Matching renewable energy to the South African electricity system

by
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Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering (Mechanical) in the Faculty of Engineering at Stellenbosch University

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April 2019

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ABSTRACT

In 1998, the signing of the white paper on Energy Policy pushed South Africa to invest in the development of renewable energy. Following the introduction of the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), the country saw a sharp increase in the production of renewable energy investments. As a result, targets have been set to generate 15 GW out of a total of 74 GW renewable electricity by 2027. Similarly, according to the Department of Energy, by 2050 wind and solar PV are expected to produce more than 50 GW, which is more than 60 % of the projected national demand. These targets are highly ambitious given that by the end of 2018, the renewable energy contribution to the grid was less than 3 % nationally.

Despite its present success with renewable energy, South Africa still lags behind countries such as Germany with regards to relative renewable energy penetration on the electricity grid. Although studies by the Council for Scientific and Industrial Research (CSIR) in South Africa show optimal cost for more than 70 % renewable generation by 2017, the current regulations in South Africa limit the renewable capacity to be added per year. With the aim of demonstrating the impact that renewable generation has on the electricity system, simulations were carried out in DigSilent's Power Factory. This is an analysis software program used for dynamic performance simulation and monitoring of power systems. Furthermore, comparisons were made to determine strategies used to match renewable energy at high penetration levels to the electrical grid in Germany, and how these can be adopted in South Africa.

The simulation results validated some of the requirements in the existing grid code document and that it is vital for renewable power plants to comply with its requirements. In addition, results in this study reveal that governmental policies play a pivotal role in encouraging connection of renewable technologies. Furthermore, the research reveals that South Africa's centralization of power supply is the main constraint in matching renewables to the grid. The research also shows that the feed-in tariff system used in Germany has been successful because it offers investors a more stable system for long term investment.

The main implications of the results are that in South Africa, there is a need to revise the regulations affecting the renewable electricity generation and engage the public in the process. Therefore, this research showed that opening the IRP draft for public consultation and releasing the IRP 2018 for public comment in 2018 is a vital step towards matching renewable energy to South Africa's electricity system.

UITTREKSEL

Die 1998 ondertekening van die witskrif rakende die energiebeleid het daartoe gelei dat Suid-Afrika al hoe meer in die ontwikkeling van hernubare energie belê het. Na aanleiding van die bekendstelling van die *Renewable Energy Independent Power Producer Procurement Program* (REIPPPP) het die land 'n skerp toename van beleggings in die opwekking van hernubare energie beleef. As gevolg hiervan was die teikens gestel om 15 GW hernubare krag opwekking van ʼn totaal van 74 GW teen 2027 te bereik. Net so, volgens die Departement van Energie, sal wind en fotovoltaïse sonkrag na verwagting meer as 50 GW produseer teen 2050, wat dan meer as 60 % van die nasionale behoefte sal wees. Hierdie teikens is baie ambisieus gegewe dat by die einde van 2018 die hernubare krag bydra tot netwerk minder as 3 % was.

Ten spyte van die huidige sukses met hernubare energie volg Suid-Afrika steeds lande soos Duitsland agterna met betrekking tot die relatiewe hernubare energie penetrasie binne die elektrisiteitsnetwerk. Alhoewel studies deur die Wetenskap- en Nywerheid Navorsingsraad (WNNR) wys dat optimale kostes bereik kon word by meer as 70 % hernubare energie opwekking teen 2017, beperk huidige regulasies in Suid-Afrika die jaarlikse toevoeging van hernubare energie kapasiteit.

In hierdie navorsing is simulasies in DigSilent's PowerFactory uitgevoer om die impak van hernubare energie opwekking op die Suid-Afrikaanse elektrisiteitsnetwerk te demonstreer. Dit is ʼn analise programmatuur vir dinamiese gedragssimulasies en monitering van krag stelsels. Vergelykings tussen die Suid-Afrikaanse en Duitse gevalle word gemaak om strategieë wat gebruik word om hernubare energie teen hoë penetrasie vlakke in Duitsland toe te pas, te ondersoek en te bepaal hoe en of dit in Suid-Afrika toegepas kan word.

Die simulasie resultate bevestig sommige van die vereistes in die bestaande netwerkkode en dat dit noodsaaklik is vir hernubare kragsentrales om aan sy vereistes te voldoen. Verdere resultate in hierdie studie dui daarop dat regeringsbeleid 'n deurslaggewende rol speel ter ondersteuning tot die toevoeging van hernubare tegnologieë tot die netwerk. Die navorsing toon ook dat die sentralisering van elektrisiteitsvoorsiening in Suid-Afrika die grootste beperking is wat die toevoeging van volhoubare kragbronne aan die netwerk teenstaan. Nog ʻn bevinding is dat die invoer tarief in Duitsland suksesvol was in die opsig dat dit beleggers 'n meer stabiele stelsel vir 'n lang termyn belegging bied.

