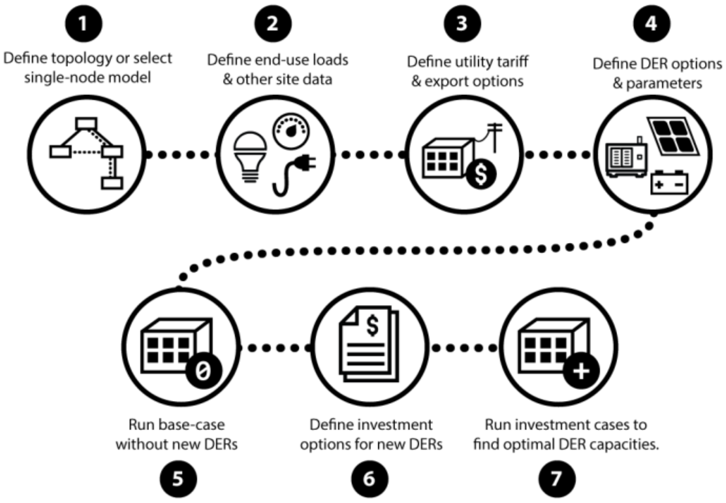


Figure 3-3: DER-CAM project flow process (copied from DER-CAM software home page)

The results of this section can provide clarity into the sensitivity of microgrid financial viability by considering the minimum cost of DER investment required for the microgrid establishment to be financially viable, the minimum tariff level at which investment in microgrid becomes more attractive and the level of energy generation or consumption that would justify the adoption of microgrids.

3.7 Data, resources and clearances

3.7.1 Modelling Software

The initial proposal for the research was to consider the use of the following specialist software listed in Table 3-1. However, DIgSILENT alone was able to provide all technical function with the exception of financial analysis.

Table 3-1: List of software required

TASK	**MAIN SOFTWARE**	**ALTERNATIVE SOFTWARE**	**REMARK**
Residential LV load modelling	GridLAB-D	PVSyst	Recorded Profiles from utility companies can be used. In this case, no modelling is required.
Load flow and short circuit	DIgSILENT	MATLAB OpenDSS GridLAB-D	DIgSILENT-Buyisa has granted the author a 50-nodes license for academic purposes for a duration of two years.
Dynamic Studies and control	DIgSILENT	MATLAB GridLAB-D	
Economic Analysis and optimisation	DER-CAM	GAMS Excel	The author will use a Multiple Integer Linear Programming platform GAMS to design an optimisation program for the research.

For financial analysis, DER-CAM was planned but due to time constraints, Excel was used in place.

3.7.2 Clearances

No ethical clearance was required for this research.

4 NETWORK MODELING AND VALIDATION

4.1 Introduction

Analysing the impact of a single feeder multiple microgrids on a power utility requires a network model. In order to evaluate the impact of multiple microgrids connected to a single feeder, it is important to use correct models and modelling techniques. Such network models can be based on test feeders developed by research groups but developing them require an understanding of the local low voltage network topology. The following section provide the methodology used to build a residential and commercial supply system for the research on the impact of single feeder-multiple microgrids on the power utility company.

4.2 Medium and low voltage network topologies

Electrical network components behave differently for different voltage categories. For this reason, networks are classified into categories of design and operations defined as Low Voltage (LV), Medium Voltage (MV), High Voltage (HV) and Extra High Voltage (EHV). Although most principles remain the same, topologies used for different voltage levels differ somewhat. However, they interface in the network in order to transfer power from one category to the other.

4.2.1 Overview of standard electricity supply systems

The electricity supply system from bulk sources to the end user, can be divided into primary and secondary distribution system. Figure 4-1 provides a high-level electrical network architecture in which primary and secondary distribution systems are demarcated. A primary distribution system comprises One or more bulk power sources, a sub-transmission system to transfer power from the bulk source to the distribution substations (at this level, power transfer medium can be overhead lines or underground cables),Distribution substations to convert the power from high voltage to medium voltage that is transmitted into one or several secondary systems. Furthermore, it has feeders that transfer power from distribution substations to distribution transformers. Like sub-transmission power transfer mediums, feeders can be overhead line, underground cable or a combination. Finally, it has distribution transformers that convert power from medium voltage to a more usable low voltage [92].

A secondary system is responsible for reticulation of low voltage to the end users such as residences, commercial or industrial buildings. Each consumer is supplied from low voltage and depending on the required load, consumers are connected as single or three-phase loads.

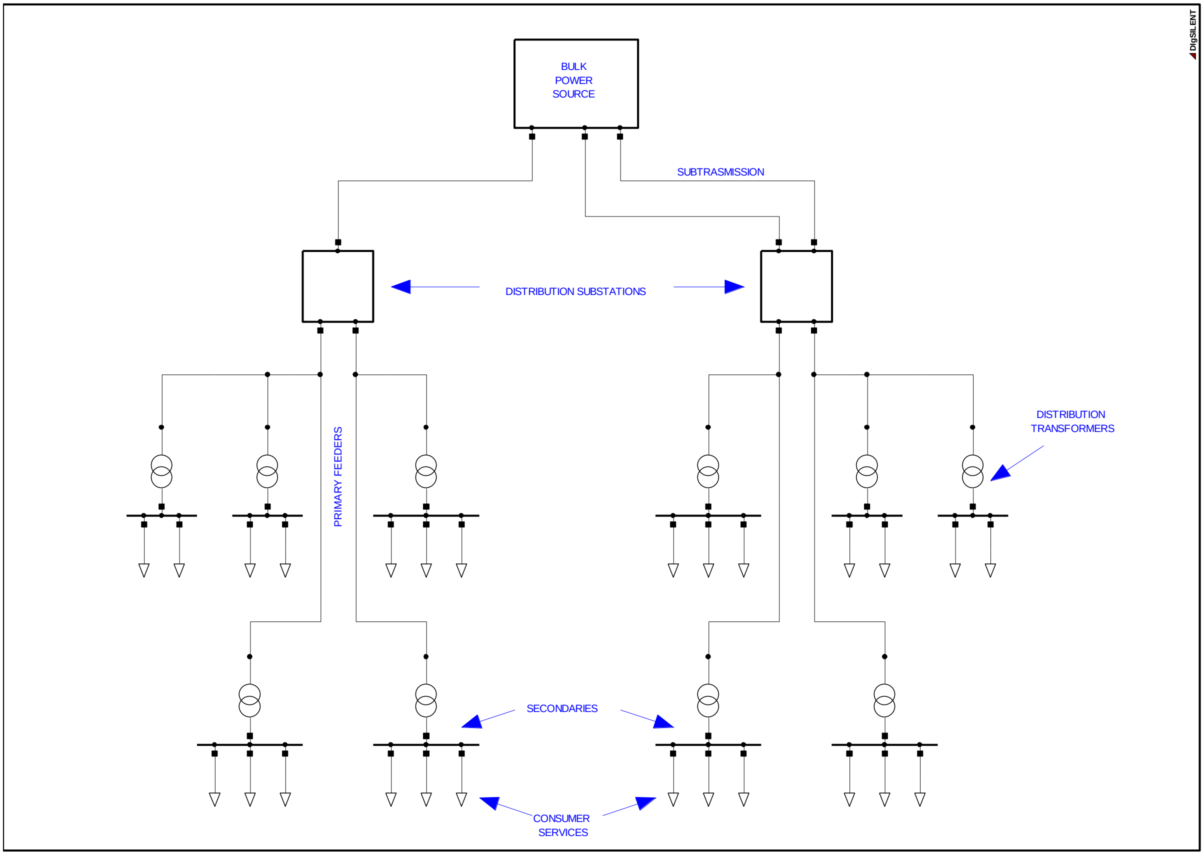


Figure 4-1: Typical electrical distribution system reproduced from [92]

4.2.2 Reliability considerations

Feeders connecting distribution substations and distribution transformers are designed as radial or meshed network topology. A radial topology such as that of Figure 4-1 is characterised by a single source of power. On loss of the feeder, any distribution transformer connected to it and consequently each consumer supplied from the affected distribution transformer will have no supply. In a meshed system, the loss of a single feeder can be back-fed by another feeder either directly or indirectly after switching operation. While the simplest form of transmitting power between distribution substations and distribution transformers is radial feeders, the use of multiple feeders in a meshed system is more reliable as far as the consumer is concerned but is also more expensive to implement [93],[94].

4.2.3 Standard voltage levels and frequency

The choice of supply voltage depends on amongst other, the electric power required by the consumer and the available standard voltages from the ENSP. Standard voltage levels vary between countries and regions. For instance in North America, earlier distribution networks used the sub-transmission voltage between 11 to 33 kV while the distribution voltage ranged from 2.40 to 4.16 kV [92]. As the demand for electricity increased, sub-transmission voltages and distribution voltages increased respectively from 12 to 34.5 kV [95]. Secondary or low voltage in this region range are 120, 208 or 240 V for single phase and 277 or 480 V for three phase supply while the supply frequency is fixed at 60 Hz [93],[95].

In contrast to North America, European standard voltage levels differ for medium voltage while they are mostly uniform for low voltage at 400 V and in some instance 416 V while the frequency is maintained at 50 Hz [96], [97]. One of the main differences between the above-mentioned networks is that in North America smaller medium to low voltage transformers are used. Each covers a relatively small number of consumers and therefore the network has longer medium voltage lines and lot of small sized distribution transformers. In contrast, European networks use larger medium to low voltage transformers and cover a large number of consumers. Low voltage lines are longer with less distribution transformers, albeit of larger sizes [98].

Standard voltage levels used in South African are 400 V for low voltage and 11, 22 and 33 kV medium voltage [99]. Like in North America and Europe, the provision of electricity to residential, small commercial and industrial consumers is achieved at low voltage 400 V for consumption up to 1000 kVA but large consumers are at medium voltage [99], [100]. Low voltage is obtained by transformation from a medium voltage feeder or source [100]. The choice of a medium voltage depends on the location and power source availability. For instance, the South African biggest ENSP Eskom sees 22 and 33 kV as the most convenient medium voltage levels due to reduced losses but 11 kV remains largely used in urban area. This is due to the cost associated with upgrading to 22 and 33 kV [101].

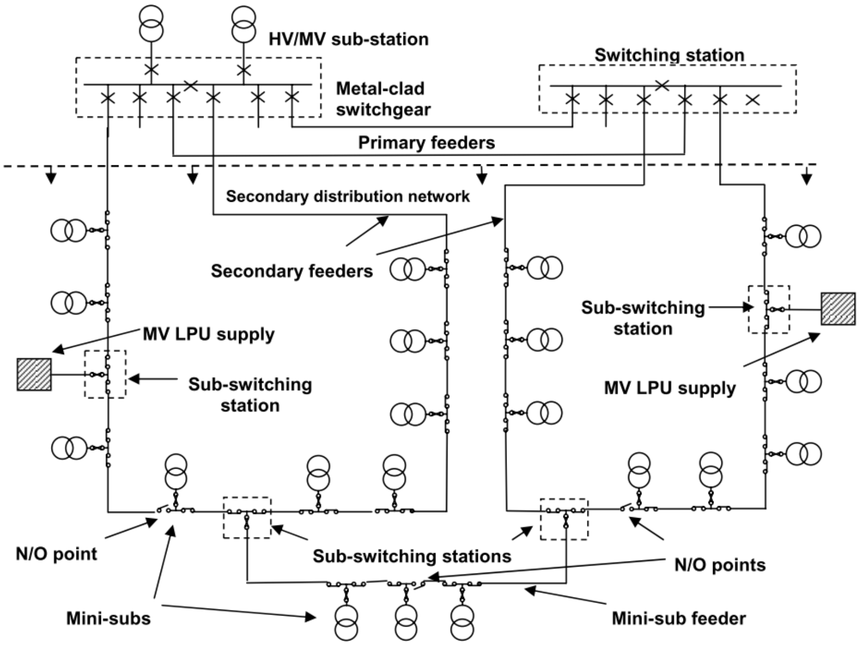


Figure 4-2: Example of an underground network in South Africa [101]

A typical network topology used in South Africa for medium and low voltage is provided in Figure 4-2. In it, a distribution substation (high to medium voltage transformation point) can supply one or more switching stations via primary feeders and one or more distribution substations (for medium to low voltage transformation) through secondary feeders. A combination of two feeders is configured to form a ring to ensure the continuity of supply in the event of the loss of one of the feeders. This is applicable for both primary and secondary feeders. Large power consumers are supplied directly at medium voltage and have dedicated medium to low voltage distribution substations. In this system, reliability is further enhanced by providing extra connection (via sub-switching station) between feeder rings, making it easier to swing part of the load from one ring feeder to the other [102].

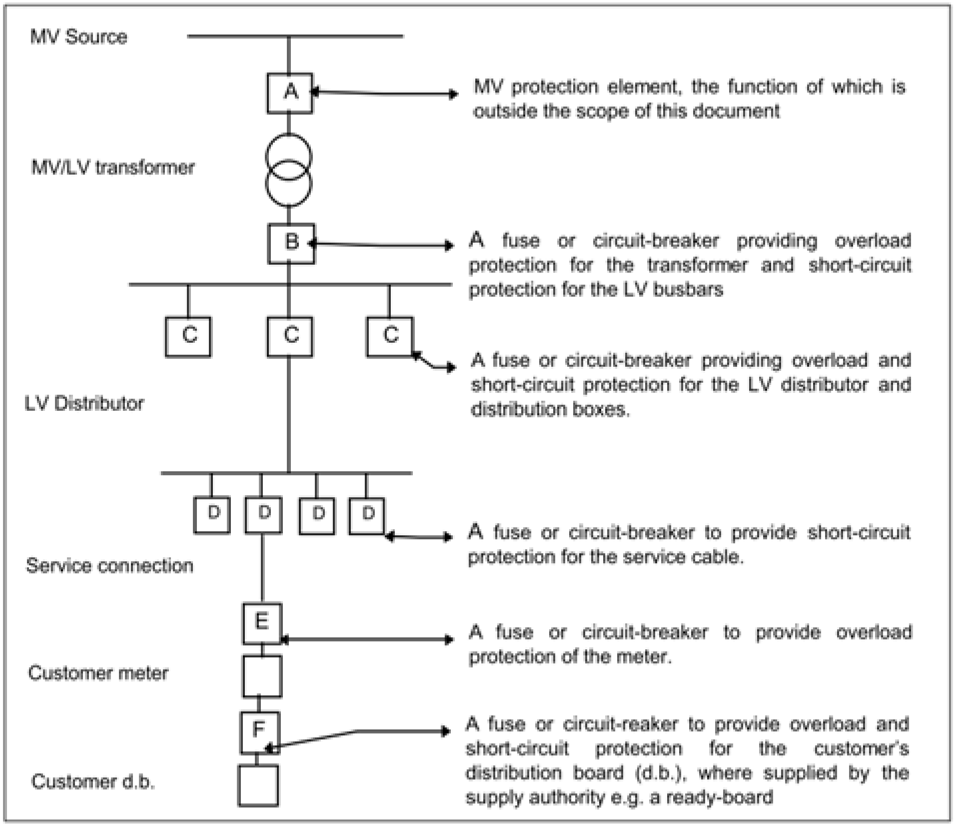


Figure 4-3: South Africa Low Voltage network topology [100]

Details of the topology used for low voltage connection are given in Figure 4-3. From the low voltage side of the distribution transformer, radial feeders supply one or more distribution kiosks located near the LV consumers. From the distribution kiosk, each consumer is supplied using a service cable. The supply phasing is selected as a function the consumer’s size and spatial location [100], [101].

4.3 Benchmark feeder models

Supply to residential and/or commercial consumers can be achieved in many ways depending on the network service provider, the consumer location vis-à-vis to the distribution infrastructure, country’s acts and regulations applicable to the production and distribution of energy. In order to benchmark electricity distribution studies, many test feeders have been developed [103], [104]. Each of the feeders was developed and adapted for one or more needs such as low voltage network analysis [93], unbalanced networks [105].

The 13, 34, 37 and 123 test feeders were developed by the IEEE developed in 1992 with the aim of providing a benchmark for developing software capable of tackling radial feeders in unbalanced network. Advanced models such as the Comprehensive and 8500-node Neutral-Earth-Voltage (NEV) were developed in 2010 as a benchmark for testing software designed for testing any component of the distribution network. In 2014, the 342-node mixed radial and meshed feeders was developed for advanced distribution network software benchmark [93] [103]. Table 4-1 provides a summary of the most common feeders developed and used for researches.

Table 4-1: Summary of test feeders [103]

Year	Test feeder name	Main characteristic	Principal usage
1992	13-bus	Small, short and highly loaded unbalanced network operated at 4.16 kV. Composed of a single voltage regulator, overhead and underground lines, shunt capacitor and an in-line transformer	Unbalance networks evaluations in medium voltages.
	34-bus	Located in Arizona, this long and lightly loaded unbalanced network is operated at 24.9 kV. It is composed of two in-line regulators, an in-line transformers and a shunt capacitor	Unbalance networks evaluations in medium voltages.
	37-bus	Located in California, this delta configured highly unbalanced network is operated at 4.8 kV. It is composed of underground cable with a voltage regulation ensured by the two single-phase open delta regulators.	Unbalance networks evaluations in medium voltages.
	123-bus	Overhead and underground cable network operated at 4.16 kV. Composed of four voltage regulators and shunt capacitor banks.	Application of voltage regulators and shunt capacitor for voltage stability.
2010	Comprehensive Test Feeder	Composed of all types of distribution equipment and load types	Distribution software test benchmark.
	8500-Node Test Feeder	Composed of all types of distribution equipment and load types	Distribution software test benchmark.
	Neutral-Earth-Voltage (NEV) Test Feeder:	Has unique feature of a line with four circuit sharing a common earth with a separate earth.	Detailed software model testing.
2014	342-Node	Representing a high-density load with the need for high reliability where the network is meshed for redundancy	Meshed network applications.
2015	European low voltage test feeder	The European LV Test Feeder is a radial and rated for nominal operation at 398V, 50Hz. Its source's operating voltage is 11 kV and the transformation to LV is achieved with an 11/0. 416kV – 800kVA transformer. It is provided with real consumers including their geographic coordinates and load	Time-dependent studies of common low voltage network configurations characterised by low feeders with multiple consumers.

		profile at a resolution of one minute over a period of 24 hours	

The majority of the LV test feeders Table 4-1 are based on the North American networks while only one represents a European network. The following section provides more information on the adoption and adaptation of a feeder model for use in South Africa.

4.4 Choice of feeder for research

In line with the research objectives, it is essential to develop a test network that encapsulates the conditions prevailing in South Africa. The South African low voltage network topology resembles much to that of the one represented by the European feeder in terms of topology, voltage and frequency. The European low voltage test feeder is supplied from an 11 kV source and its low voltage network is rated 415 V while 11 kV and 400V are common respectively for medium and low voltage networks in South Africa's urban areas. Given these close similarities, the European low voltage network is herein adopted as benchmark for the proposed research.

4.4.1 European LV test feeder characteristic and validation

The European LV Test feeder provides power to fifty single-phase consumers distributed across all three phases over a total length of 1432 m shown in Figure 2 layout.

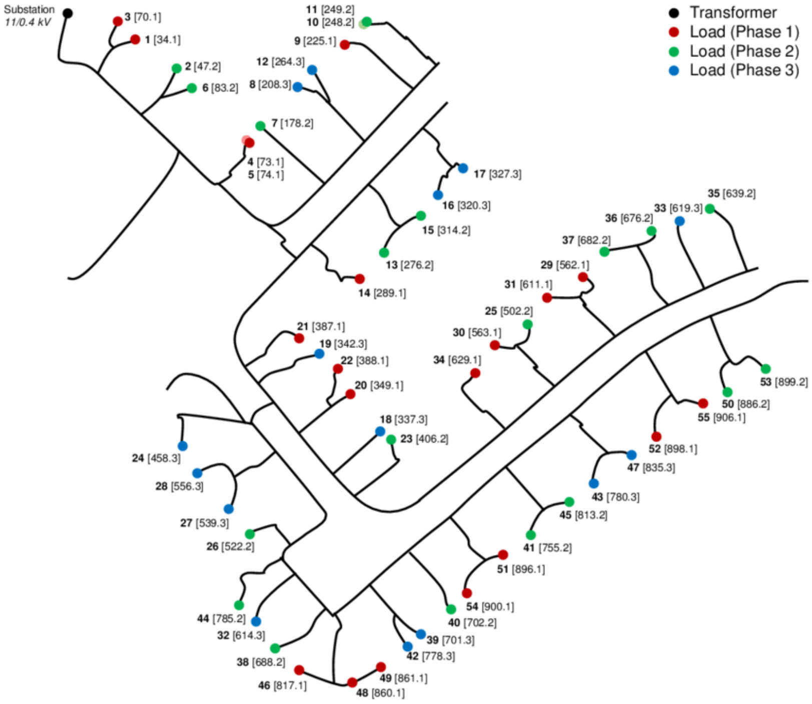


Figure 4-4: European LV Test Feeder layout [106]

The network model was developed and validated by the IEEE in 2015 using open source software OpenDSS and GridLab-D respectively developed by the Electric Power Research Institute (E PRI) and by the U.S. Department of Energy (DOE) at Pacific Northwest National Laboratory (PNNL).