Die belangrikste implikasies van hierdie resultate is dat dit nodig is om die regulasies rakende die opwekking van hernubare elektrisiteit in Suid-Afrika te hersien en die publiek in die proses te betrek. In hierdie opsig kan die opening van die IRP konsep

ontwerp vir openbare konsultasie en die vrystelling van die IRP 2018 vir openbare kommentaar gedurende 2018, as belangrike stappe beaam word om hernubare energie te versoen met die kragstelsel van Suid-Afrika.

ACKNOWLEDGEMENTS

I would like to express my appreciation to the following people for their contribution to the completion of this work:

Prof. F. Dinter and Prof. T. Harms, for their being my supervisors; and for affording me the opportunity to be part of the solar energy thermal research group, STERG.

My fellow students, and friends who I met throughout my postgraduate studies who contributed directly or indirectly to this work.

Dr. A. Taylor, my former employer for affording me the opportunity to advance my studies.

My parents, for their unwavering support throughout my studies.

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NOMENCLATURE

LIST OF ABBREVIATIONS

AC	Alternating Current
CSP	Concentrated Solar Power
DG	Distributed Generation
PowerFactory	Digital Simulation and Electrical Network Power Factory
DNI	Direct Normal Irradiance
GCCA	Generation Connection Capacity Assessment
GHI	Global Horizontal Irradiance
GW	Giga Watt
HVRT	High voltage ride-through
FIT	Feed-in Tariffs
IPP	Independent Power Producer
IRP	Integrated Resource Plan
kV	Kilo Volt
LVRT	Low voltage ride-through
MVA	Mega Volt Ampere
MW	Mega Watt
PCC	Point of Common Coupling
POC	Point of Connection
PUC	Point of Utility Connection
PV	Photovoltaic
RE	Renewable Energy
REIPPPP	Renewable Independent Power Producers Procurement Program
ROCOF	Rate of Change of Frequency
RPP	Renewable Power Plants
SINTEG	*Schaufenster intelligente Energie – Digitale Agenda für die Energiewende*
TDP	Transmission Development Plan
TSO	Transmission System Operators
TWh	Tera Watt Hour
vs.	Versus

LIST OF SYMBOLS

Symbol	Description	Unit
ɳ	synchronous speed	rpm
p	number of poles in a motor or generator	
%	percentage	
LC	impedance of an inductor and capacitor connected in series	Ω
P	active power	W
Q	reactive power	var
R_1	line resistance	Ω
v_g	voltage at generator point of contact	V
ΔV	change in voltage	V
X_f	inductive voltage	V
X_t	transformer impedance	Ω

CHAPTER 1

1. INTRODUCTION

1.1. Background to Study

In 1998, South Africa began its journey to provide access to affordable energy for all its citizens (Portfolio Committee on Energy, 2018). This was accomplished through the signing of the white paper on Energy Policy that also pushed the government to prioritise renewable energy projects (Banks & Scaffler, 2006). As a result, in comparison to the existing 3.2 GW of variable generation, South Africa set ambitious targets to achieve high penetration of approximately 15 GW by 2027 as shown in Figure 1.1.