The source is rated 11 kV with 3kA fault level with sending end voltage set to 1.05 p.u. The interface between the MV and LV is provided via an 11/0.416kV-800kVA Δ-Y transformer. Each feeder is composed of two or more section. Each feeder section is modelled based on one of the line code parameters of Table 4-2 [107].

Table 4-2: Line parameters of the European LV test feeder

Line code	Positive sequence resistance R1 (Ω/km)	Positive sequence reactance X1 (Ω/km)	Zero sequence resistance R0 (Ω/km)	Zero sequence reactance X0 (Ω/km)
2c_.007	3.970	0.099	3.97	0.099
2c_.0225	1.257	0.085	1.257	0.085
2c_16	1.150	0.088	1.200	0.088
35_SAC_XSC	0.868	0.092	0.760	0.092
4c_.06	0.469	0.075	1.581	0.091
4c_.1	0.274	0.0730	0.959	0.079
4c_.35	0.089	0.0675	0.319	0.076
4c_185	0.166	0.068	0.580	0.078
4c_70	0.446	0.071	1.505	0.083
4c_95_SAC_XC	0.322	0.074	0.804	0.093

Whereas a load is modelled as a single value for planning purposes in traditional loadflow problems, each load of the European LV test feeder is represented by a one-minute load profile for a twenty-four hours period, hence a total of one thousand four hundred and forty timestamps. Having this data, a series of time-dependent unbalanced load flow studies was carried out instead of a single load flow. The validation consisted of comparing the time series results from both software packages for voltages, active and reactive power for all nodes computed. The results obtained between the two sets of software showed a difference varying from -0.02 to 0% for real power and -0.01 to 0% for reactive power. These values are deemed acceptable.

4.4.1.1 European LV test feeder model in PowerFactory

Using the parameters downloaded from IEEE [103], the European LV test feeder is modelled in PowerFactory using the topology presented in Figure 4-4. The model set up is similar that that developed by Kevin Schneider [107] in OpenDSS and GridLab-D. The network has one hundred and seven nodes rated 398V (phase-to-phase). The nodes are connected together by nine hundred and five lines/cable that use ten different types or sets of parameters given in Table 4-2. Each of the fifty-five single-phase loads is connected to a unique node that is connected to the one or more nodes as per Figure 4-4 layout.

The network modelled in PowerFactory is used to produce one thousand four hundred and forty timestamp's profile for voltages along the feeder and power flow from the transformer's LV side. Although every node's result is available after computing for each time-series point, only Load 1 (at node 34, Phase A), 32 (at node 614, Phase C) and 53 (at node 899, Phase B) are considered for comparison and validation as provided in the following sections. Voltage, active and reactive power are calculated for each timestamp using the Quasi-dynamic functionality of PowerFactory software. The results derived from time-series simulations in PowerFactory are compared to those obtained by the IEEE using OpenDSS and GridLab-D as provided by [103]. For each time-series point, the differences in voltage magnitude, active and reactive power are presented in the following sections.

4.4.1.2 Voltage results validation

Using OpenDSS as a reference, the IEEE voltage validations showed GridLab-D results deviations from -2.02% to 1.67% across all phases. Figure 4-5 and provides a 24-hours profile generated from PowerFactory model. All three phase voltage profile have similar shape as those produced by [107]. The corresponding error between the two sets of results is given in Figure 4-6 where the error ranges from -0.01 to 0.18%. Overall, the difference in the results obtained from PowerFactory is lower that produced between GridLab-D and OpenDSS. The error range is narrower and results in lower values than those of the IEEE benchmark in [103].

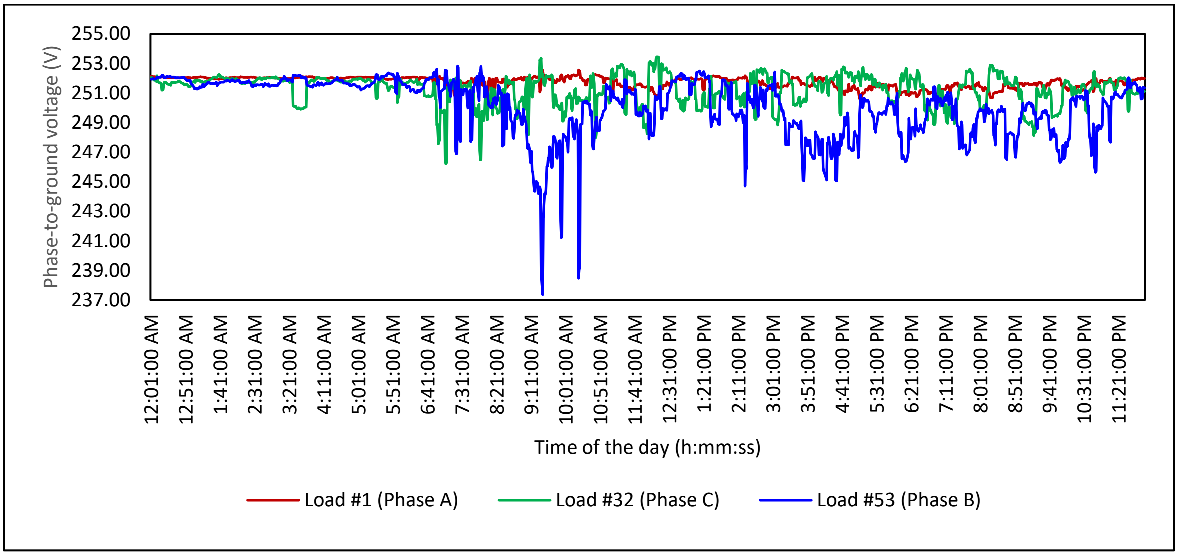


Figure 4-5 : PowerFactory calculated voltages at selected load terminals.

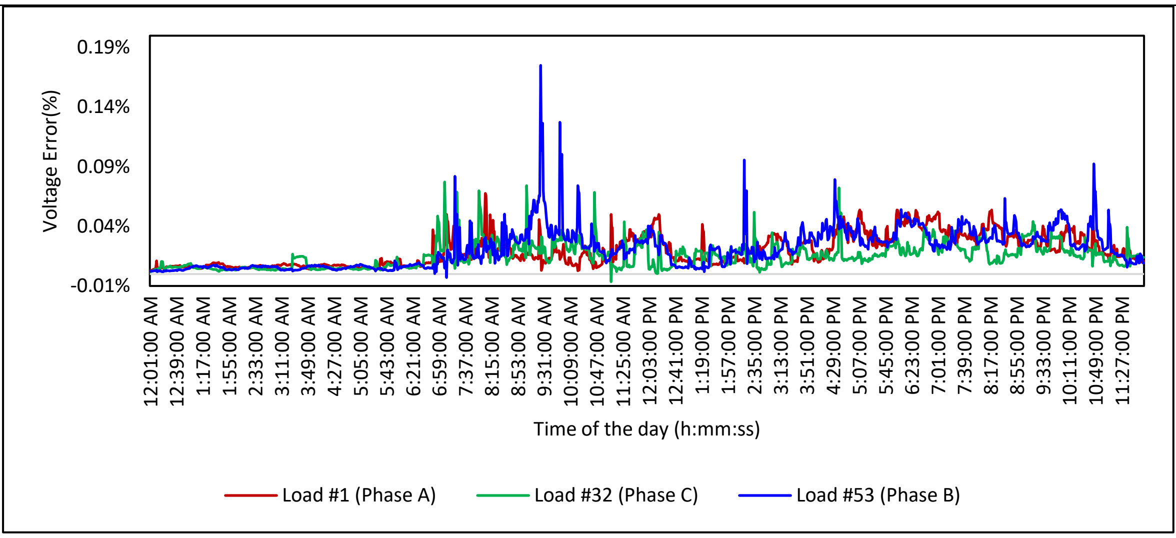


Figure 4-6 : PowerFactory voltage result error in comparison to OpenDSS.

4.4.1.3 Power flow results validation

Similarly to voltage results comparison, Figure 4-7 shows the magnitudes and shapes of time-series based power flow are similar to those provided by [103]. The error between values produced from OpenDSS and Power Factory varies between -0.02% and 0.36% for real power and -0.09 and 00% for reactive power. The error is bigger that obtained between OpenDSS and GridLab-D but remains acceptable.

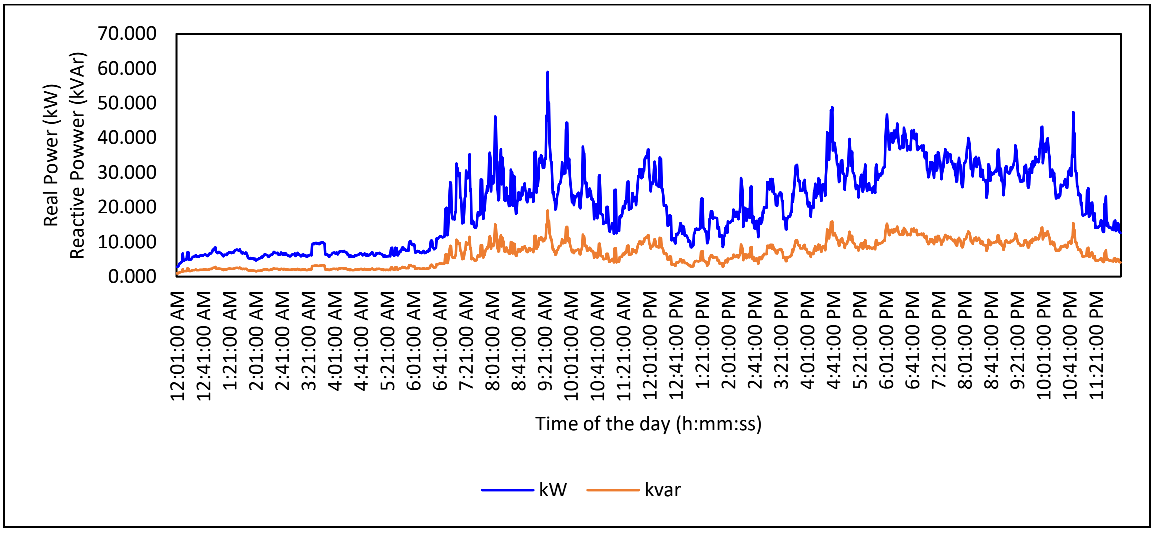


Figure 4-7 : Active and Reactive Power at Transformer LV (PowerFactory)

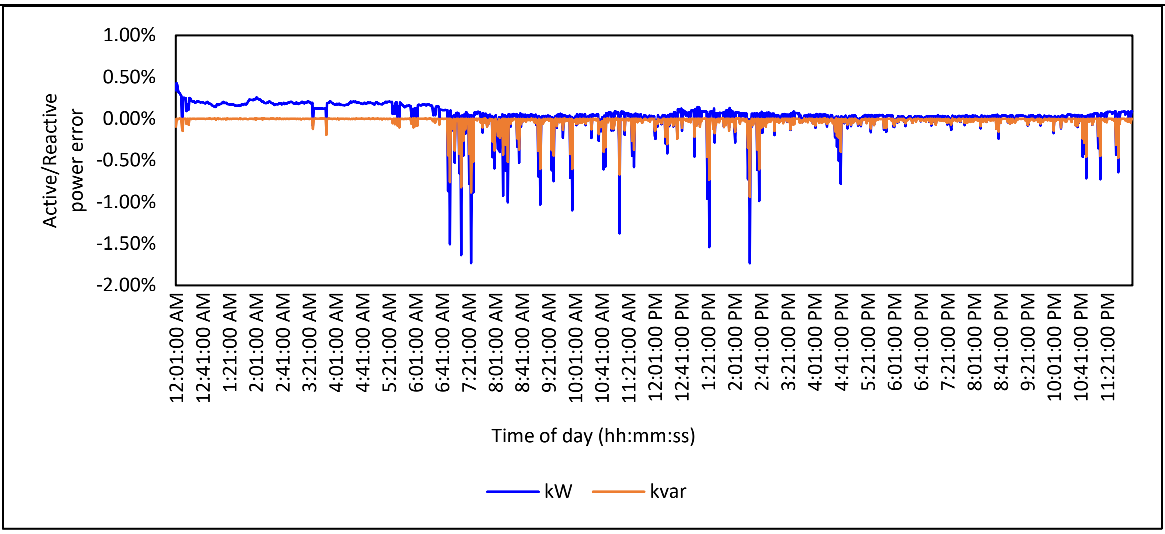


Figure 4-8 : PowerFactory voltage result error in comparison to OpenDSS.

4.4.2 Research Test Model

Based on the results obtained in the previous section, the European LV network model developed in PowerFactory is stable and therefore, it is used to represent a single microgrid for the research network. The test model is based on a residential load presented in Figure 4-9 where a selected portion of a residential area is supplied by a ring feeder with a normally open point. The feeder originates from a high voltage substation (SST). Under normal conditions, the feeder supplies six secure complexes of different size and shapes but is operated radially. Each secure complex is treated as a microgrid modelled on the European LV network test feeder. For each of the six microgrids created, a centralised PV and battery storage systems are added. Each microgrid local generation consisting of decentralised PV arrays and a centralised battery energy storage system. Furthermore, each microgrid is connected to distribution grid through a single point of common coupling represented by a distribution transformer as presented in the topology of Figure 4-2.

Figure 4-9: Proposed single feeder-six microgrid layout

Interaction between microgrids depends on feeder topologies, the simplest being radial and ring [102][108]. Figure 4-10 shows a ring topology applied to multiple microgrids environment in which the feeder configuration can be changed by selecting the switch to open or close along the ring. This allows changing the number of microgrid per feeder.

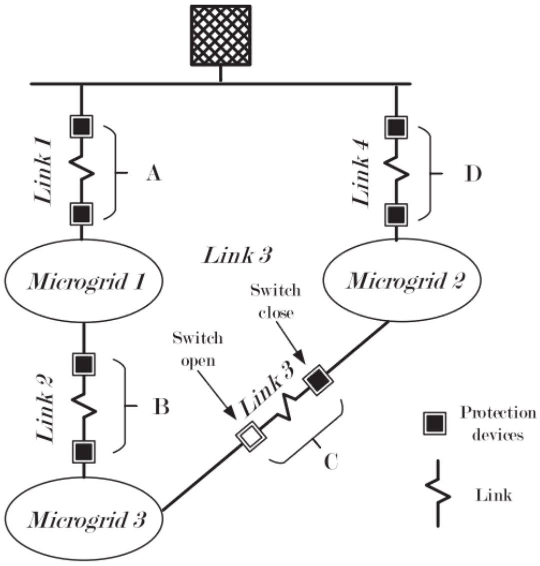


Figure 4-10: Microgrid architecture [108]

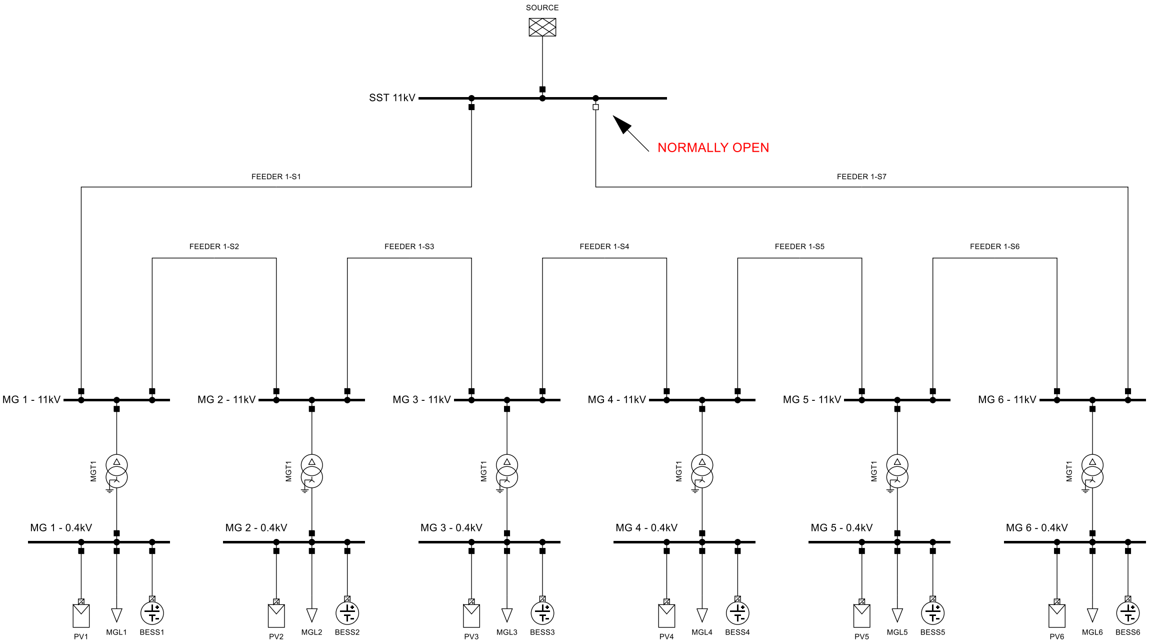


Figure 4-11: Proposed single feeder-six microgrid single line diagram

Using the layout of Figure 4-9 and the topology of Figure 4-10, PowerFactory is used to combine all microgrid and create a model presented in Figure 4-11. In it, each microgrid is based on the equivalent network of the European LV feeder in which only the transformer and the load are represented while the source substation is replaced by the 11 kV feeder. The overall load profile obtained from the European LV network validation is used as input to each microgrid. However, the magnitudes are adjusted by use of scaling factor to allow increasing or decreasing the power consumed in each individual microgrid.

The maximum size of each microgrids solar plant is based on the available roof space while the battery storage size is based on the scenario to be studied. Such scenario includes the export of excess, zero export/import with the utility grid or import of shortage of generation from the utility grid.

5 RESULTS AND DISCUSSIONS

In this chapter, the technical and economic impact of various microgrid configuration and collaboration on the ENSP are analysed.

5.1 Case studies for analysis

As detailed in 3.4, four case studies are explored to derive results required for the assessment if the impact of multiple microgrids on the power utility companies:

- Case study 1 - Base Case;
- Case study 2 - Grid-tied and local generation;
- Case study 3 – Grid-tied operation with local generation and energy storage system)
- Case study 4 (controlled exchange with the utility's grid).

These study cases are studied as stand-alone for technical evaluation but for the economic evaluation they are treated on per town basis.

5.2 Characteristics of the microgrids

The technical model developed in Chapter 4 consists of six microgrids supplied from the same medium voltage feeder was developed. The number of consumers and their combined installed capacity are provided in Table 5-1 for each microgrid, along with the estimated demand and allocated PV capacity.

Table 5-1: Six-microgrid system's basic data

Microgrid #	1	2	3	4	5	6
Number of Consumers	54	35	38	53	61	59
Estimated ADMD (kW)	270	175	190	265	305	295
PV Capacity (kW)	600	400	400	600	700	700

The size of each microgrids PVPP is estimated on the basis of the available combined roof space of each urban secure complex considered for collaborative microgrid evaluation. It is assumed that each microgrid PVPP would be designed to higher capacity to ensure that its internal consumption is cover as much as possible.

5.3 Technical evaluation

The technical analysis is achieved by use of PowerFactory's Quasi-Dynamic simulation designed to perform a series of steady state load flows for a defined time step. Due to the limitation in PowerFactory software used for simulations, each microgrid loads and generators are lumped at the MV/LV transformer's LV side. The technical analysis considers the impact at the point of connection of each microgrid and at the sending end (as viewed from the utility's grid) of the feeder when configured as cluster. For the purpose of technical compliance, the simulations are performed for a duration of twenty-four hours. Each of the loadflow takes into consideration the load and generation variations. Although loading is assumed to use the same pattern throughout the year, the PV generation is based on the prevailing weather conditions and is included in the simulation model as such.

5.3.1 Combined microgrid load profile

From the model validation, each microgrid load was assumed residential and of the same profile shape owing to the life style of working-class consumers. The load profile assumes users working during the day time. The resulting load profile is such that the network experiences a peak in the morning and in the late evening as presented in Figure 5-1 graph that when integrated result in combined daily energy drawn from the ENSP of 12.4 MWh.

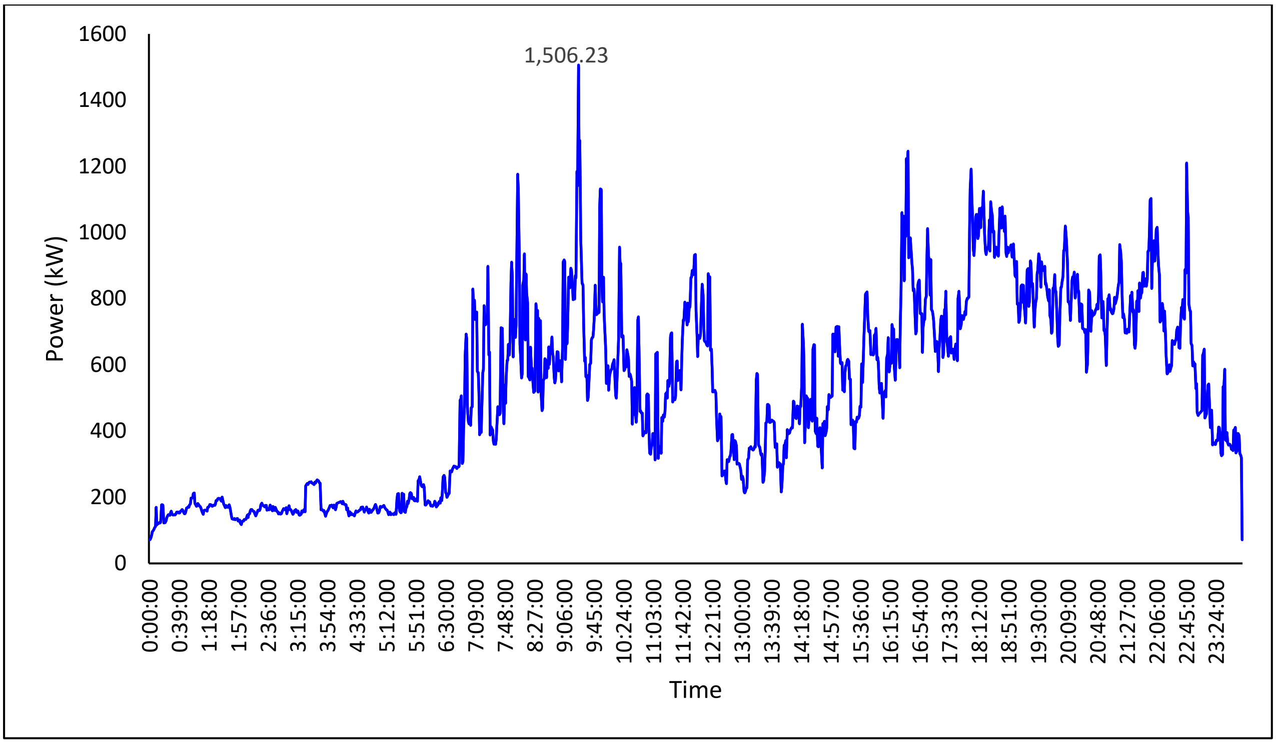


Figure 5-1: Combined feeder load from microgrids

From Figure 5-1, the load profile also shows the lowest demand at night between mid-night and the early hours of the morning. During the day, the lowest load is experienced at mid-day. This load profile is the input to the model and configuration of each case study herein. It forms the basis upon which variable necessary for the technical and financial evaluation are based.

5.3.2 Case study 1 – Base Case

The base model used is represented in Figure 5-2 where each microgrid is represented as a single load at PUC’s connection point (on the LV side of the MV/LV transformer). All six microgrids are connected through an 11 kV radial line (when the normally open point is active) each has an 11/0.415 kV stepdown transformer to which all consumers are represented by a lumped load on the LV side. The value of each microgrid load is calculated using the number of consumers and assuming that they all have the same living standard and of working class.

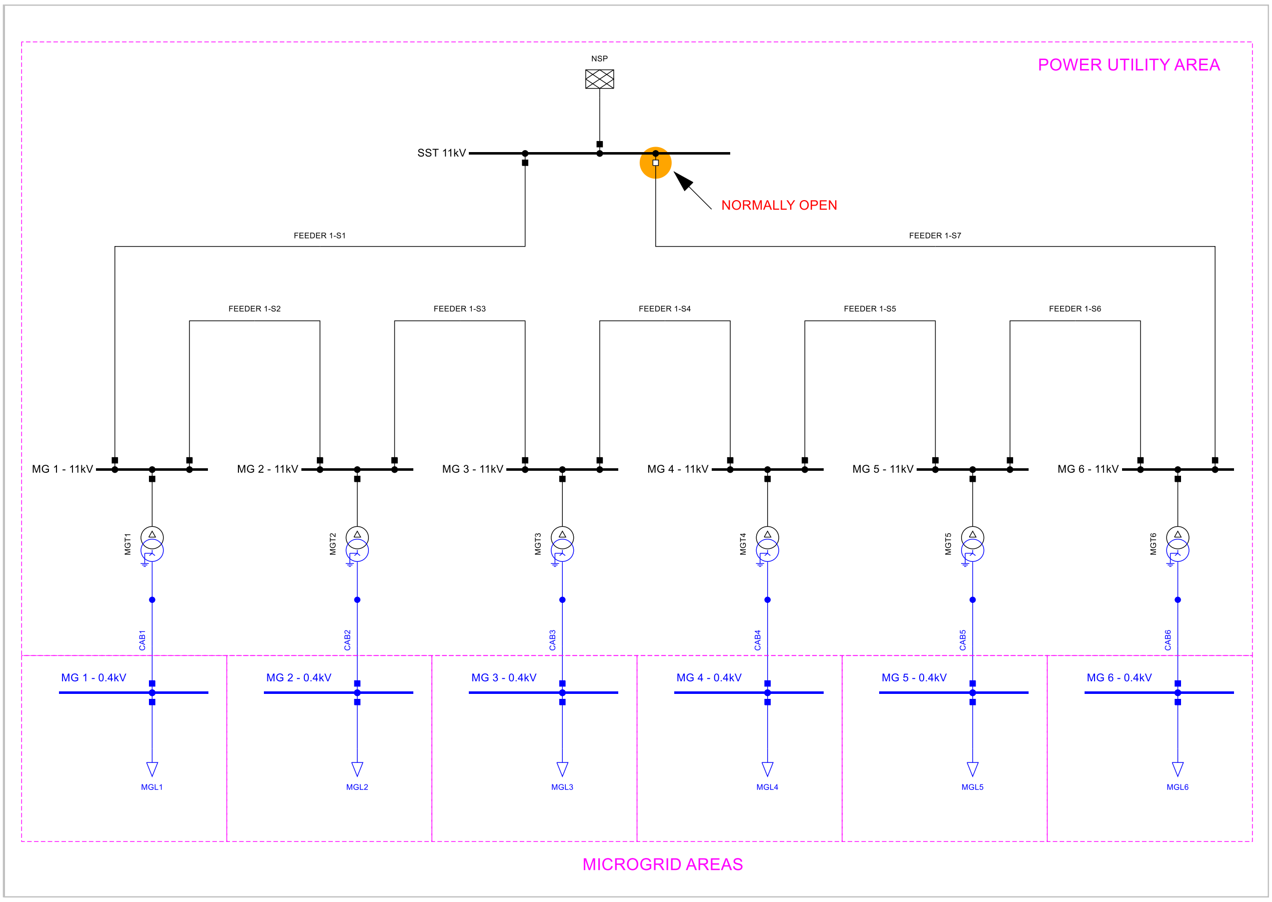


Figure 5-2: Microgrid base case model

Since each microgrid has no other sources of energy but the PUC, the energy consumed is entirely imported from the PUC’s grid. One particularity of this set up is that the power flows in one direction from the PUC’s grid into each of the microgrid, therefore allowing for simple protection grading, predictable losses and voltage drops.

5.3.2.1 Network performance

Each microgrid embedded PV generation capacity was estimated using the available roof space and the assumed peak load included in the model of Figure 5-2 to produce time series of loadflow. The transfer of power from the PUC's grid into each of the microgrids results into current flow in the feeder linking the microgrid. As such, voltage drops and losses are accumulated along the feeder.

Taking into consideration the voltage drops along the feeder, the lowest voltage on the network occur for microgrids at the end of the feeder. In the research model, it is expected for such to occur at microgrid 6. Instead of a single load flow during peak load, a series of one-minute interval loadflow is used to visualise the voltage profile of every microgrid. Each time step takes into consideration load variation and therefore the resulting voltages are time dependant. As the load varies over a twenty-four hours period, so is the voltage variations resulting from the voltage drops due to the passage of load current in the supply feeder. In this way, it is possible to assess the network voltage during peak and light load conditions.

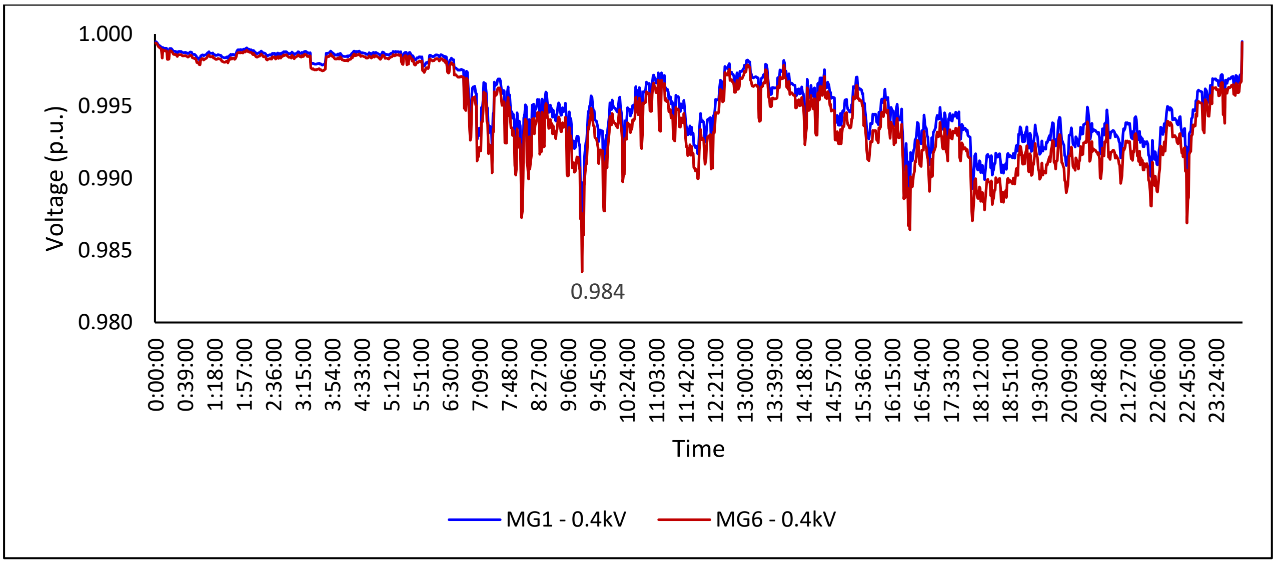


Figure 5-3: Voltage at first and last microgrid on the feeder without PVPP (10/01/2019)

For example, Figure 5-3 shows the full day load profile for microgrid 6 when considering a substation sending end voltage fixed at 1.00 p.u. Over this period, simulation results shows that the lowest voltage at the feeder's microgrid 6 is 0.984 p.u at peak load that occur around 9:25 AM on this occasion.

For a typical day, the maximum and minimum voltage values for each microgrid and the feeder-sending end are given in Figure 5-4 where they range between 0.983 to 1 p.u. Since these results are derived from a full day profile, they cover the extreme cases that occur at peak load and light load on the feeder. Referring to the general South African Grid Code and quality of supply standards in NRS-048, all voltages are within ±5% deviation and therefore compliant. Additionally, all feeder sections (between the substation or microgrid and microgrid) are loaded below their thermal capacity. The maximum loading of 17.7 % occurs between the first microgrid and the substation. On this basis, all voltages and loadings are within the limits. Therefore, all microgrid have stable voltage while operating in steady state. Understandably, microgrids closer to the source could have higher voltages than those at the end of the feeder or furthest from the source but this depends on the load. For instance, the second microgrid has a better voltage profile than the first one that is electrically closer to the substation. This can be justified because of the higher load of the first microgrid.

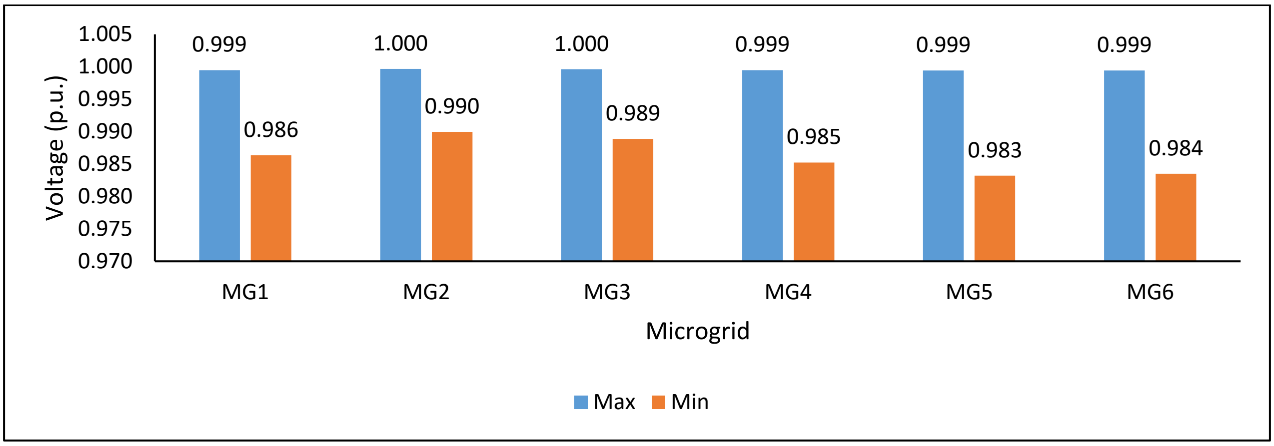


Figure 5-4: Minimum and maximum voltage at each microgrid without PVPP

Notwithstanding the fact that these results are simulated at lower voltage side of each of the microgrid transformer, distribution transformer commonly have an offload tap changer allowing them to adjust voltage for voltage drop compensation along the low voltage feeder within ±5% of the nominal voltage. For voltage drops of less than 2% indicated for the microgrids, compensation can be achieved by adjustment of the tap changer when needed.

5.3.2.2 Energy trading between microgrids and the utility grid

Energy trading forms the basis of billing from the utility to the consumer. It also can also provide an equitable balance between the energy imported and exported by the microgrid vis-a-vis of the ENSP. For this scenario, the only power source is the utility grid because there are no other of energy sources in the microgrids. Energy is flowing only in one direction, from the source to the loads embedded into each of the microgrids. Therefore, there is no energy traded between any of the microgrids and the utility's grid.

The energy consumption as seem at substation includes microgrid loads and losses on the feeder and transformer. From the simulation results, the combined microgrids' peak load is 15602.2 kW including 6.6 kW of losses as seen from the supplying substation at peak time around 9:25 AM. Using successive integration on the 24-hours load profile, the energy sent from the substation into the feeder is 12 409 kWh inclusive of losses of 24 kWh. The losses represent 0.2% of the total load and therefore relatively insignificant.

5.3.3 Case study 2 – Grid-tied with local generation

In this scenario, the network remains the same except for the addition of distributed PV plant on each consumer's roof. However, the software limitation required for the combined PV plants to be modelled as a single source lumped and the connection point as shown in Figure 5-5. Depending on the consumption, at any given time a microgrid in this configuration receives energy from the utility's grid, the PVPP or a combination.

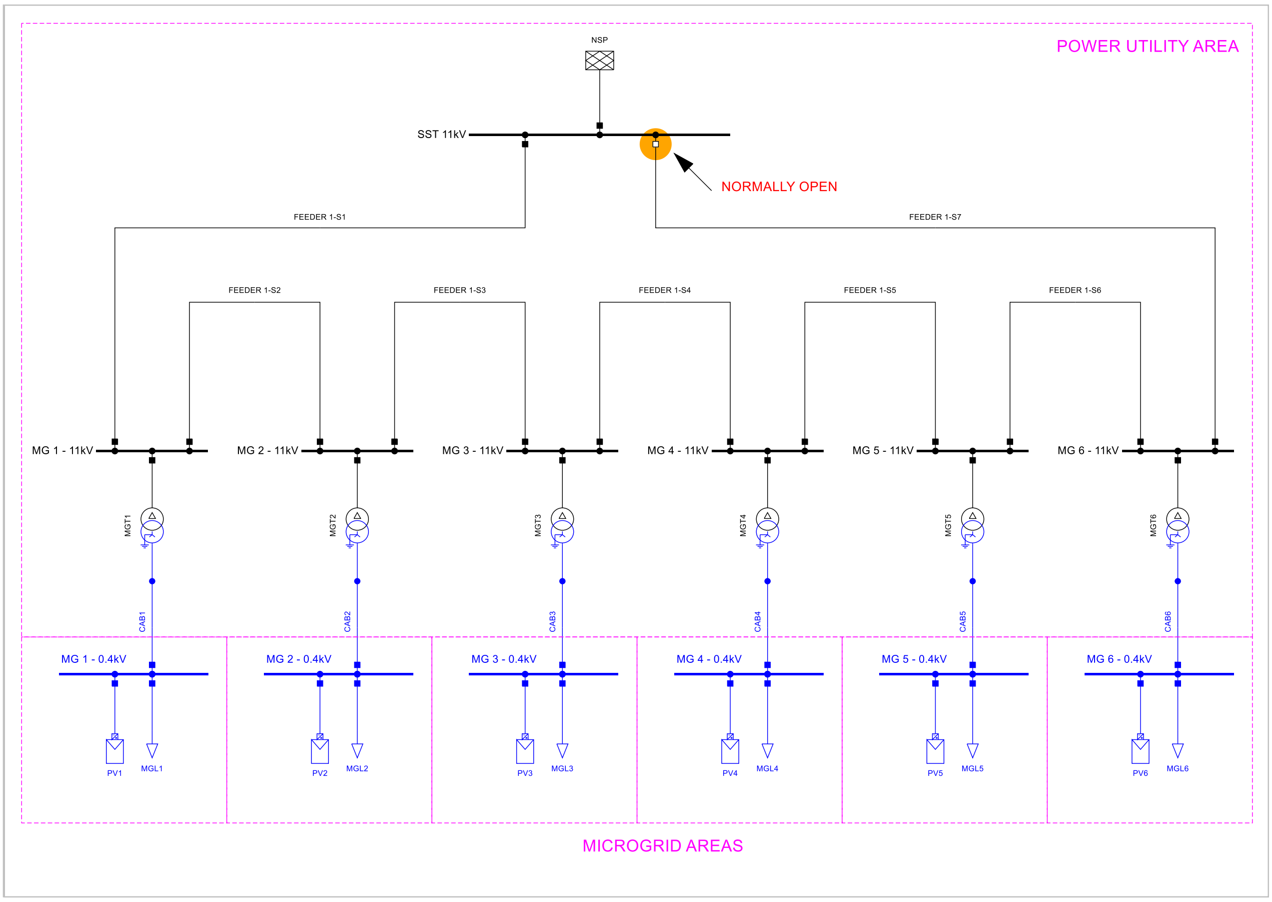


Figure 5-5: Microgrid operating scenario with export capacity

In Figure 5-5, the feeder under the "power utility area" remains part of the utility grid and therefore under its control too. The point of interface to each microgrid could be on the MV or LV side of the MV/LV transformer but in this instance, it is assumed to be on the LV for this analysis. In fact, this is the most common configuration in which the miniature substation belongs to the ENSP.

5.3.3.1 *Network performance*

Unlike the base case in which the power direction was from the substation towards the microgrids, this scenario has the potential for reverse the power flow, hence the importance of accounting for energy or power direction with respect to each microgrid. In this context, the import refers to the flow of power from the utility's grid into a microgrid and vice-versa for the export. The net energy at each microgrid point of connection is the difference between the imported and the exported energy over a defined period.

The quantity of imported or exported energy depends on the duration of the direction of power flow. For instance, Figure 5-6 provides a typical winter day's load-generation balance of microgrid 6 as seen through its interface MV/LV transformer. For a considerable part of the day, microgrid 6 generated solar power (red curve) is higher than the load (blue curve) and therefore a reversal of power flow through the transformer (green curve) occurs around mid-day. The inverse is true during morning and late afternoon hours during which the microgrid imports power from the utility's grid.