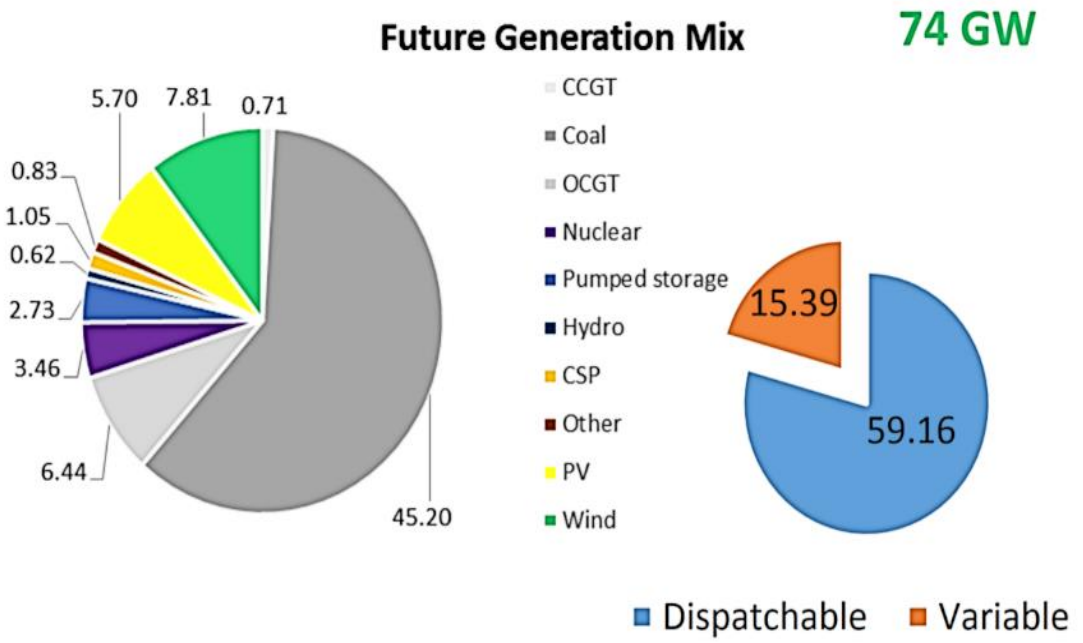


Figure 1.1: Electricity supply mix target for 2027 in gigawatts (Govender, 2017)

Apart from reducing reliance on fossil fuels and consequently reducing greenhouse gas emissions, these targets were set to increase the national electricity generation capacity. The main motivation behind high renewable penetration in the energy mix in Figure 1.1 was to ensure that by 2050, non-electrical energy loads such as the transport industry may also be supplied from energy from renewable sources. By 2050 the aim is to generate 18 GW from solar photovoltaic (PV) and 37 GW from wind (Department of Energy, 2016a). For the ten years between 1998 and 2008, investments in renewable energy sources were slow and very little was accomplished. However, between 2008 and 2012, government policy interventions converged with market forces to drive the country towards the deployment of renewable energy technologies at a large scale.

After 2011, the country showed a sharp increase in the production of renewable energy after the request of proposals by South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP). The REIPPPP encourages contractors from the private sector to supply the national grid with electrical energy generated from renewable sources. Within four years, the REIPPPP had escalated the country into the top ten of countries with the fastest growing renewable energy investments and development (Department of Energy, 2015).

1.2. Challenges of Renewable Energy Integration

The current electricity transmission and distribution system was designed for a centralized system where coal was the major energy source. This implies that the transmission network was constructed around the coal concentrated areas. Due to the outdated nature of this electrical network infrastructure, integration of new generation capacity raises many technical challenges. For example, , despite the fact that studies by Wright *et al*. (2017) show the lowest cost for more than 70 % renewable penetration by 2017, the restrictions on the infrastructure have resulted in limits on the amount of renewable energy which can be added to the electrical network per year (Department of Energy, 2016a; Thopil *et al.*, 2018).

In addition, the grid connection code for renewable power plants connected to the electricity transmission or distribution system (grid code), has been developed to outline the technical requirements for connections to the grid (Eskom, 2012). The grid code requirements are in relation to the strength of the power network. Unfortunately, renewable resources such as solar and wind are more dispersed across the country (Kost *et al.,* 2017). Therefore, to optimize the integration of renewable energy, the existing electrical network infrastructure will need to be altered significantly to cater for the renewable power plants (World Wildlife Fund, 2014).

The technical risks associated with the integration of renewable generation to support Eskom, South Africa's power utility, is currently under heavy debate (Wright *et al*., 2017). In South Africa, while the integration of RE technologies, mostly photovoltaic (PV) and wind may be growing, the inherently intermittent nature of these sources poses a threat on the reliability of electricity generation. At present, assuming no occurrence of unusual cloud cover, only concentrating solar power (CSP) with storage can manage dispatchability, whenever electricity is needed within a 24-hour charge and discharge cycle.

Moreover, because electrical network infrastructure will vary with regions, matching renewable energy with Eskom's electricity network is necessary to ensure that not only is demand met but also, the new power plants will be integrated to the grid at the correct frequency and voltage.

1.3. Research Objectives

The main aim of this study is to show how renewable energy generation can be incorporated without compromising the integrity of the South African electricity grid. Given enough financial investments, according to GreenCape (2017), 70 % renewable energy penetration is realizable within the next few years. However, this research will focus on the technical feasibility of increasing the integration of mainly wind, CSP and solar PV power plants to the electrical grid. The research will also aim to achieve the following:

1. Demonstrate the impact on an electricity network, of integrating renewable energy technologies such as solar PV, CSP, and wind into an electricity system. The aim will be to show how network performance can be affected by these technologies.

2. Conduct simulations in PowerFactory (DigSilent, 2017) using existing wind and solar generator models. By characterizing renewable energy matching strategies, the simulations will validate the impacts uncovered in literature.

3. Determine strategies used to match renewable energy generation to the electricity supply in a selected country with high renewable energy penetration. Hence, investigate if any of these strategies can applied to the South African electricity system to increase grid support and penetration of renewable energy.

1.4. Report Structure

Chapter 1 includes a background to the challenges facing renewable energy integration in South Africa. The work includes an introduction to the research objectives and the South African power supply network. Finally, this chapter also includes the scope of the project and the expected result of the project.