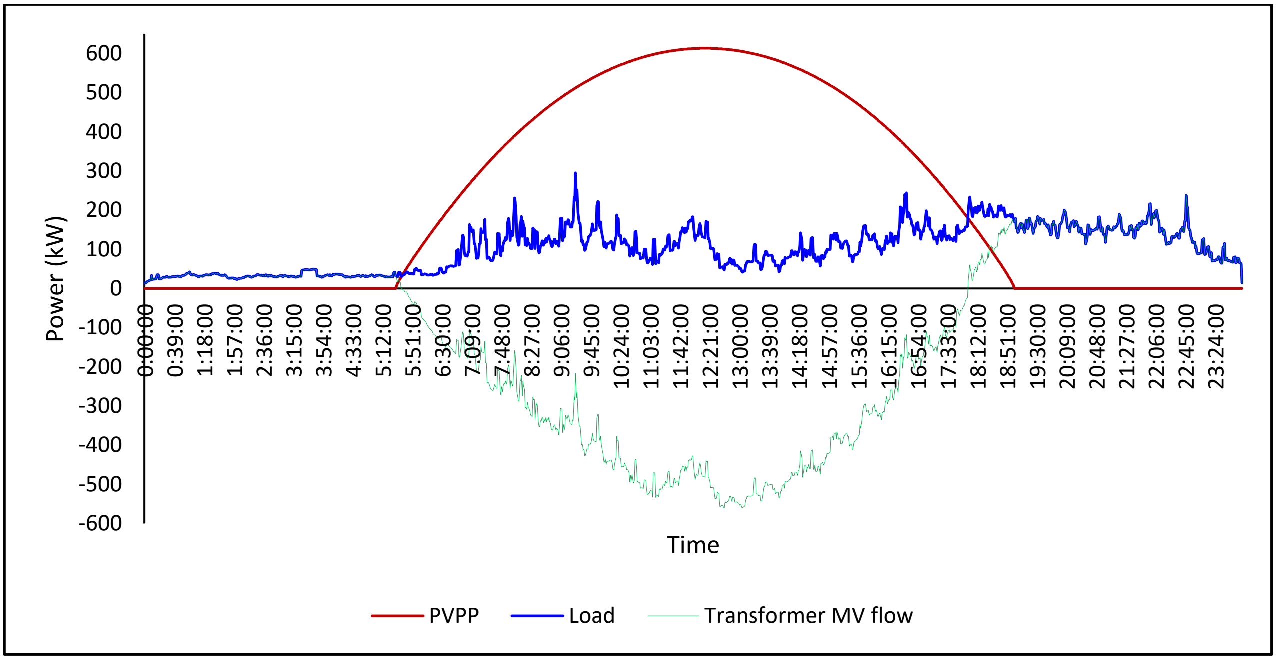


Figure 5-6: Load-generation balance at microgrid 6 (10/01/2019)

Given the reversal of power from the microgrid cluster to the substation during the day, the influence on the voltage along the feeder needs to be investigated. In the base case, power was transferred from the substation to the microgrid cluster and in the process, created voltage drops along the feeder. In contrast, the case where power flows from the utility's grid into the microgrids, the reverse condition can cause the opposite effect whereby the voltage rise is experienced along the feeder, especially near its receiving end. With a PVPP installed at the point of utility connection of each microgrid, it is expected for the voltage profile of the feeder to change, particularly that of the feeder's last microgrid.

Figure 5-7 provides a twenty-four hours voltage profiles for microgrid with the base case voltage profile. This provides a comparison between two voltage profiles, one before and the other after the connection of embedded PVPP. The comparison shows a voltage rise from 7AM to 7PM during which the embedded PVPP is actively producing and injecting power into the microgrid. The voltage is highest across the twenty-four hours profile during peak power export into the utility's grid; that is around mid-day. Conversely, during peak load periods (early morning and late evening), the embedded generation does not produce significant power and the voltage profiles remain the same as in the base case. This behaviour is expected as all the energy delivered to the microgrid is imported from the utility grid in the same way as in the base case scenario (without embedded generation). This comparison shows that voltage rise will occur when the PVPP is generating.

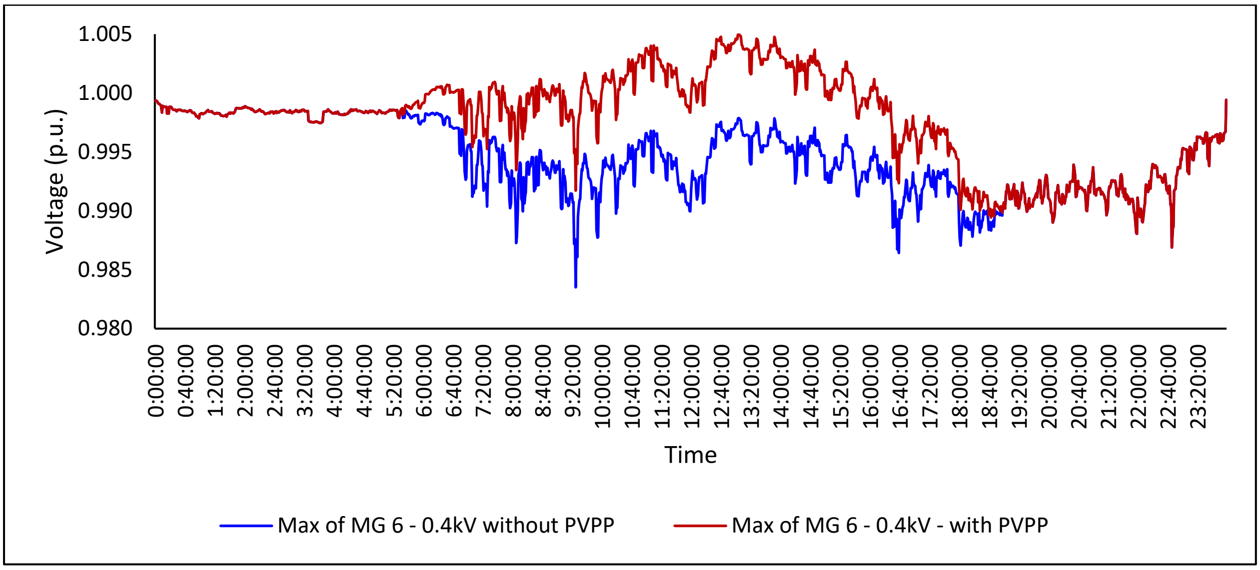


Figure 5-7: Voltage at the last microgrid on the feeder with and without PVPP (10/01/2019)

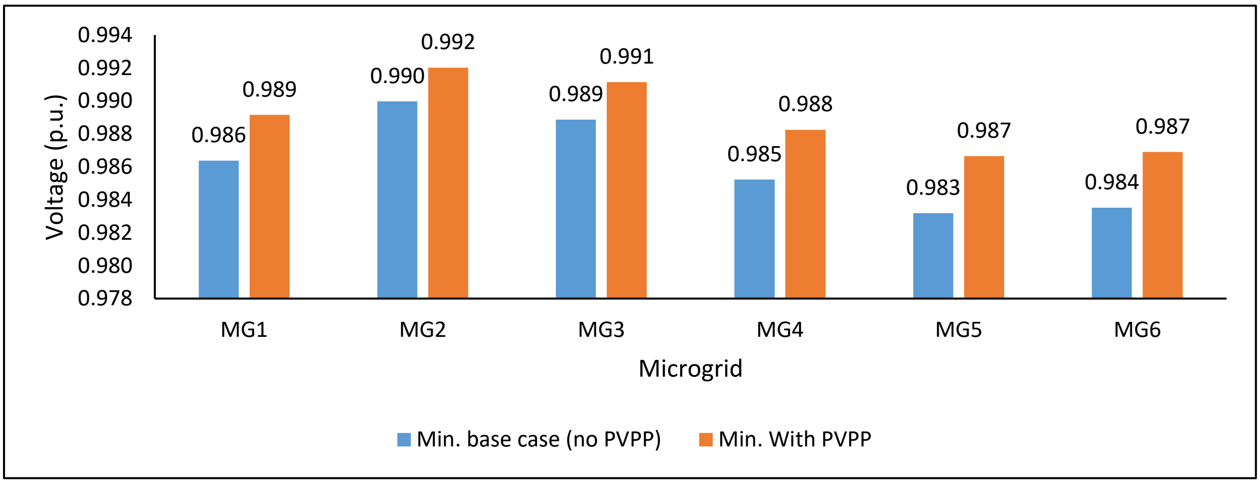


Figure 5-8: Comparison of minimum voltage for base case and PVPP connected

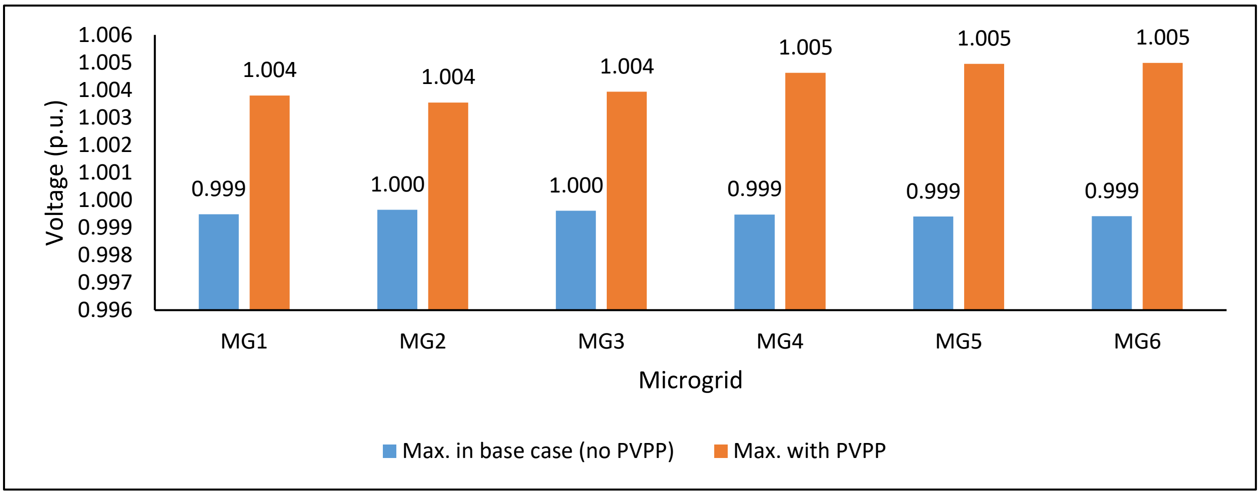


Figure 5-9: Comparison of maximum voltage with and PVPP connected

The maximum and minimum voltages are compared to the base case to assess the deviations and compliance to the grid code. Figure 5-8 and Figure 5-9 show the minimum and maximum voltages with PVPP connected are slightly higher than the base case (no PVPP). Despite the rise in voltage occasioned by the connection of PVPP, the overall network voltage is within the regulatory limits for this network.

5.3.3.2 Energy trading and microgrids and the utility grid

A PVPP relies on solar irradiation to produce power and this leads to less power produced in earlier mornings and late evening while the peak power production occurs near mid-day. Although the PVPP generation pattern is somewhat predictable, the profile of consuming loads is not always obvious as it depends on the consumer behaviour. In order to reduce or offset the energy imported from the ENSP's grid, there is a need for the PVPP to be dimensioned slightly bigger as emphasized in Chapter 4. This is the case in the study case where an attempt is made as much as possible to reduce the imports from the ENSP.

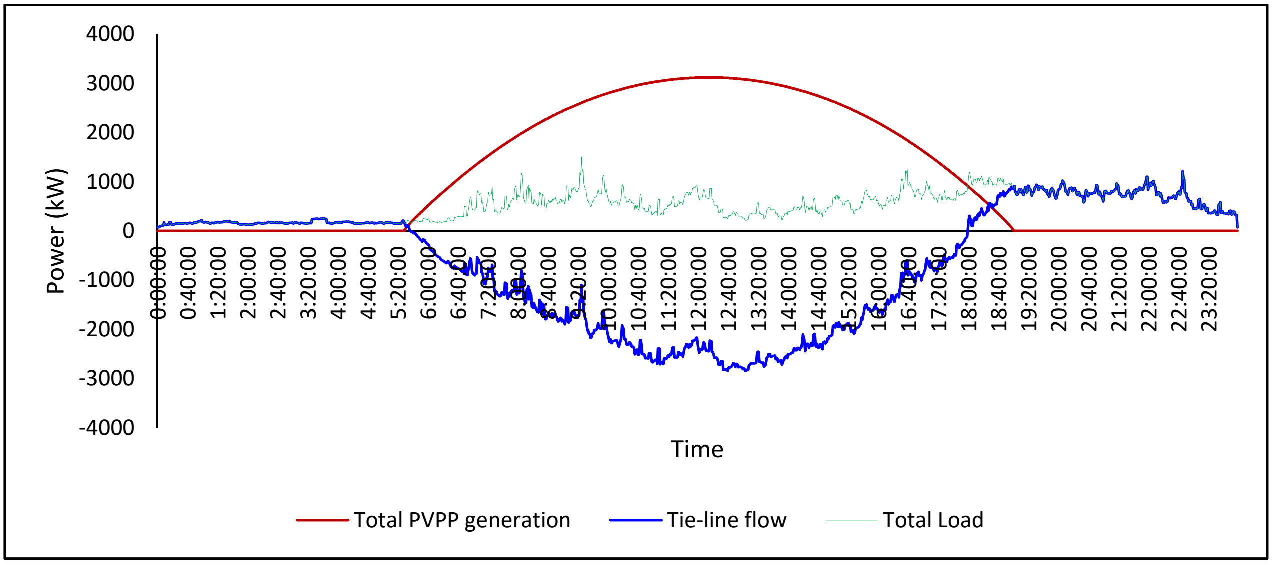


Figure 5-10: Daily energy trading between ENSP and microgrid cluster with PVPP (10/01/2019)

Figure 5-10, represent a typical day's energy trading between the zones covered by the microgrids and the utility's grid viewed from the substation. The peak production of all PV combined (blue curve) is higher than that of all loads combined (green curve) for most part of the day. This excess production creates reverse flow or "export." Early mornings and late evenings are characterized by little power generation while no power is produced at night. In the absence of local generation within the microgrids, energy is imported from the utility's grid (red curve).

The local production and consumption of energy is season dependant. To this effect, power produced by a PVPP in winter season is less than that produced in summer. For this reason, the excess energy is lower and so is the energy exported back into the utility's grid. For example, a typical summer day scenario of Figure 5-10 results in 28516 kWh generated and 4997 kWh imported energy. This represents a significant decrease from the base case in which the total consumed energy was imported from the ENSP. Accounting for a daily consumption of 12409 kWh for all combined microgrids, this implies a balance of 21104 MWh of combined microgrids solar energy is exported into the grid. The total losses are 124 kWh, reaches 21.1 kW at peak generation and represents about 1% of the load in comparison to 0.19% in the base case (when no PVPP) was connected.

To analyse PVPP generation variation throughout the year, the energy load-generation of microgrid 6 is used. As shown in Figure 5-11, a net import or export (load-generation balance) between the microgrid and the utility grid for each month in full year period. Considering a monthly billing period from Figure 5-11, the excess energy occur in low season (non-winter) months, from September to May while the opposite happens during high season (winter) months, from June to August.

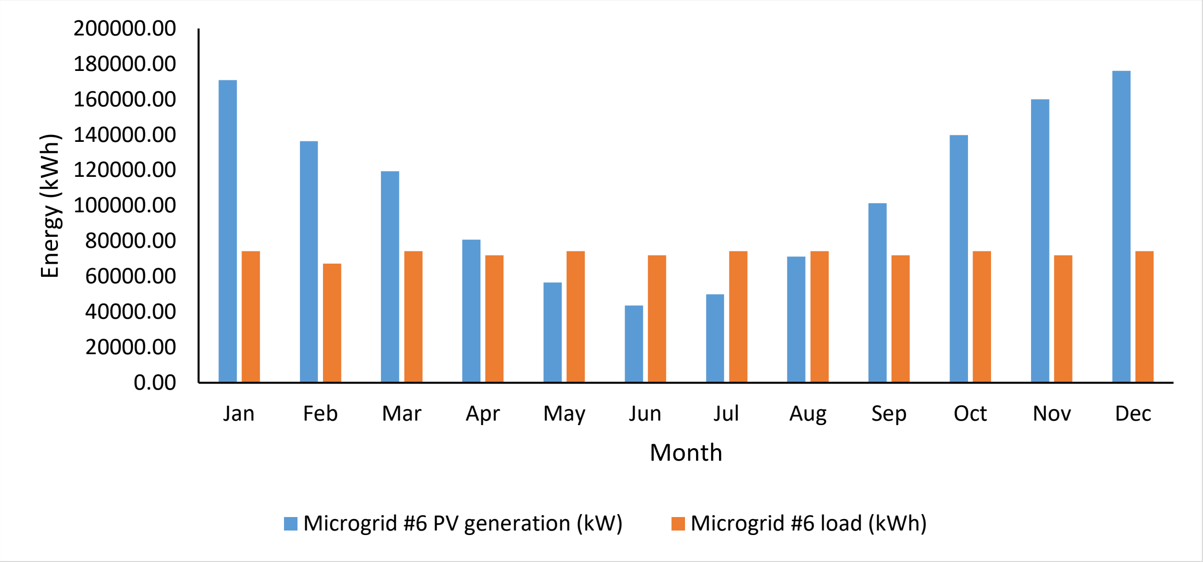


Figure 5-11: Full year sixth microgrids' internal load and generation

Although this research considers a constant consumption load profile for low and high season, PVPP generation on the other hand is modelled to take into account the seasonal solar irradiations. Hence the low generation capacity experienced in winter is taken into account. This leads to deficits and therefore less net import scenario over the billing period during winter seasons. Considering that the research assumes a constant daily load profile for all seasons, the reduction in generation in winter is likely to create higher import scenarios since winter season are associated with higher consumption.

For summer period, it is challenging to achieve a net consumption or net offset of billing unless the embedded PVPP generation is curtailed to reduce the excess power export into the utility's grid. Although curtailing simply reduces the quantity of energy exported and forfeited to the benefit of the utility, it also reduced the positive financial impact on the microgrid. For example, the excess energy could have been sold to nearby consumers of allowed by the country's regulation.

Since excess energy occur in low seasons and deficit in high seasons, each microgrid's PVPP has to be oversized if the excess energy has to be maintained in order to offset the energy import from the ENSP's grid during low season month. However, oversizing will not only create substantial reverse power in low seasons but the resulting infrastructure cost would be higher. Equally important, the cost of energy is higher during high seasons. Ultimately, deciding on the PVPP size should take into consideration the tariff of the applicable ENSP.

5.3.4 Case Study 3 – Grid-tied with local generation and Energy storage

5.3.4.1 Need for energy storage system

In the previous two scenarios, overdesigning the PV plant could significantly offset each microgrid consumer’s bill in winter but also could result in a significant excess energy for the microgrid during summer time when the solar plant produced more power. Conversely, reducing the PV plant capacity could still offset the energy bill in summer while resulting in significant deficit and considerable bills for consumers in winter.

When the energy generated and transferred into the utility grid in summer surpasses the energy drawn from it during over a billing period, a microgrid experiences two main disadvantages:

- The energy fed into the utility grid is credited at a much lower tariff over which the microgrid owners have no control;
- The feed-in credit is capped to a maximum of the same monetary value equivalent to the energy consumed from the utility grid over the same billing period. This implies that any excess energy will be forfeited to the power utility’s advantage and to some extent this can be interpreted a loss of income for the microgrid.

By using an energy storage system, it is possible to store energy during PV peak production time and release it during no generation periods, for instance in the late evenings and nights. In this way, the amount of imported energy from the utility grid can be minimised. Although this technique is essential in minimising the imported energy, the addition of energy storage system increases the capital expenditure and this could make the project non-viable. This analysis is carried out in the financial analysis of section 5.4.

5.3.4.2 Battery energy storage system sizing

From the previous case studies, the energy calculated for each microgrid results in an average daily energy consumption of 2068 kWh per microgrid. Assuming a minimum state of charge of fifty percent, a battery storage system of 5000 kWh per microgrid should be sufficient to provide at least a day of autonomy and for the purpose of this research.

This case study explores the possibility of providing energy storage to microgrid and explore the financial benefits associated to storing excess energy instead of exporting to the ENSP’s grid at tariffs beyond the microgrid control. The case study model is based on the same network as the previous two case studies with the exception that it has added battery energy storage system added to each microgrid as show in Figure 5-12.

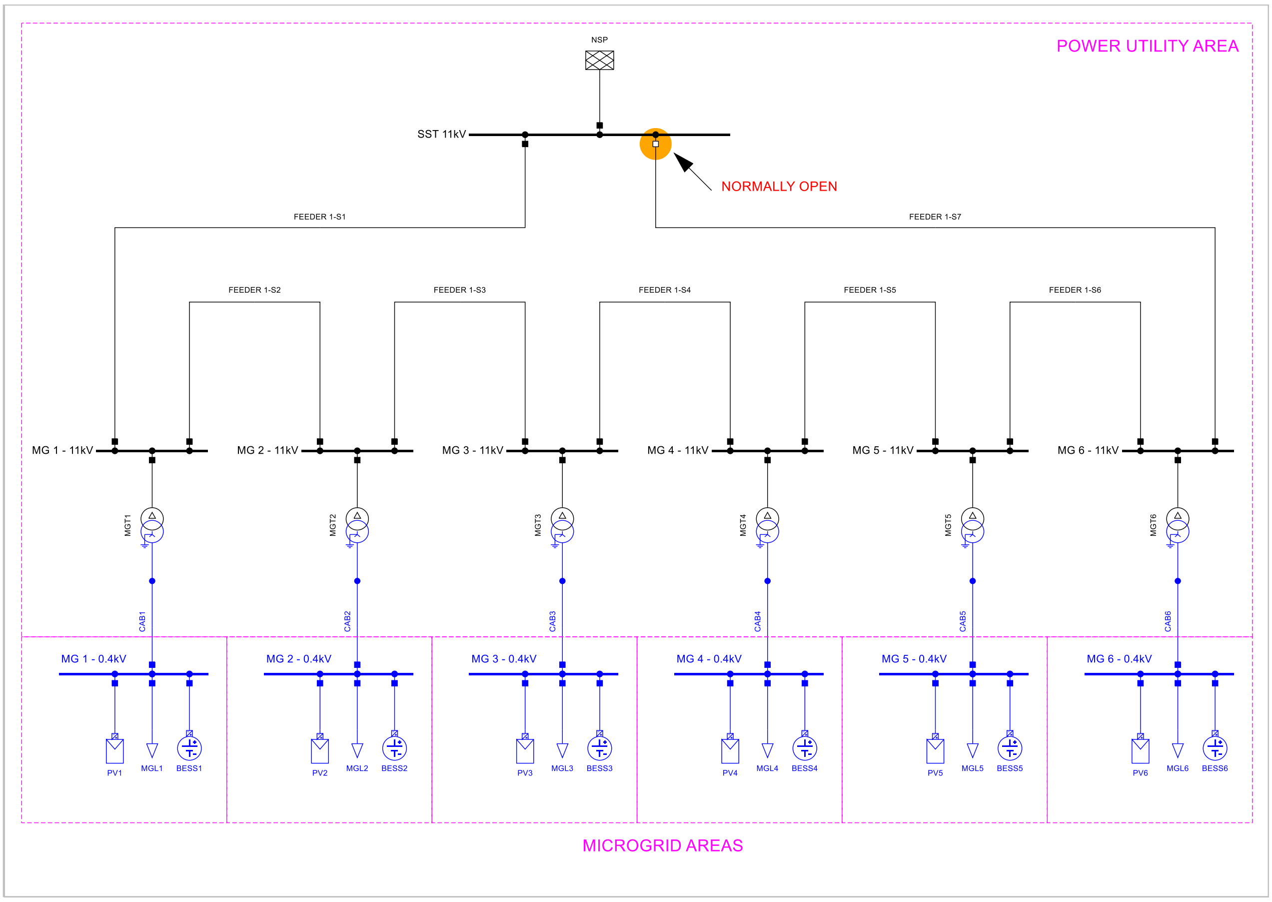


Figure 5-12: Microgrid operating scenario with export and storage capacity

Once more, a central point is used for the storage while the PV generation is dispersed within the microgrid but represented as lumped due to the software constraint.

5.3.4.3 Battery charge and discharge control

Although the combined microgrids' 21655 kWh solar energy generated is sufficient to meet the 12409 kWh total demand in Case study 2, the production of energy is dependent on the availability of solar radiation but this is not available at night times.

Case study 3 explore the use of Battery storage systems to store excess energy either partially or fully and release it during the time when the load is higher than the generation capacity within the microgrid. The battery storage system is assumed central and connected at the point of utility connection for each microgrid. Figure 5-13 provides a battery control strategy used for each microgrid energy storage system [109]. The controller is set in such a way to charge or discharge the storage system under predetermined conditions based on the available excess of deficit power, the state of charge.

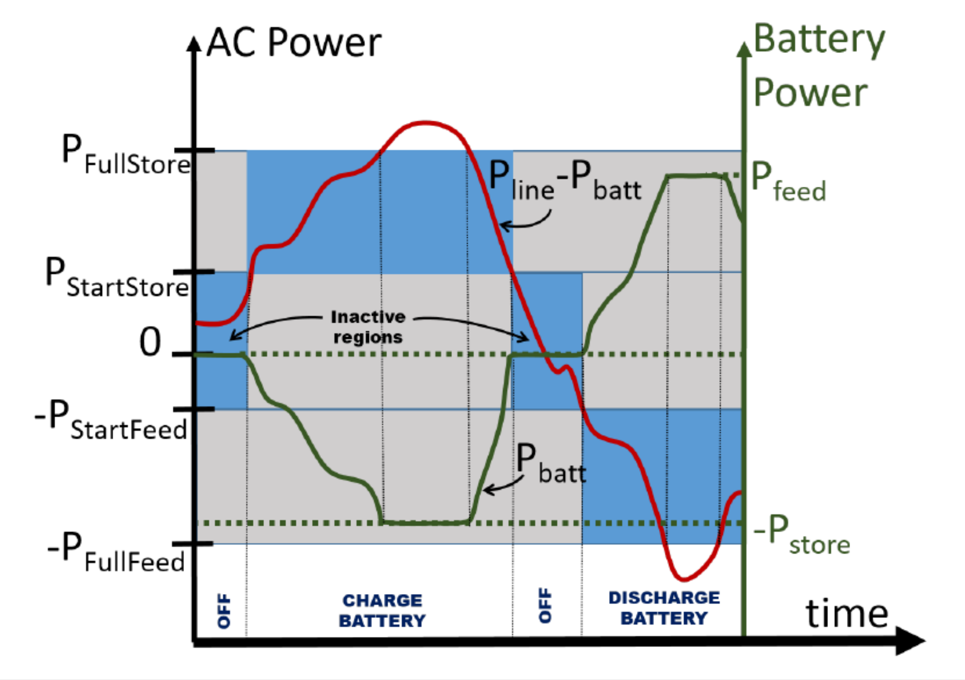


Figure 5-13: Generic Battery Control strategy for each microgrid BES [109]

By using this control or similar, it is possible to manage the storage and usage of the excess energy to draw the financial benefits for the microgrid consumers. The control of reactive power is disabled while other parameters are set to control the flow of power between the microgrid, the energy storage system and the network service provider.

Table 5-2: Preliminary parameters for the microgrids' Battery Energy Storage Control

Parameter	Description	Unit	Microgrid number					
			1	2	3	4	5	6
Eini	Storage Energy Size	MWh	5	5	5	5	5	5
SOCini	Initial state of charge	%	100	100	100	100	100	100
SOCmin	Minimal state of charge	%	50	50	50	50	50	50
SOCmax	Maximal state of charge	%	100	100	100	100	100	100
Pstore	Nominal storing active power	MW	0.4	0.4	0.4	0.4	0.4	0.4
Qstore	Nominal storing reactive power	MVAr	0	0	0	0	0	0
PFullStore	Power to store at full power	MW	0.57	0.38	0.38	0.57	0.665	0.665
PStartStore	Power to start storing	MW	0.24	0.16	0.16	0.24	0.28	0.28
Pfeed	Nominal feeding active power	MW	0.4	0.4	0.4	0.4	0.4	0.4
Qfeed	Nominal feeding reactive power	MVAr	0	0	0	0	0	0
PStartFeed	Power to start feeding	MW	0.081	0.0525	0.057	0.0795	0.0915	0.0885
PFullFeed	Power to feed at full power	MW	0.27	0.175	0.19	0.265	0.305	0.295

By optimally sizing of and adjustment of the battery energy storage system's parameter for each microgrid, it is possible to manage the energy to ensure a net zero import, net import or net export between each microgrid or a combination of these microgrids and the power utility's grid.

5.3.4.4 Network performance

From a power flow perspective, the use of Battery Energy Storage Systems (BESS) allows energy to be stored during excess generation in the microgrid, thereby reducing the amount of power transferred from the microgrid into the ENSP's grid. As far as the voltage profile is concerned, this scenario ranks somewhat between the base case and the PVPP plant-based scenario with grid-tie microgrid.

The case studies with and without PVPP represent respectively the scenario with maximum export and no export into the grid. For both cases, the voltage profile showed a stable voltage across twenty-four hours. In this case study, the PVPP are combined with BESS and therefore the energy exported into the grid is not as much as in the case without BESS. Noting that power flow from the grid into the microgrids leads to voltage drops, power flow from the microgrid into the utility grid leads to voltage rises and that the change in voltage profile is dependent on the amount of power transferred, Figure 5-12 shows a stable voltage profile for microgrid 6 when PVPP and BES are added.

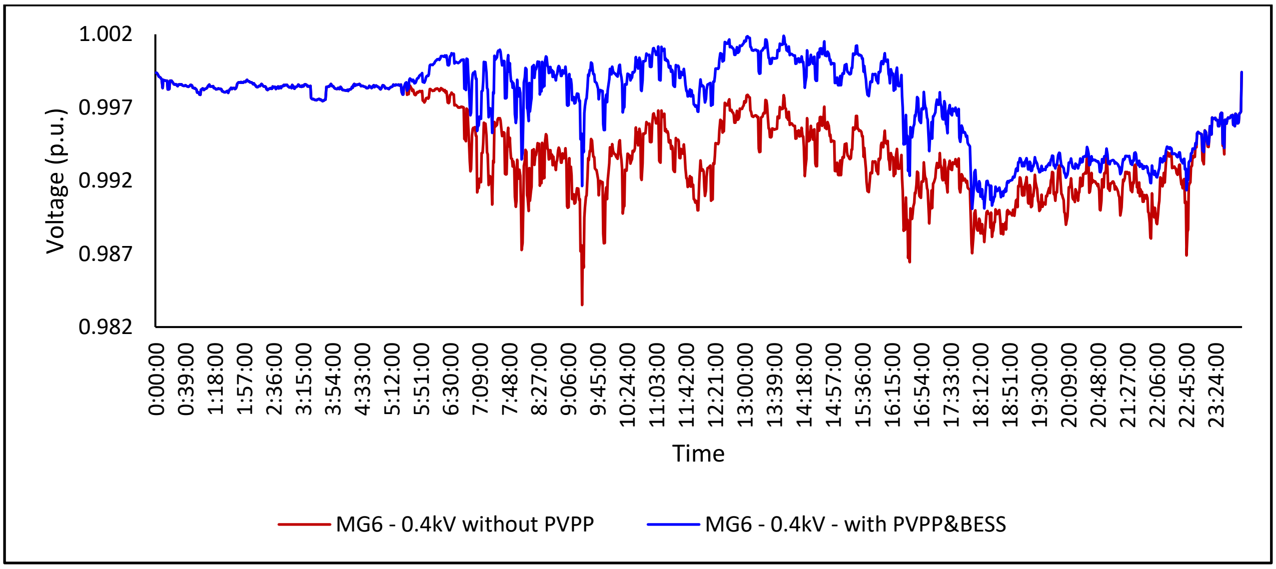


Figure 5-14: Voltage at the last microgrid on the feeder with and without PVPP & BESS (10 JAN)

Figure 5-12 also provides a comparison of a voltage profile before and after the addition of PVPP and BESS but applicable to microgrid 6. The overall improvement in voltage can be observed when PVPP and BESS are added. The minimum voltage has improved from 0.984 p.u. to 0.990 p.u. and still therefore within the limits defines in the grid code.

5.3.4.5 Energy trading and microgrids and the utility grid

In section 5.3.3, the introduction of PVPP provided local generation but due to the nature of solar energy, the peak production of the PVPP did not coincide with the peak load in the microgrids. This implies that the excess power was transferred back into the utility grid at fed-in tariff, subject to the maximum commercial value or energy allowed by the local ENSP. One way of ensuring that the microgrid is not obliged to curtail or sell excess energy at a rate imposed by the ENSP is to use Battery Storage Systems.

The addition of BESS to the microgrids allows to for energy to be stored into battery when there is excess generation and released at peak time when the PV plants are not producing. Operating this way implies that the excess energy is not sold at ENSP prices during peak production. Instead, it is stored and later released for use in the microgrids when their PV plants are not producing energy. By storing and releasing the energy, microgrids are able to control the import/export to their advantage, most likely by reducing the imports from the ENSP's grid. The BESS is tuned to start charging the battery under a set of conditions. These could include for example a state of charge and a power threshold defined by the flow difference between the grid and the load power.

For operation of microgrids with PVPP and BESS, Figure 5-15 provides a view of the energy trading between the utility grid and a microgrid as viewed from the MV/LV transformer. The PVPP peak production (blue curve) is higher than that the load (red curve) for most part of the day and therefore would cause the power flow direction to reverse when no storage is available. When BESS is used, the excess energy is stored in it (green curve) at a rate determined by the setting and the balance exported into the ENSP's grid (brown curve).

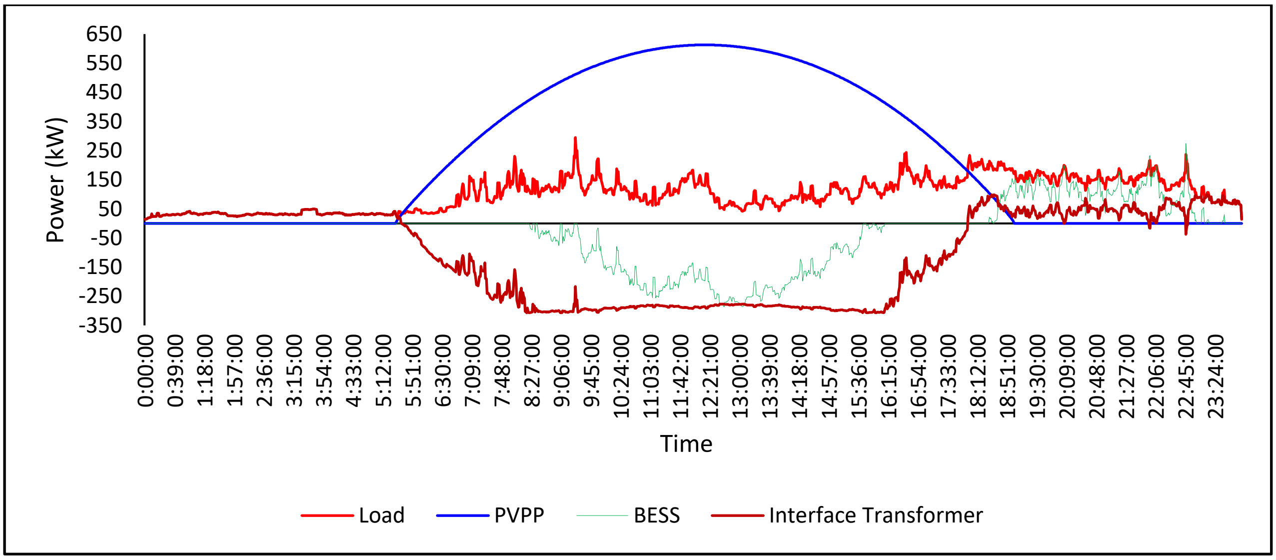


Figure 5-15: Daily energy trading for the scenario 3 (10 JAN)

During the night times, there is no power generated from the PVPP. Therefore the energy is supplied from the BESS and the balance is imported from the ENSP's grid, for example in Figure 5-15, the battery discharge can be observed after 7PM. By careful choice of the battery size and the settings for the rate of charging and discharging as well as the state of charge limits, it is possible to adjust the system's behaviour to minimise the power imported from the utility grid as much as possible.

Compared to the base case, the import has decreased from 12432 to 3299 kWh while the export has gone from nothing to 12889 kWh. The total losses on the feeder is calculated at 47 kWh per day or 0.38% of the total load compared to 1% while the maximum feeder loading is 16.6% compared to 17.8% in the base case.

5.3.5 Case study 4 – Collaboration between microgrids

In the second and third case studies, it was noticed that the energy exported back into the utility could either sold to a lower price than when importing the same mount from the same source (5.4). Moreover, the energy transferred back into the utility grid could either restricted not to exceed the import or for its feed-in monetary value not to exceed that of the energy imported from the grid over the same billing period. It was also noted that for each microgrid to reduce the energy imported from the utility grid, its combined PV capacity needed to be largely higher than the peak load within the same microgrid. This was necessary to ensure that the production in winter is still sufficient to meet the microgrid objective.

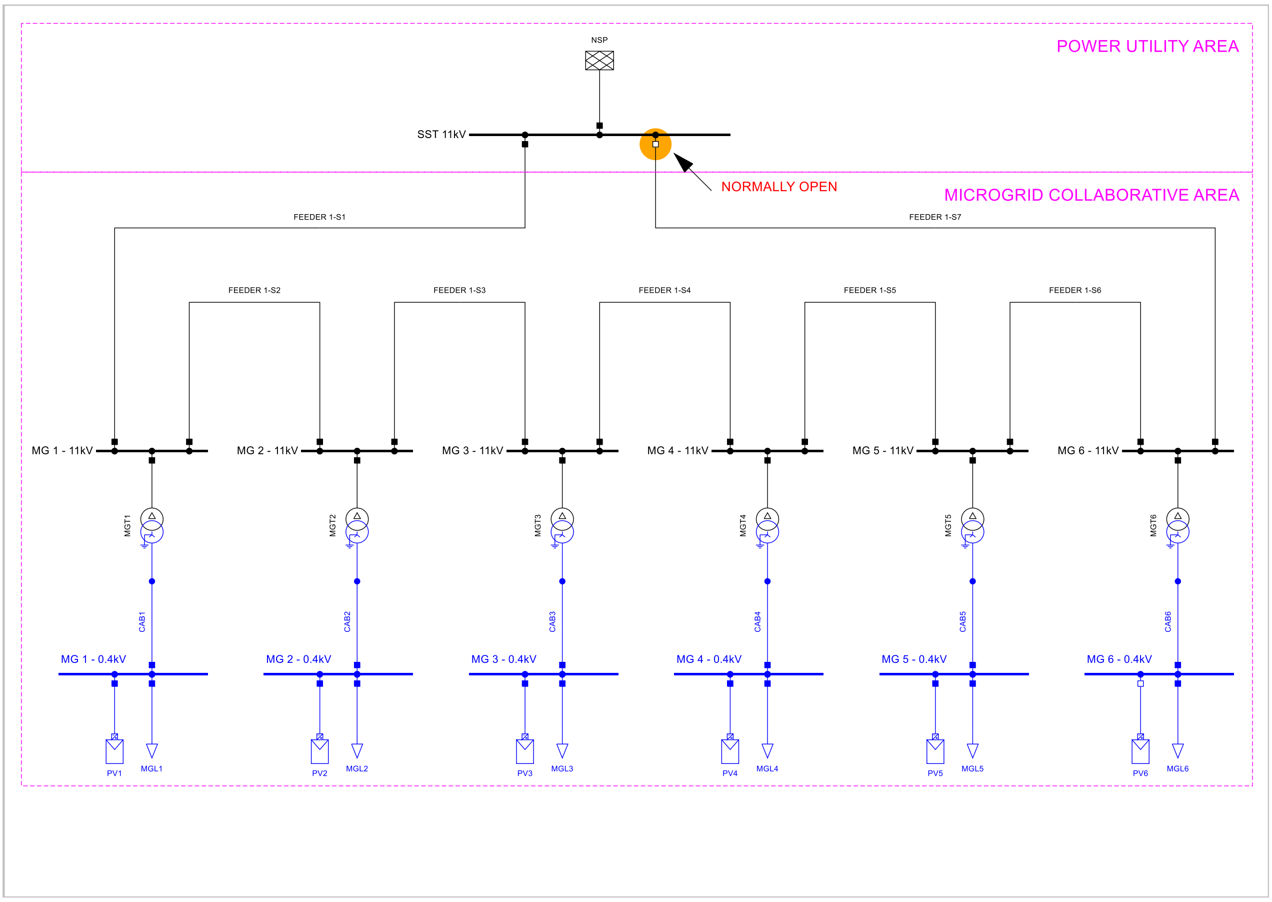


Figure 5-16: Network model for collaborating microgrids

In order to reduce the plant size and the energy exported at the same time, BESS was introduced in Case study 3. Although this technique works, the required capital expenditure could make the project less viable as discussed in more detail in section 5.4. An alternative explored herein the fourth case study include reducing the generation capacity. This can be achieve by providing collaboration between microgrid and reducing the capacity of each microgrid PVPP or by allowing certain microgrids not have no PVPP while drawing their energy from the pool or cluster as illustrated in Figure 5-16.. In this way, the collaboration across microgrids could ensure that the excess power of one microgrid or more microgrids is used by other microgrids instead of selling back to the power utility at lower tariff.

The possibility of microgrid collaboration is explored in this section by removing the generation from one or more microgrid while accounting for the energy imported or exported at the substation level. This implies that the ENSP does not have to charge each microgrid on individual basis and therefore benefit from excess energy that could have otherwise been sold to other consumer.

This scenario mimics a configuration in which the point of connection for the microgrids' cluster or collaborative boundary is considered at the substation. The MV feeder and all microgrids form a mini-grid for which the energy exchange is evaluated at the utility's substation. The operation of embedded PVPP is coordinated amongst microgrids. The power generation is managed by curtailing the excess instead of feeding back into the ENSP's grid. Unlike in case studies two and three, excess energy-producing microgrid are not wholly selling to the utility at feed-in price and the receiving microgrid importing most of its energy from the utility at higher tariffs.

5.3.5.1 Network Performance

From the previous cases, the base case (no PVPP) provided the scenario with the lowest voltage on the system. AT the same time, Case study two provided the scenario with the highest voltage cause by the export of power from microgrids to the ENSP's grid. By this that represented the case with no export (no PV plant in any microgrid), maximum export (with PV plant in each microgrid), and reduced export (when local storage is used), this case is much similar to the third case study as far as power flow is concerned. This implies that the voltage profile will not violate the grid code under normal operating conditions as confirmed in the profile of the furthest microgrid in the cluster.

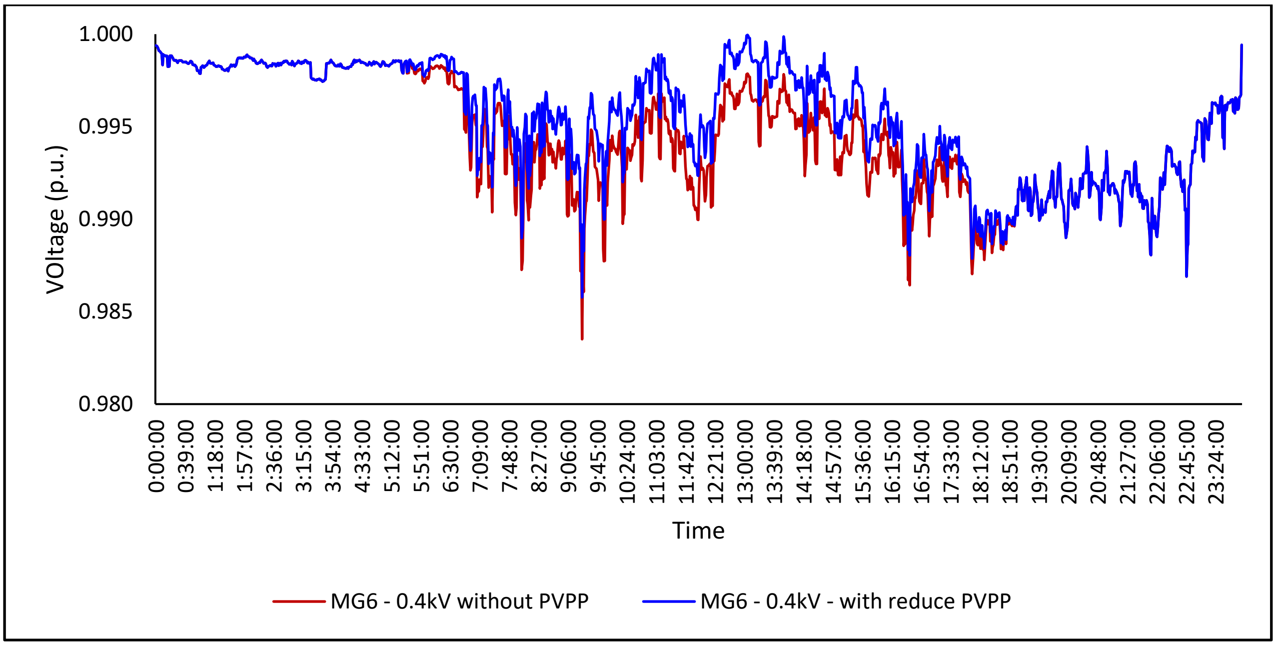


Figure 5-17: Voltage at the last microgrid on the feeder with and without reduced PVPP (10 JAN)

One advantage of forming a pool for microgrid collaboration is that the pool exchange power at a single point of connection. For example, at the substation’s MV board. With a single point of connection for all microgrid, the main advantage is that the pool generation can be controlled. For example, the production can be reduced in summer time while the full production can be activated in winter times. Curtailment can be carried out fairly while every consumer is still benefiting equally from the generation pool.

5.3.5.2 Energy trading and microgrids and the utility grid

In this scenario all microgrids inject the excess power into the grid. The non-producing microgrids draw power from the pool and the balance is exported to the ENSP grid. In the case of deficit in the pool, energy is imported from the ENSP’s grid. Since the cluster of microgrid is viewed from a single point, the flow of power into the ENSP grid can be significantly reduced. To demonstrate this, the comparison is made between case study two and the present case study four.

The comparison between two case studies for daily operation shows that there are no significant changes in the minimum voltage. In comparison to case two, this case sees a reduction in feeder losses from 1% to 0.73%, maximum feeder loading from 31.9% to 25.1%. The generation is reduced from 28516 kWh to 22909 kWh due to the reduction in capacity by switching microgrid 6’s PVPP out of service. Consequently, the export of energy is reduced from 21104 kWh to 15512 kWh while the import is increased from 4997 kWh to 5102 kWh.

5.4 Financial analysis

The financial analysis herein is based on the recent market values and trends for PVPP, tariffs, battery energy storage systems, interest rate, inflation rate, discount rate, etc. The aim is to analyse the viability of the microgrid case studies as also determine the decrease in energy revenue for the utility companies.

5.4.1 Costing of PV energy plant

In order to consider the financial merit or demerit of adopting embedded PV generation in microgrids, it is essential that its cost be modelled as accurately as possible. The cost of such plant varies depending on the location and supplier or Original Equipment Manufacturer. However, the global price trend shows a net decrease cost per unit over the past few years.

For the purpose of this research, unit costs obtained from [110], [111] and [112] are used to create an average cost of PVPP and BESS infrastructure. To this cost is, a balance of the plant the operational and maintenance cost are added to calculate the overall cost of the PVPP needed for financial viability analysis.

5.4.2 Tariff analysis and application

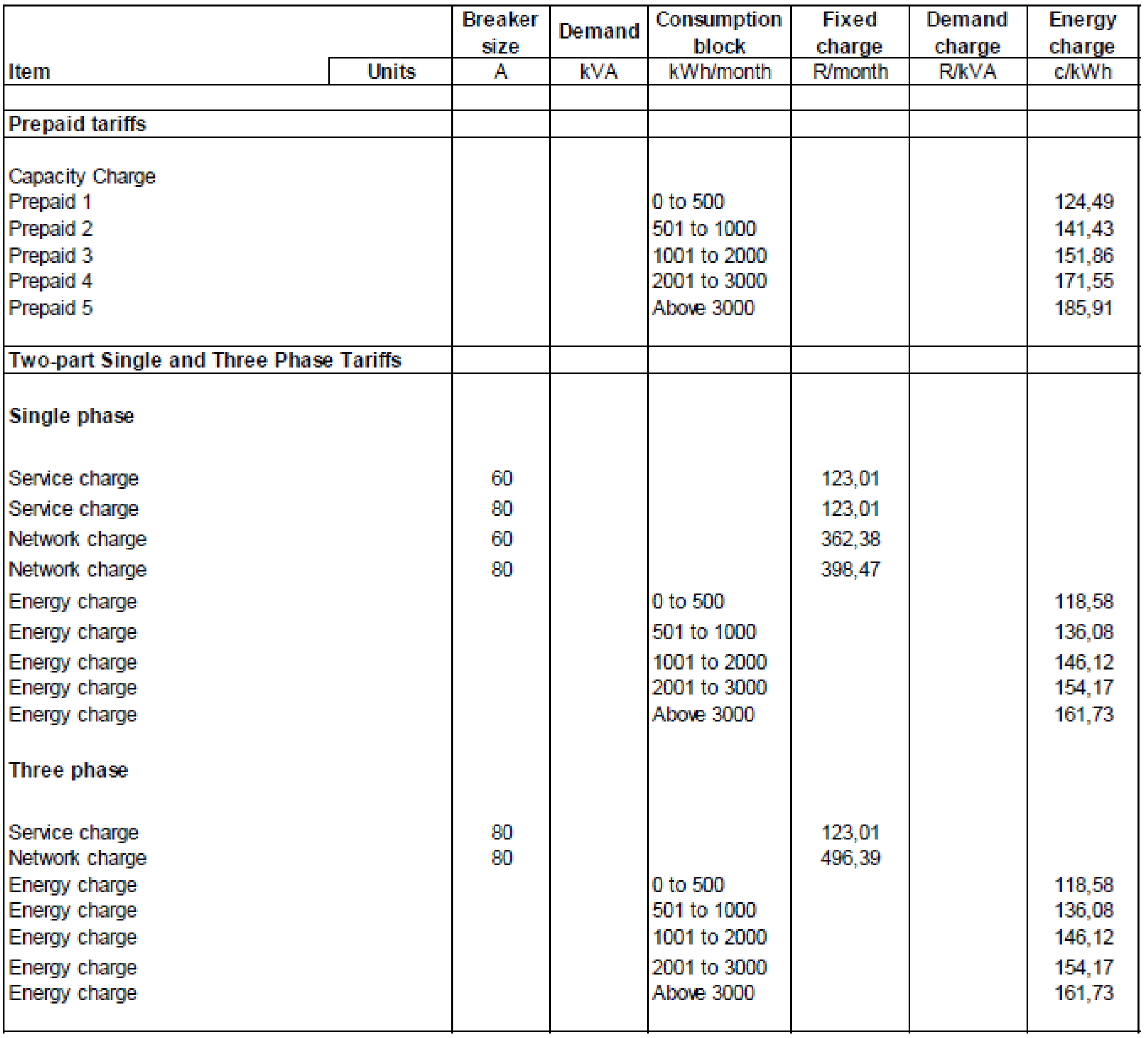
The cost of energy consumed depends on the consumer category, the connection voltage, the availability of embedded generator on their system, the phase technology for connection to the power utility network and the ENSP. For most power utilities companies in South Africa, the main tariff structures include residential, commercial and industrial. Furthermore, each structure may have sub-categories in some instances. It is also common for NSPs to segregated small power users and large power user. This grouping and segregation allow for administering tariff in a way that promote an efficient distribution of power to consumers. For the purpose of this research, the focus is on residential consumer as analysed in the following sections.

Given that each ENSP has an independent tariff structure approved by NERSA, the following section is dedicated to the analysis with the emphasis on middle-range residential and feed-in tariffs. The section is not exhaustive but it provides sufficient information for understanding the impact of locating a load a particular ENSP's supply area.

5.4.2.1 Electrical energy tariffs in Johannesburg

Residential tariff within the City of Johannesburg licensed area include prepaid, post-paid, conventional reseller, time of use and seasonal classes. In some instance, tariff classes have various sub-classes that are designed as product to suit consumer's categories and behaviour. Table 5-3 provides details of tariff regime sub-classes available to homeowners in single and three-phase in which energy charges for prepaid and post-paid consumers if further separated into blocks of consumption. Sub-categories of prepaid and post-paid are based on the user consumption. This implies that unit costs will vary with the consumer's behaviour.

Table 5-3: City of Johannesburg's residential tariffs for electricity [113]



		Breaker size	Demand	Consumption block	Fixed charge	Demand charge	Energy charge
Item	**Units**	A	kVA	kWh/month	R/month	R/kVA	c/kWh
Prepaid tariffs							
Capacity Charge							
Prepaid 1				0 to 500			124,49
Prepaid 2				501 to 1000			141,43
Prepaid 3				1001 to 2000			151,86
Prepaid 4				2001 to 3000			171,55
Prepaid 5				Above 3000			185,91
Two-part Single and Three Phase Tariffs							
Single phase							
Service charge		60			123,01		
Service charge		80			123,01		
Network charge		60			362,38		
Network charge		80			398,47		
Energy charge				0 to 500			118,58
Energy charge				501 to 1000			136,08
Energy charge				1001 to 2000			146,12
Energy charge				2001 to 3000			154,17
Energy charge				Above 3000			161,73
Three phase							
Service charge		80			123,01		
Network charge		80			496,39		
Energy charge				0 to 500			118,58
Energy charge				501 to 1000			136,08
Energy charge				1001 to 2000			146,12
Energy charge				2001 to 3000			154,17
Energy charge				Above 3000			161,73

Prepaid and post-paid residential

In chapter 4, it was calculated that a single house electrical energy consumption ranges between 1000 and 2000 kWh per month. On this basis, the applicable tariffs are Prepaid 3, Residential 60 and 80 A Single Phase as well as 80A three phase. It is also fair to say that most of residential consumers are connected to the grid at single phase low voltage.

Considering the calculated monthly energy, a choice of the correct tariff can be compiled and summarised as given in Table 5-4. From the applicable tariffs, prepaid is the most expensive but does not attract service and demand charges. Post-paid tariffs are availed in single and three phase versions and further split into the connection ratings of 60 A and 80 A but with three-phase connections available only at 80A. The cost of energy for post-paid connections is charged at 146.12 c/kWh for energy with an additional service charge of R123 per month regardless of the connection rating. The difference between different ratings and phasing is encapsulated in monthly demand charges where 60A is the cheapest while 80A three phase connection is the highest.

Table 5-4: Residential prepaid and post-paid tariffs in City of Johannesburg

Charge types	Prepaid	Residential 60A - Single Phase	Residential 80A - Single Phase	Residential 80A - Three Phase
Energy Charges (c/kWh)	151.86	146.12	146.12	146.12
Other charges (R/Month)	-	485.39	521.48	619.40
Service Charges (R/Month)	-	123.01	123.01	123.01
Demand Charges (R/Month)	-	362.38	398.47	496.39

Although individual consumer’s energy ranges between 1000 and 2000 kWh, operating into a microgrid environment with a single connection point to the power utility implies a higher aggregated energy value as seen from the ENSP. For such range of energy, it is possible to switch to the most convenient tariff for the benefit of the microgrid consumers. In such case, in order to determine the most beneficial tariff, a comparison of tariff regimes is carried out in Table 5-5 for energy consumption up to 30 000 kWh.

Table 5-5: Cost of 1000 and 10000 kWh of energy based on COJ tariffs

Energy (kWh)	Prepaid	Post-paid (60A, Single Phase)	Post-paid (80A, Single Phase)	Post-paid (80A, Three Phase)
<1 000	1,518.60	1,946.59	1,982.68	2,080.6
<10 000	15,186.00	15,097.39	15,133.48	15,231.4
<30 000	45,558.00	44,321.39	44,357.48	44,455.4
Cost with respect to Prepaid				
<1 000	0.00%	28.18%	30.56%	37.01%
<10 000	0.00%	-0.58%	-0.35%	0.30%
<30 000	0.00%	-2.71%	-2.64%	-2.42%

Applying the tariffs to a range of energy consumptions, results in Table 5-5 shows that prepaid electricity is cheaper for consumption lower than 1000 kWh and that post-paid tariffs becomes more economic only when the energy consumption exceeds 10 MWh. Although grouping of consumers for instance in a microgrid show financial benefit of a single bill at the designated connection point (if post-paid tariffs are applied), the application of reseller tariffs within the group could erode this benefit of lower tariffs and return the consumer’s invoice to the same level as when delivered in isolation.

Time of Use (TOU) residential tariff analysis

From the analysis of conventional prepaid and post-paid tariff in the previous section, it can be noted that the options to reduce electricity consumption bills are very limited when it comes to the use of tariff regimes. One major way of reducing the monthly electricity bill is to adopt the use of alternative and/or embedded sources of energy.

Although power utility allows embedded generation such as photovoltaic to be connected to their grids, it is done with a set of conditions. For instance, in Johannesburg the embedded generator is allowed to connect if and only it complies with the technical requirements and is used to supplement the consumption from the utility grid. Furthermore, the connection of an embedded generator requires the consumer to switch from prepaid or post-paid to residential Time of Use (TOU) tariff.

TOU tariff is essentially a predetermined cost of electricity based on the usage time. For instance, the TOU has three time-periods definition. The peak, standard and off-peak time. Furthermore, this time slots are applied differently depending on the day of the week that could occur in week-days, Saturday and Sundays. Figure 5-18 provide a time definition and application to the day category.

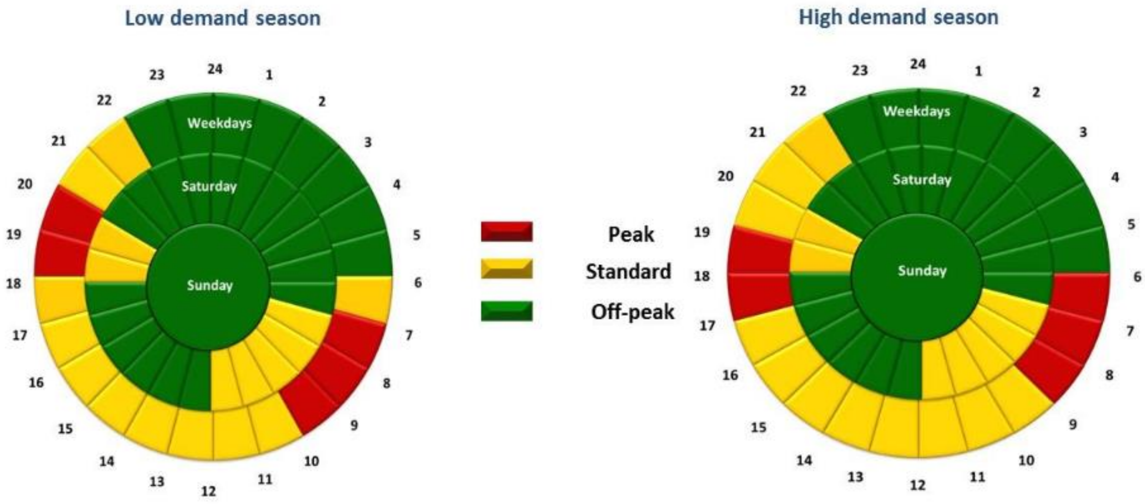
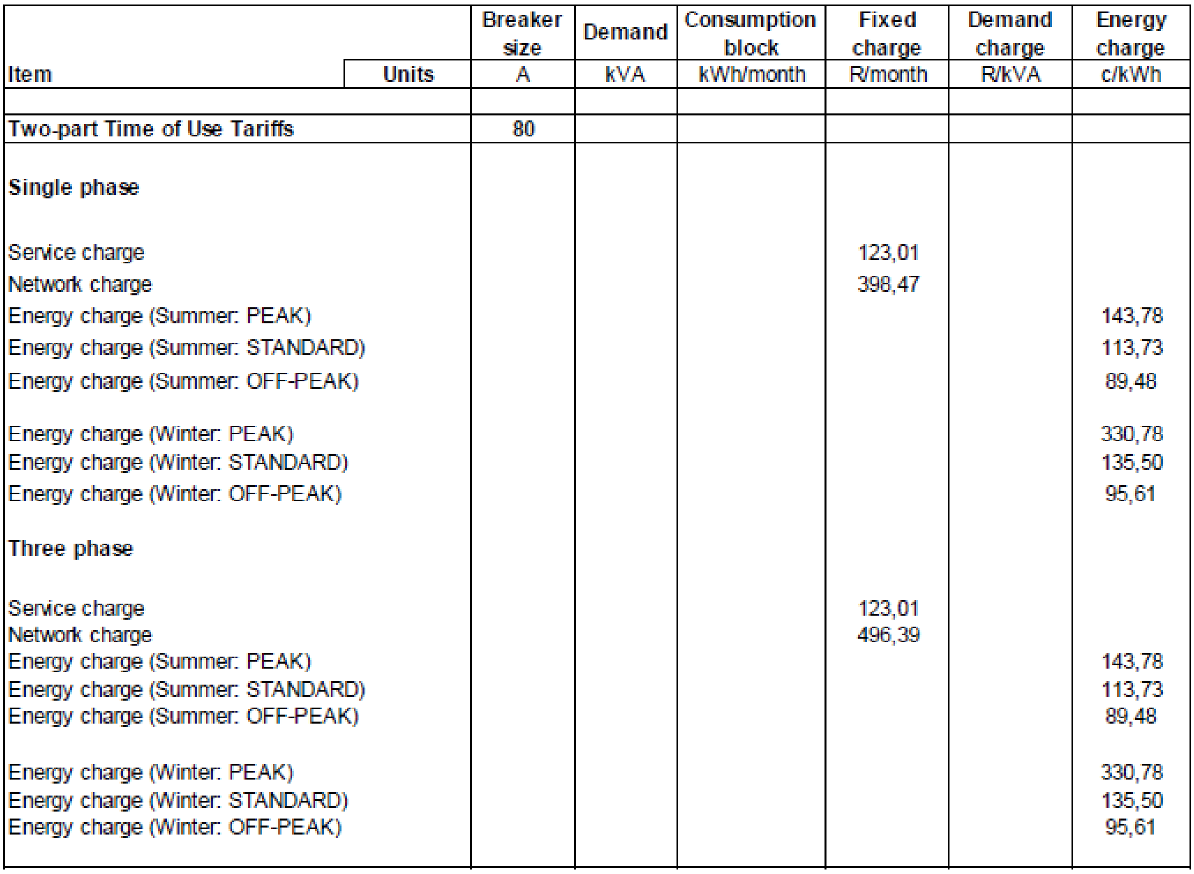


Figure 5-18: Time of use definition [114]

Each time slop has a fixed rate, the cheapest rate is during off-peak, and the highest rate is during peak hours. Standard time slots use a rate that is located between the two extreme ends of peak and off-peak rates. Table 5-6 as published by the City of Johannesburg [113] indicated that the rates or energy and service charges are the same for single and three phase connections but the network charges are different and more expensive for three phase systems. Demand changes are not applicable in Johannesburg’s TOU tariffs.

Table 5-6: Time of Use (TOU) tariff in Johannesburg [113]



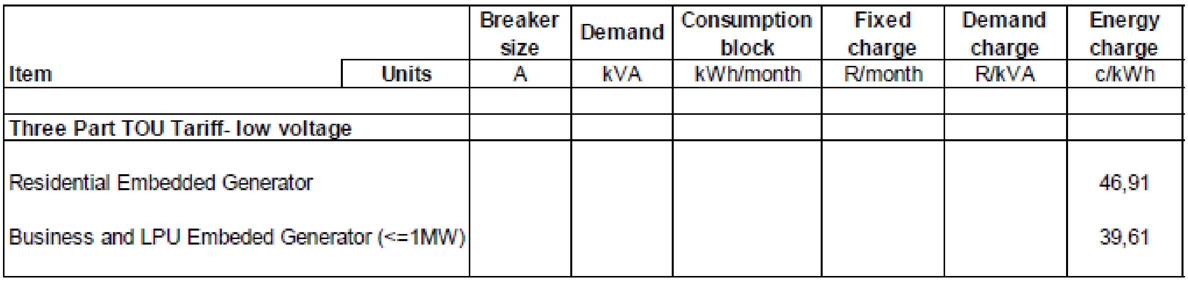
		Breaker size	Demand	Consumption block	Fixed charge	Demand charge	Energy charge
Item	Units	A	kVA	kWh/month	R/month	R/kVA	c/kWh
Two-part Time of Use Tariffs		80					
Single phase							
Service charge					123,01		
Network charge					398,47		
Energy charge (Summer: PEAK)							143,78
Energy charge (Summer: STANDARD)							113,73
Energy charge (Summer: OFF-PEAK)							89,48
Energy charge (Winter: PEAK)							330,78
Energy charge (Winter: STANDARD)							135,50
Energy charge (Winter: OFF-PEAK)							95,61
Three phase							
Service charge					123,01		
Network charge					496,39		
Energy charge (Summer: PEAK)							143,78
Energy charge (Summer: STANDARD)							113,73
Energy charge (Summer: OFF-PEAK)							89,48
Energy charge (Winter: PEAK)							330,78
Energy charge (Winter: STANDARD)							135,50
Energy charge (Winter: OFF-PEAK)							95,61

In Chapter 4, it was established that the residential load profile used for this research has morning and evening peaks. During the morning peak load, embedded PV generations are yet to reach the maximum generation to provide a meaningfully supplement the utility grid. Similarly, evening peaks occur when the embedded PV generations are producing little. To the consumers' disadvantage, these load peaks also fall within the peak time tariff's time slots. As result, the application of this TOU tariff results in more cost for PV based microgrids and therefore reduce the financial benefit of feed-in tariff sought by the consumers.

Embedded generators tariff analysis

Although embedded generators are allowed in Johannesburg utility grid, the capacity is limited to one MW with a further condition for the embedded plant owner to be a net consumer. This implies that the energy generated by the embedded plant has to be lower than or equal to the energy imported from the utility grid [113]. Whilst the first condition can be tackled and limited by the embedded generator's design capacity, the second condition requires careful control of the plant to ensure that the net consumption can be achieved. Any export into the utility grid is credited at the rate indicated in Table 5-7 against the imports over the same period. Any embedded generator connected to the ENSP's network in Johannesburg for the purpose of supplying and not consuming energy from is considered an additional supplier under a Power Purchase Agreement (PPA). Despite this incentive, the credit value is not allowed to exceed the monetary value of imported energy over the same period. Any excess energy produce would be forfeited to the power utility and therefore a loss for the embedded generator's owner.

Table 5-7: Feed-in tariff rate for embedded generators in Johannesburg [113]



Item	Units	Breaker size	Demand	Consumption block	Fixed charge	Demand charge	Energy charge
		A	kVA	kWh/month	R/month	R/kVA	c/kWh
Three Part TOU Tariff- low voltage							
Residential Embedded Generator							46,91
Business and LPU Embeded Generator (<=1MW)							39,61

Considering the residential load profile, the bulk of energy is consumed in early morning and late evening. These time slots coincide with two major factors working to the consumer disadvantage. Firstly, the solar power is not fully available during that period. Secondly, those time slots fall within the peak period and therefore attract the highest energy rate. Since the microgrids in this research have only PVPP that peak during the day, all microgrids' generated power cannot be absorbed and will therefore flow into the ENSP's grid. Already energy charges are higher than feed-in tariffs. This implies that any microgrid with the objective of offsetting the bill must be prepared to transfer more energy into the ENSP's grid than it receives. For some, this could imply installing a larger PVPP.

5.4.2.2 Electrical energy tariffs in Johannesburg

Cape Town employs almost the same tariff structure as Johannesburg but with different rates. For instance, energy charges are the most expensive but the feed-in tariff is also the most favourable for residential consumers.

5.4.2.3 Tariff comparison between Johannesburg, Cape Town and Durban utilities

Although utilities in Johannesburg, Cape Town and Durban allow the use of embedded generators in their network, the conditions are somewhat different from one to another. Mostly, tariff structures differ on energy rates and additional cost such demand, network and service charges.

The prepaid system is popular in Johannesburg, Cape Town and Durban. A comparison of tariffs summarised in Table 5-8 shows that prepaid is highest in Cape Town while Durban has almost the same rate as Johannesburg.

Johannesburg utility allows embedded generator for residential consumers on condition of migrating from prepaid to conventional TOU tariff and that the consumer is a net importer. Cape Town ENSP allows the connection of embedded generation on condition for the consumer to use a fixed rate (same as prepaid) for importing energy from its grid and another rate for feed-in of excess energy. Furthermore, Cape Town charges an additional network charge per month for every embedded generator.

With regards to embedded generators, Durban structure is similar to Cape Town. The embedded generator is subject to a flat energy charges for import (same as prepaid rate) and another rate for export. Additionally, a monthly network charge is also applicable. In terms of credit through feed-in tariff, the exported energy revenue is used to offset the cost of electricity import from the grid but subject to maximum equivalent to the value of imports or a predetermined amount of R1750 per consumer [115].

From the analysis of three city tariffs, it is evident that a microgrid needs to export more energy into the ENSP’s grid to achieve financial parity. This is in turn could require bigger PVPP and hence the concern about the financial viability.

Table 5-8: Summary of common residential tariffs in big three cities in South Africa

Charge types		City of Johannesburg	City of Cape Town	Durban Metro
PREPAID				
	Energy Charges (c/kWh)	151.86	242.14	151.61
	Other charges (R/Month)	None	None	None
TIME OF USE (TOU)				
WINTER	Peak	330.78	395.66	Not Applicable
	Standard	135.50	139.71	
	Off-peak	95.61	88.91	
SUMMER	Peak	143.78	148.26	Not Applicable
	Standard	113.73	110.94	
	Off-peak	89.48	80.79	
OTHERS	Service Charges (R/Month)	123.01	None	Not Applicable
	Demand Charges (R/kVA)	None	102.74	
	Capacity Charges (R/Month)	496.39	None	496.39
EMBEDDED GENERATION				
	Energy Charges (c/kWh) - import	See TOU	242.14	151.61
	Energy Charges (c/kWh) - export	46.91	68.51	74.02
	Network Charges (R/Month)	None	215.93	353.76

Given the differences in tariff regimes used across the three utilities in Johannesburg, Cape Town and Durban, the impact of a grouping consumers into a PVPP dominated microgrids requires further investigations. In the following sections, the load and generation profiles along with the tariffs of Table 5-8 are used to simulate the cost of electricity under import and export conditions for any period. Furthermore, long-term financial projections are also carried out by assuming an annual cost increase for tariff, therefore assessing the viability of implementing microgrids for long term planning.

5.4.3 Basis of financial analysis

When faced with increasing electrical energy cost, the consumers would opt for alternative sources such as embedded generation. Regardless of the embedded generation type, capital expenditure is required upfront for their establishment. It is possible for consumers to finance such plant through financial institutions. However, for any sound decision, a cost-benefit analysis is crucial in making such decision on the basis of the current cost of electricity as well as the cost required to set up a local generation plant.

In the following sections, financial results of the simulated revenue are presented for each of the utility companies representing the three metropolitan cities under consideration herein. For each utility, the financial analysis are based on the Net Present Value of the following parameters for a period of fifteen years for each of the technical case studies assessed in the technical evaluation in section 5.3:

1. Embedded PV Cost: cost of establishing a PV system based on the global market's per unit cost of installed PV solar power [110]. These costs represent the capital and operational expenditures but does not take into consideration replacement costs of plant parts;
2. Imported Energy Cost: the monetary value for the total of energy imported from the utility considering an eight percent yearly tariff increase;
3. Exported Energy (Utility Value) Cost: the monetary value for the total of energy exported from the microgrids into the utility's grid at the applicable energy and network charges;
4. Base Electricity Cost: the base cost of electricity for electricity without PV plant installed in the microgrid.

The comparison between these parameters provides a platform for assessing the opportunistic value of using an embedded PVPP in the microgrid environment.

5.4.4 Energy trading between microgrids and utility grids

Based on detailed technical simulation, Table 5-9 provides a summary of energy exchange between the microgrids and the utility companies for a period of twelve months. In the base case, power flows in one direction only, from the utility to each microgrid. For the second and third case studies, both import and export occur but the energy accounting is based on the sum of individual microgrids energy trading with the utility grid. The fourth case study is similar to the second and third except that the energy accounting considers all microgrids in a cluster with a single connection point.

Table 5-9: Summary of annual energy trading between microgrids and utility grid

Energy Accounting	Base Case MWH	Study Case 2 MWh	Study Case 3 MWh	Study Case 4 MWh
Local Production	-	6,643.37	6,643.37	5,337.00
Imported	4,453.10	2,273.68	1,456.87	2,344.35
Exported	-	4,448.73	3,286.76	3,209.95
Import Reduction	Not applicable	49%	67%	47%

The annual energy exchange between microgrids or cluster of microgrids with the utility grid is provided in Table 5-9 and the details are provided in Annexure. By adding local PV generation, the energy imported from the utility grid is reduced for all case studies with the most severe occurring when BESS is in use (Case study 3). The energy exported from microgrids to the utility grid is increased with the most occurring in case study 2 where the plant size is bigger and no BESS is implemented.

5.4.5 Financial impact on the power utility companies

For case studies one (no PVPP), two (PVPP without BESS) and three (PV with BESS), each microgrid was considered stand-alone and therefore the analysis was carried out on individual basis. In the last or fourth case study, all microgrid are grouped in a single pool with a single connection point located at the substation.

5.4.5.1 Financial analysis for the Base case (no local generation)

In this scenario, the energy consumed in the microgrid is provided from the utility grid only. The cost of electricity is evaluated on an individual basis and aggregated to determine the yearly cost of energy. Unit cost are based on the assumption that each consumer is on prepaid tariff. This provides the worst-case scenario on residential consumers' tariff.

Table 5-10: Annual cost of energy consumption of combined microgrids with no PV plants

SEASON/ ENERGY DIRECTION	Energy (kWh)	Johannesburg (1000xR)	Cape Town (1000xR)	Durban (1000xR)
SUMMER	3,330,678.27	5,057.97	8,064.90	5,049.64
OFF-PEAK	1,127,792.31	1,712.67	2,730.84	1,709.85
PEAK	746,759.20	1,134.03	1,808.20	1,132.16
STANDARD	1,456,126.76	2,211.27	3,525.87	2,207.63
WINTER	1,122,426.38	1,704.52	2,717.84	1,701.71
OFF-PEAK	404,075.76	613.63	978.43	612.62
PEAK	203,975.45	309.76	493.91	309.25
STANDARD	514,375.17	781.13	1,245.51	779.84
TOTAL	4,453,104.65	6,762.48	10,782.75	6,751.35

Using one-minute resolution load profile, the energy consumption is calculated for each day, month and finally for the whole year. From the energy calculation and the applicable tariff for each city, the monthly and yearly cost of electrical energy is determined for each microgrid, thus culminating into the summary in Table 5-10 that provides the total energy and associated cost for the big three towns in South Africa.

A comparison of the cost shows that for a similar group of loads, the cost of electrical energy in Durban is slightly cheaper than in Johannesburg while Cape Town is significantly higher. The total cost of Table 5-10 is used in subsequent energy flow case studies as basis of comparison for assessing the viability of PV embedded generation use in the microgrids.

5.4.5.2 Financial analysis for Johannesburg ENSP

The use of embedded generation in Johannesburg is subject to the consumers to be net importer. There is no minimum import value set and therefore this implies that it would acceptable to the ENSP for a consumer to maintain zero consumption.

Table 5-11: Annual cost comparison for microgrid case studies in Johannesburg

Energy and Charges	Base Case 1000xZAR	Case Study 2 1000xZAR	Case Study 3 1000xZAR	Case Study 4 1000xZAR
Imported energy	6,762.48	2,836.28	1,735.59	2,939.57
Exported energy	0	2,086.90	1,541.82	1,505.79
Fixed Charges	0	1,877.33	1,877.33	6.26
Utility Revenue	6,762.48	2,626.71	2,071.10	1,440.04
Utility revenue losses	0%	61%	69%	79%

Comparing the revenue between the base case and the case studies containing embedded generation in the form of PVPP within the microgrid, the summary of power utility revenue collection in Table 5-11 shows that the power ENSP revenue decreasing by more than a half in all cases. Furthermore, when microgrids collaborate and share a common connection point, the associated fixed charges are applicable to a single point, hence the massive drop in fixed charge for case study four. Amongst all the case studies, the worst case of 79% decrease in revenue collection occurs under the fourth case study when microgrid are collaborating. On average, an ENSP in Johannesburg can expect average revenue losses of 70%.

5.4.5.3 Financial analysis for Cape Town ENSP

Like in Johannesburg, the embedded generator in Cape Town grid must be a net importer with no minimum import value set. This implies that it is acceptable for a consumer to maintain the consumption at zero net import.

Assuming that the export amount of energy is not limited and applying Cape Town tariffs to the energy consumption, the results in **Error! Not a valid bookmark self-reference.** shows that the ENSP will lose more revenue when microgrid adopt embedded PV plants coupled with BESS. Once more, all case studies result.

Table 5-12: Annual cost comparison for microgrid case studies in Cape Town

Energy and Charges	Base Case 1000xZAR	Study Case 2 1000xZAR	Study Case 3 1000xZAR	Study Case 4 1000xZAR
Imported energy	10,782.75	5,505.48	3,527.66	5,676.60
Exported energy	0.00	3,047.82	2,251.76	2,199.14
Fixed Charges	0.00	777.35	777.35	2.59
Utility Revenue	10,782.75	3,235.01	2,053.25	3,480.06
Utility revenue losses	0%	70%	81%	68%

in revenue collection decrease of more than half the value in the base case. Although case studies two and three differ only by 2%, a severe revenue loss is expected when energy storage system is added to each microgrid. On average, the Cape Town is exposed to revenue losses of 73% across all three scenarios.

5.4.5.4 Financial analysis for Durban ENSP

As in the previous two cases, the power utility in Durban requires for the embedded generator to be a net consumer. Furthermore, the amount of power to be injected into the utility grid is limited either by energy injected or by monetary value.

Table 5-13: Annual cost comparison for microgrid case studies in Durban

Energy and Charges	Base Case 1000xZAR	Study Case 2 1000xZAR	Study Case 3 1000xZAR	Study Case 4 1000xZAR
Imported energy	6,751.35	3,447.12	2,208.76	3,554.26
Exported energy		3,292.95	2,208.76	2,376.00
Fixed Charges		1,273.54	1,273.54	4.25
Utility Revenue	6,751.35	1,427.71	1,273.54	1,182.50
Utility revenue losses	0%	79%	81%	82%

A cost comparison between the base case and case studies comprising embedded generators is provided in Table 5-13. All case studies result in reduced revenue collection but with the worst case of 82% occurring when collaboration between microgrids is allowed. The revenue losses for the three case studies are almost the same and therefore making Durban revenue losses exposure the highest of all ENSP at 81%.

5.4.5.5 Financial viability of microgrids

For the consumers wanting to form one or more microgrid connected to the ENSP grid and managed either as single entities or as part of a collaborative environment, it is necessary to determine the viability of such projects. One of the objective functions of microgrids is to minimise the cost of electricity from the utility grid for a cluster of microgrids connected to a single feeder. Doing that require internal generation for which in this case photovoltaic is used. Such onsite generation capacity requires significant investment and therefore needs to be evaluated to test the system's financial viability.

The financial viability of each microgrid is calculated by considering the capital expenditure required to set it up and the savings resulting from its use (the difference between the cost of electricity with and without microgrids PVPP). These values are integrated into a financial model to calculate the Net Present Value (NPV) as an indicator for the project viability. Other factors considered in the economic model include an interest rate of 11%, a discount rate of 8%, an annual electricity tariff increase of 8%, R7000/kWh for BESS R14.5/kW for PV installation [111] and 5% of the capital expenditure for operation and maintenance.

Table 5-14: Summary of NPV for microgrids operations for fifteen years

NPV - 15 Years	Case study 2 1000xZAR	Case study 3 1000xZAR	Case study 4 1000xZAR
Required Investment	49,300.00	259,300.00	39,150.00
City of Johannesburg	- 10,743.88	- 385,439.02	20,388.22
City of Cape Town	39,179.52	- 325,856.23	49,353.87
City of Durban	2,617.22	- 373,573.84	20,868.41

The NPV values are calculated for each ENSP against the case study for a period of fifteen years. The NPV analysis summary is provided in Table 5-14 from which it can be deduced that Case study 2 (grid-tied microgrid with embedded PV plants) requires the second most expensive capital expenditure. It is viable for microgrids tied to Cape Town utility, is marginally viability for microgrids tied in Durban and not viable for microgrid establishment in Johannesburg.

Case study 3 (grid-tied microgrid with embedded PV plants and battery energy storage systems) attracts the highest capital expenditure due to the introduction of batteries for storage and is therefore not viable for any utility tied microgrid in Johannesburg, Cape Town or Durban.

Case Study 4 (reduce capacity and microgrid collaborative pool) require the least capital expenditure but is the most viable. However, when compared to the other financially viable option in case study two (only for Cape Town and Durban), it also results in the biggest loss of revenue for the ENSP in any of the towns under consideration.

5.4.5.6 Sensitivity analysis

The profitability of the microgrid depends mostly on the CAPEX and the cost of electricity from the ENSP grid. On this basis it is possible for Case study 2 and 3 to become financially viable if one or more of these conditions are met.

Doubling the ENSP electricity price from 8% to 16% per annum is considered steep for the consumer but is still not sufficient to justify the operation of any of the microgrid independently of the other connected to the same feeder (i.e.: no direct exchange of power amongst them) when used in conjunction with BESS.

A decrease of at least 15% in PVPP cost is needed to ensure that stand-alone microgrids (case study 2) are profitable. On the basis of the present trend this is achievable [34],[111]. Reduction in cost of PVPP implies that collaboration between microgrids could be even more profitable than at current rate.

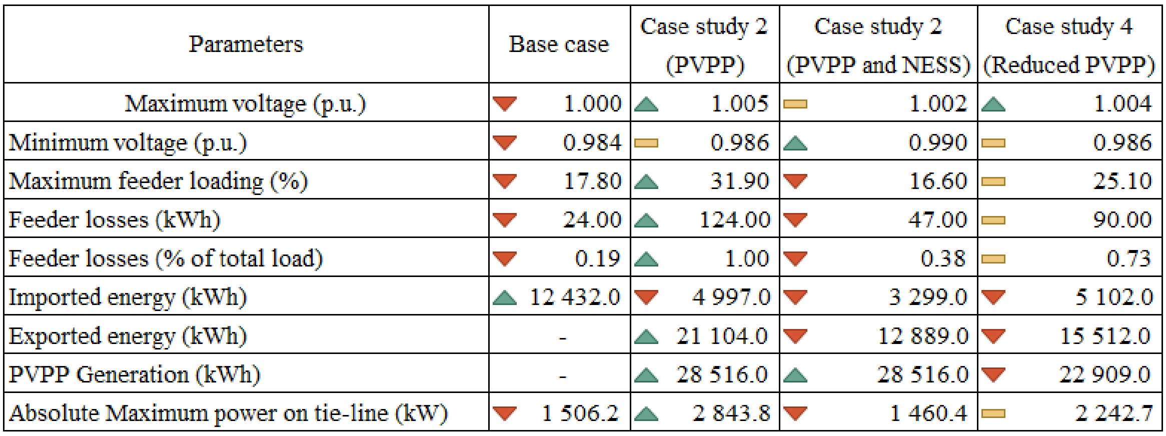
For each of the microgrid operating independently of the others but with BESS while connected to the ENSP's grid, the cost of PVPP and BESS have to decrease simultaneously and respectively by 50% and 75% for the possibility to achieve any financial viability. The required reductions in cost for economic viability are achievable for PVPP but envisaged for BESS only beyond 2030 [34], [111], [112].

5.5 Key Findings

5.5.1 Technical findings

From the technical analysis of the multiple microgrid connected to the single feeder for the supply to residential areas, voltage, network losses, import and export energy, feeder loading and maximum power flow in feeders were considered the most vital information.

Table 5-15: Summary of technical parameters for case studies



Parameters	Base case	Case study 2 (PVPP)	Case study 2 (PVPP and NESS)	Case study 4 (Reduced PVPP)
Maximum voltage (p.u.)	▼ 1.000	▲ 1.005	▬ 1.002	▲ 1.004
Minimum voltage (p.u.)	▼ 0.984	▬ 0.986	▲ 0.990	▬ 0.986
Maximum feeder loading (%)	▼ 17.80	▲ 31.90	▼ 16.60	▬ 25.10
Feeder losses (kWh)	▼ 24.00	▲ 124.00	▼ 47.00	▬ 90.00
Feeder losses (% of total load)	▼ 0.19	▲ 1.00	▼ 0.38	▬ 0.73
Imported energy (kWh)	▲ 12 432.0	▼ 4 997.0	▼ 3 299.0	▼ 5 102.0
Exported energy (kWh)	-	▲ 21 104.0	▼ 12 889.0	▼ 15 512.0
PVPP Generation (kWh)	-	▲ 28 516.0	▲ 28 516.0	▼ 22 909.0
Absolute Maximum power on tie-line (kW)	▼ 1 506.2	▲ 2 843.8	▼ 1 460.4	▬ 2 242.7

From the technical analysis summary of Table 5-15, the following are the findings:

- The integration of PV plants in each of the microgrids has little impact on the voltage profile of and therefore does not affect the utility grid's voltage stability;
- The addition of PVPP alone reduced the imported energy but at same time increases the exported energy into the ENSP. Furthermore, most of the energy produced from the microgrids' PVPP is exported into the ENSP's grid;
- Further to the above, the addition of PV plants and BESS yield decrease in import and decrease in export of energy. Furthermore, the least import amount occurs under this scenario;
- Using collaboration amongst microgrid and a single account (feeder) model, viewed from the substation, import and export can be reduced considerably by only the addition of batteries could render this option a lot more attractive;
- Power flow in the main feeder is increased in all cases except for case 3 where the storage system absorbs or releases a significant portion of energy to support the microgrid and thereby reduces the amount of power required from the ENSP grid.

Since the above provide a global view, the following sections provide an on-the-case basis for providing the network performance.

Case study 2: Overall, the addition of PVPP in the microgrids enable them to produce sufficient energy to meet their need for most of the time. The local production reduces importing of energy from the ENSP but at the same time increases the export in in the process increasing the losses by about five times. The impact on the minimum voltage is little since it occurs in late evening or early mornings when the PVPP is producing at its lowest levels.

Case study 3: The above basis, the use of PVPP and BESS has improved the voltage profile, provided sufficient energy for the microgrid by reducing the imported capacity significantly. However, the exported capacity has increased also significantly and thereby doubling the losses on the tie-line connected the microgrids cluster to the ENSP.

Case study 4: Derived from case study 2, this study case has the lowest generation capacity and therefore it imports more and export less in comparison with Case study 4.

5.5.2 Financial Findings

5.5.2.1 Revenue Losses

From the studies carried out on the previous sections, the establishment of microgrid has been proven to cause significant loss of revenue for electrical network service providers.

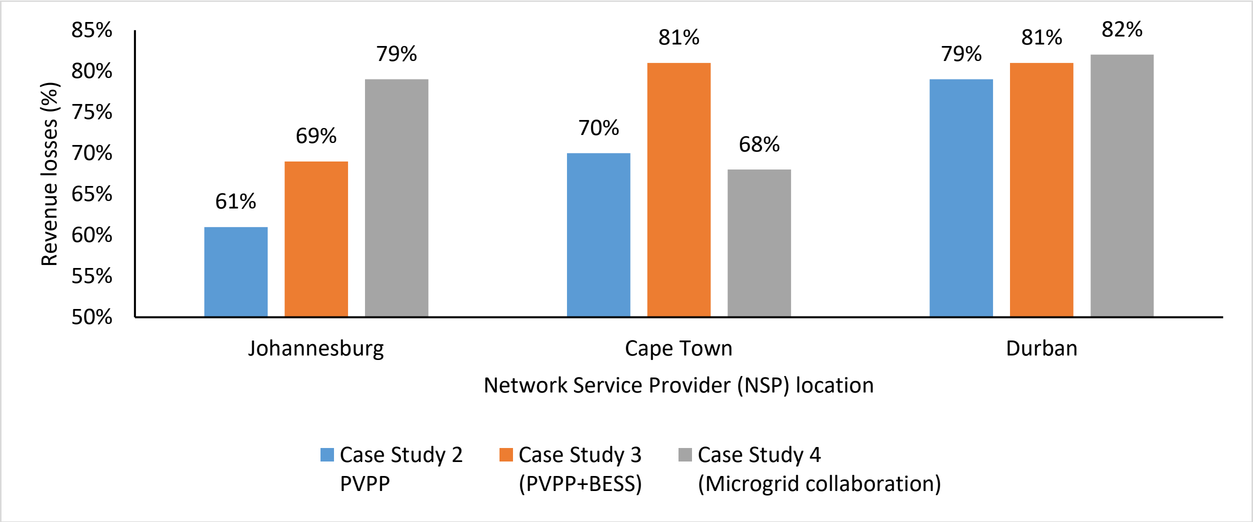


Figure 5-19: Summary of revenue losses for various microgrid configurations and locations

For each case study and associated ENSP, Figure 5-19 provides the associated loss of revenue. Regardless of the microgrid set up, ENSP stand to lose more than fifty percent of their revenue if clustering and collaboration of amongst microgrid is allowed.

5.5.2.2 Financial viability

For all cities, selling of the excess energy to the utility grid yields little revenue with the worst-case being Johannesburg. Durban provides the highest offset value but it surpasses the amount of energy purchased from the grid and will therefore be limited to a value below its import levels to ensure that they remain a net consumer.

In light of the above observations, the use of PV dominated microgrid brings benefit to the consumers while impacting severely on the utility revenues:

- The establishment of such microgrids is mostly viable when microgrids are clustered with a single connection point to the utility grid;
- The viability is more pronounced for microgrids tied to Cape Town ENSP;
- Using PVPP coupled with BESS is not financially viable under the current market conditions. It still has a long way to go before it can be considered for successful financial integration into microgrid.
- Collaboration between microgrids in a cluster is the most economically viable options of establishing microgrids for urban secure complexes.

6 CONCLUSIONS AND FUTURE WORKS

6.1 Regulatory

Existing regulatory framework that includes the electricity act of 4 of 2006, the grid code and national standard are leaned towards the integration of distributed generators (all types) for a single consumer. Distribution of power from one residential consumer to the other is not allowed, whether directly or by wheeling through the ENSP's grid.

The single DG approach is not suitable for a microgrid environment where each generator contributes to a virtual power pool from which the excess or deficit determines the exchange with the Network service provider through a defined point of common coupling. From the application, assessment and billing of a consumer owning a DG, the process does not favour the establishment of microgrids, let alone their collaboration.

A further handicap to the microgrid is the inability for the existing regulatory framework to provide a methodology for the assessment of microgrids, notably with regards to the maximum export capacity and tariffs cost ceiling. Furthermore, the regulatory framework does not explicitly cover microgrids. Currently, microgrids could be implicitly treated as mainstream grid without legal status. Under the existing regulatory framework, collaboration between microgrids is possible only through an ENSP network on condition of establishing an agreement. This renders the task even harder for collaboration between microgrids due to financial risks from any wheeling agreement.

For microgrid to work in the targeted environment such as urban secure complexes, the ownership model needs distinct attention to navigate politics and aim towards a common goal of achieving reliability, resilience and economic independence from established ENSP.

The above challenges can be resolved by expanding the existing regulations to include clauses for microgrid establishment. Such clauses should bear a clear definition of microgrids including the supply boundary, typical ownership model, tariff adjustments and limitations and evaluation. Furthermore, collaboration between microgrids will be possible only if regulations allow for takeover of collaboration enabling network components (such as substation to microgrids radial feeder and miniature substations) by microgrid owners or allow for special arrangement between microgrid clutters and ENSP to facilitate the collaboration.

6.2 Technical

The additions of DG and a microgrid environment for residential consumers is not prone to large voltage deviation when the network's LV feeders are shorter. Particularly, the margin of tolerance seems large in microgrid friendly environments such as urban secure complexes that have a dedicated MV/LV substation.

Due to reversed power flow magnitudes exceeding the pre-microgrids values, losses and feeder loading on the network as higher but do not result in overloading of any section of the radial feeder.

The best technical compromise that offers good voltage control, fair feeder loading, acceptable network losses while reducing the imported and exported energy is the enabling of collaboration between microgrids in case study four.

In the event of overloading due to the enabling of microgrids, export from microgrid can be curtailed or the network infrastructure can be upgraded at the microgrids cost to enable a safe exchange of power through the radial feeder. Furthermore, microgrids DGs (in this case PVPP) can be used for voltage regulation when required. Furthermore, energy injected from the microgrid into the ENSP causes less power flow in the upstream network, thereby reducing the network losses and improving on the voltage stability.

6.3 Economic

Microgrids need to export more energy than they import in order to cancel the utility bill. This is achievable only where there is not limitation to the power and energy exported into the ENSP.

More energy and power to balance the utility bill require the collective microgrid generation to be significantly oversized in the absence of energy storage facilities. Such oversized generation requires higher CAPEX and therefore makes the project less viable from an economics perspective. The microgrid viability can improve in this case only if the electricity tariffs increase or the PVPP decrease.

The use of battery energy storage systems in microgrid results in the highest CAPEX. At current market prices, this type of microgrids is not economically viable. For it to become viable, the cost of electricity has to increase dramatically while the cost of battery storage remains. Alternatively, the viability could be achieved only if the ENSP’s tariffs remained the same while the battery cost decreased significantly.

Enabling collaboration between microgrids allows for excess energy from one microgrid to be transferred to adjacent microgrids supplied from the same feeder. Under this cluster operation, excess energy from one microgrid can be used by another microgrid experiencing a deficit of energy but at the same price as importing the same from an ENSP. This is advantageous given that the excess could have been sold to the ENSP at lower cost.

Collaboration between microgrids is economically viable under the current market conditions. However, this success creates a loss of revenue for the ENSP. The loss of revenue is location and tariff dependant. This research as established an average loss of income for the ENSP of 70% in Johannesburg, 73% in Cape Town and 81% in Durban.

At the same time, the ENSP cost of maintenance, operation and network expansion are decreased due to lowered demand in the concerned feeder. This could also lead to reduced requirement for manpower for the ENSP but an increase for the microgrid owners, hence a self-regulating labour exchange.

6.4 Future works

The establishment of microgrids and their collaboration has impact on the ENSP from technical, financial and labour's perspective. It can be enabled only if the changes are made to the existing regulatory frame works for the electricity industry. Each of the enabling work could requires further research works.

The impact of changing the regulatory framework to accommodate microgrids collaboration could have technical and financial implications on the ENSP. Although some of these implications have been covered in this research, consideration should be given to the response of ENSP to such changes. For instance, they could rise the cost of charges such as maximum demand/export capacity, capacity charge, etc. to control their financial losses. Furthermore, for microgrids to collaborate, they require a medium for power exchange. For existing areas, this can is possible only if there is a willing agreement with the ENSP for energy wheeling. Again, this is an area that if not regulated could be exploited by the ENSP to slow down microgrid proliferation. More focus should be given to these aspects.

On the brighter side, establishing microgrid and letting them collaborate reduce the pressure on the utility to upgrade the LV and to some extend the MV network. Moreover, the operation and maintenance is reduced for the ENSP in virtue of a decreasing grid size when handing over or selling part of the asset to the microgrids. It is therefore necessary to quantify the deferred cost of network upgrades, reduction of operation and maintenance cost on LV networks and reduced power flow and losses on upstream ENSP's network.

As the ENSP network size reduces, so does the need for manpower. At the same time, the need for manpower increases for the microgrid. Impact of adopting microgrid on the energy labour market due to the flow of manpower between the ENSP and microgrid is therefore interesting to explore and quantify.

Looking any microgrid as a small-scale utility, there is a need for an organisation to own, manage and operate the microgrid as a small utility. This requires an effective and efficient ownership model and tariff for the benefit of consumers in a community financed microgrid.

7 ANNEXURES

Table 7-1: Annual cost of energy consumption of individual microgrids without PV plants

SEASON/ ENERGY DIRECTION	**Energy (kWh)**	**Johannesburg (1000xR)**	**Cape Town (1000xR)**	**Durban (1000xR)**
SUMMER	**3,330,678.27**	**5,057.97**	**8,064.90**	**5,049.64**
EXPORT	**-**	**-**	**-**	**-**
OFF-PEAK	-	-	-	-
PEAK	-	-	-	-
STANDARD	-	-	-	-
IMPORT	**3,330,678.27**	**5,057.97**	**8,064.90**	**5,049.64**
OFF-PEAK	1,127,792.31	1,712.67	2,730.84	1,709.85
PEAK	746,759.20	1,134.03	1,808.20	1,132.16
STANDARD	1,456,126.76	2,211.27	3,525.87	2,207.63
FIXED CHARGES	**-**	**-**	**-**	**-**
WINTER	**1,122,426.38**	**1,704.52**	**2,717.84**	**1,701.71**
EXPORT	**-**	**-**	**-**	**-**
OFF-PEAK	-	-	-	-
PEAK	-	-	-	-
STANDARD	-	-	-	-
IMPORT	**1,122,426.38**	**1,704.52**	**2,717.84**	**1,701.71**
OFF-PEAK	404,075.76	613.63	978.43	612.62
PEAK	203,975.45	309.76	493.91	309.25
STANDARD	514,375.17	781.13	1,245.51	779.84
FIXED CHARGES	**-**	**-**	**-**	**-**
Imports	4,453,104.65	6,762.48	10,782.75	6,751.35
Exports	-	-	-	-
Fixed Charges		-	-	-

Table 7-2: Annual cost of energy consumption of individual microgrids with PV plants and without BESS

SEASON/ ENERGY DIRECTION	**Energy (kWh)**	**Johannesburg (1000xR)**	**Cape Town (1000xR)**	**Durban (1000xR)**
SUMMER	**(2,460,988.45)**	**1,235.95**	**1,654.82**	**365.92**
EXPORT	**(4,049,326.51)**	**(1,899.54)**	**-2,774.19**	**(2,997.31)**
OFF-PEAK	(902,125.19)	(423.19)	-618.05	(667.75)
PEAK	(545,713.11)	(255.99)	-373.87	(403.94)
STANDARD	(2,601,488.22)	(1,220.36)	-1,782.28	(1,925.62)
IMPORT	**1,588,338.06**	**1,727.50**	**3,846.00**	**2,408.08**
OFF-PEAK	750,802.13	671.82	1,817.99	1,138.29
PEAK	343,254.47	493.53	831.16	520.41
STANDARD	494,281.46	562.15	1,196.85	749.38
FIXED CHARGES		**1,408.00**	**583.01**	**955.15**
WINTER	**285,938.77**	**1,390.76**	**1,580.19**	**1,061.79**
EXPORT	**(399,400.38)**	**(187.36)**	**-273.63**	**(295.64)**
OFF-PEAK	(93,291.29)	(43.76)	-63.91	(69.05)
PEAK	(2,385.61)	(1.12)	-1.63	(1.77)
STANDARD	(303,723.48)	(142.48)	-208.08	(224.82)
IMPORT	**685,339.15**	**1,108.79**	**1,659.48**	**1,039.04**
OFF-PEAK	311,135.31	297.48	753.38	471.71
PEAK	155,809.26	515.39	377.28	236.22
STANDARD	218,394.59	295.92	528.82	331.11
FIXED CHARGES		**469.33**	**194.34**	**318.38**
Imports	2,273,677.21	2,836.28	5,505.48	3,447.12
Exports	(4,448,726.90)	(2,086.90)	(3,047.82)	(3,292.95)
Fixed Charges		1,877.33	777.35	1,273.54

Table 7-3: Annual cost of energy consumption of individual microgrids with PV plants and BESS

SEASON/ ENERGY DIRECTION	**Energy (kWh)**	**Johannesburg (1000xR)**	**Cape Town (1000xR)**	**Durban (1000xR)**
SUMMER	**(1,881,119.96)**	**1,100.28**	**1,044.21**	**344.75**
EXPORT	**(2,888,983.52)**	**(1,355.22)**	**-1,979.24**	**(2,138.43)**
OFF-PEAK	(636,146.18)	(298.42)	-435.82	(470.88)
PEAK	(498,310.72)	(233.76)	-341.39	(368.85)
STANDARD	(1,754,526.63)	(823.05)	-1,202.03	(1,298.70)
IMPORT	**1,007,863.56**	**1,047.50**	**2,440.44**	**1,528.02**
OFF-PEAK	577,946.89	517.15	1,399.44	876.23
PEAK	137,809.67	198.14	333.69	208.93
STANDARD	292,107.01	332.21	707.31	442.86
FIXED CHARGES	**-**	**1,408.00**	**583.01**	**955.15**
WINTER	**51,226.90**	**970.82**	**1,009.04**	**704.68**
EXPORT	**(397,776.31)**	**(186.60)**	**-272.52**	**(294.43)**
OFF-PEAK	(92,856.77)	(43.56)	-63.62	(68.73)
PEAK	(2,384.52)	(1.12)	-1.63	(1.77)
STANDARD	(302,535.02)	(141.92)	-207.27	(223.94)
IMPORT	**449,003.21**	**688.09**	**1,087.22**	**680.73**
OFF-PEAK	235,888.34	225.53	571.18	357.63
PEAK	88,991.75	294.37	215.48	134.92
STANDARD	124,123.12	168.19	300.55	188.18
FIXED CHARGES	**-**	**469.33**	**194.34**	**318.38**
Imports	1,456,866.77	1,735.59	3,527.66	2,208.76
Exports	(3,286,759.83)	(1,541.82)	(2,251.76)	(2,432.86)
Fixed Charges		1,877.33	777.35	1,273.54

Table 7-4: Annual cost of energy consumption of individual microgrids with PV plants and BESS

SEASON/ ENERGY DIRECTION	Energy (kWh)	Johannesburg (1000xR)	Cape Town (1000xR)	Durban (1000xR)
SUMMER	**(1,316,929.24)**	**398.90**	**1,928.45**	**292.47**
EXPORT	**(2,946,105.36)**	**(1,382.02)**	**-2,018.38**	**(2,180.71)**
OFF-PEAK	(658,268.24)	(308.79)	-450.98	(487.25)
PEAK	(373,111.37)	(175.03)	-255.62	(276.18)
STANDARD	(1,914,725.75)	(898.20)	-1,311.78	(1,417.28)
IMPORT	**1,629,176.12**	**1,776.23**	**3,944.89**	**2,469.99**
OFF-PEAK	759,827.00	679.89	1,839.85	1,151.97
PEAK	358,155.41	514.96	867.24	543.00
STANDARD	511,193.71	581.38	1,237.80	775.02
FIXED CHARGES		**4.69**	**1.94**	**3.18**
WINTER	**451,327.70**	**1,041.14**	**1,551.60**	**890.03**
EXPORT	**(263,842.25)**	**(123.77)**	**-180.76**	**(195.30)**
OFF-PEAK	(62,618.79)	(29.37)	-42.90	(46.35)
PEAK	(776.10)	(0.36)	-0.53	(0.57)
STANDARD	(200,447.36)	(94.03)	-137.33	(148.37)
IMPORT	**715,169.95**	**1,163.34**	**1,731.71**	**1,084.27**
OFF-PEAK	317,374.37	303.44	768.49	481.17
PEAK	164,320.97	543.54	397.89	249.13
STANDARD	233,474.61	316.36	565.34	353.97
FIXED CHARGES		**1.56**	**0.65**	**1.06**
Imports	2,344,346.06	2,939.57	5,676.60	3,554.26
Exports	(3,209,947.61)	(1,505.79)	(2,199.14)	(2,376.00)
Fixed Charges		6.26	2.59	4.25

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