Chapter 2 covers the relevant literature around the scope of this research. It provides a framework for South African electricity grid. The discussion centres mainly on the existing network infrastructure, availability of resources and potential for using renewable energy generation in South Africa.

Chapter 3 presents a case study on Germany, a country with 100 % renewable energy penetration in some areas. The aim here is to identify the technical challenges faced in matching the renewable energy to the respective electricity supply system and how they were resolved. A list of some requirements for integration of renewable technologies is then derived.

Chapter 4 will consider the information presented in chapters 2 and 3 and compare the two systems. Based on this, recommendations will be made on how to match renewables to the current South African system more effectively.

Chapter 5 gives a brief description of the South African grid code laws to which renewable power plants are required to comply before they can be connected to the electricity network. Furthermore, an analysis of grid codes from Germany, United States of America and China is carried out to create a framework for the simulations to be carried out in chapter 6.

Chapter 6 involves the simulation of a simplified model of an electricity network, in PowerFactory (DigSilent, 2017). By applying some of the theories discussed in chapters 2 to 4. Comparisons are made to determine how the integration of renewable energy generators affect the electricity system.

Chapter 7 concludes the research findings. The level to which the research objectives have been met is also validated.

Appendix A provides extracts of some technical documents for PowerFactory and appendix B gives a summary of some regulations which influence renewable energy in Germany and in South Africa. Finally, appendix C provides some of the data used for the simulation model.

CHAPTER 2

2. SOUTH AFRICA'S ELECTRICITY SYSTEM DESIGN

2.1. Power Generation Overview

2.1.1. Electricity network topology

High renewable energy penetration has been said to result in grid instability unless the grid infrastructure is upgraded. The main challenge faced by the utility is constantly refurbishing the existing electrical network infrastructure and ensuring that the incorporated generators and loads match the acceptable power quality levels (Ramdhin, 2014). Where there is evidence that the integrity of the grid will not be compromised, the independent power producer, (IPP) can choose to decommission or build new sections of the electrical network as required (Barday, 2016). While the constraints around instability may be disapproved or corrected using various control technologies, the current grid infrastructure in South Africa will require significant modification to enable connection of the projected capacity for 2050 (Department of Energy, 2016a). In general, the electricity network chain in South Africa will typically consist of Transmission Networks which are used to transport electricity over long distances and Distribution Networks which are designed to deliver electricity to the consumers.

The transmission and distribution networks consist of sections, each operating at a specific nominal voltage and separated by transformers. Table 2.1. shows the lengths and operational voltages of the electrical networks in South Africa

Table 2.1: Operational voltages in South Africa

Electricity system	Voltage Level	Network Length (km)
Transmission	33 kV – 765 kV	27 770
Distribution	< 33 kV	325 000

From the daunting lengths of networks shown in Table 2.1 above, it can be observed that the modification costs of the grid to accommodate renewables is likely prohibitive. In South Africa, renewable energy technologies are connected to either the distribution or transmission networks. This report focuses on transmission network connected power plants.

2.1.2. Limitations in the connection of distributed generation

In Europe, the main motivation for construction of transmission lines until 2050 is to enable access to areas where the wind and solar resource are abundant. These areas are often located far from the load centres, where the outputs from the power stations are dispatched depending on demand (Fursch *et al.*, 2013). While the construction of a wind or Concentrated Solar Sower (CSP), plant will take approximately two to three years, upgrading the electrical network will take a period of seven to ten years (World Wildlife Fund, 2014).

In general, due to the relatively short private industry driven installation times required for renewable technologies, a rapid increase in the deployment of this distributed generation can be expected. However, this could then result in integration challenges on the existing, slow developing infrastructure (De Sisternes, 2014). Before approval of a new connection to the grid, network studies are carried out using specialized computer software packages. The main objective of the network studies, carried out prior to the approval of new connections, is to evaluate the new connection's impact on the network and to determine whether there are any network planning criteria exceeded. The network criteria with which new power plants will need to be compliant in South Africa, are explained in more detail in Chapter 3.

Studies carried out by Mushwana (2014) determined the available capacity by considering various power system conditions. The study considered both transient and steady state power system conditions. The result was that, further transmission and distribution network upgrades will be necessary to accommodate addition of renewable plants to the network. In 2017, approximately 500 MW CSP, 3 300 MW wind and 2 400 MW solar photovoltaic (PV) had been approved by the Department of Energy for independent power producers. According to World Wildlife Fund (2015), the bid windows 1 to 4 in REIPPPP had used up most of the extra grid capacity, although more than 30 000 MVA or 6799 km of new transmission lines had been constructed since 2005. This reinforces the need for further construction of transmissions lines, protection systems and transformer substations (Govender, 2017).

Historically, the South African Electricity grid was constructed to get power from Mpumalanga, a coal rich area to other areas (Thopil *et al.*, 2018). Figure 2.1 shows most of the transmission network routing is around the coal power plants.

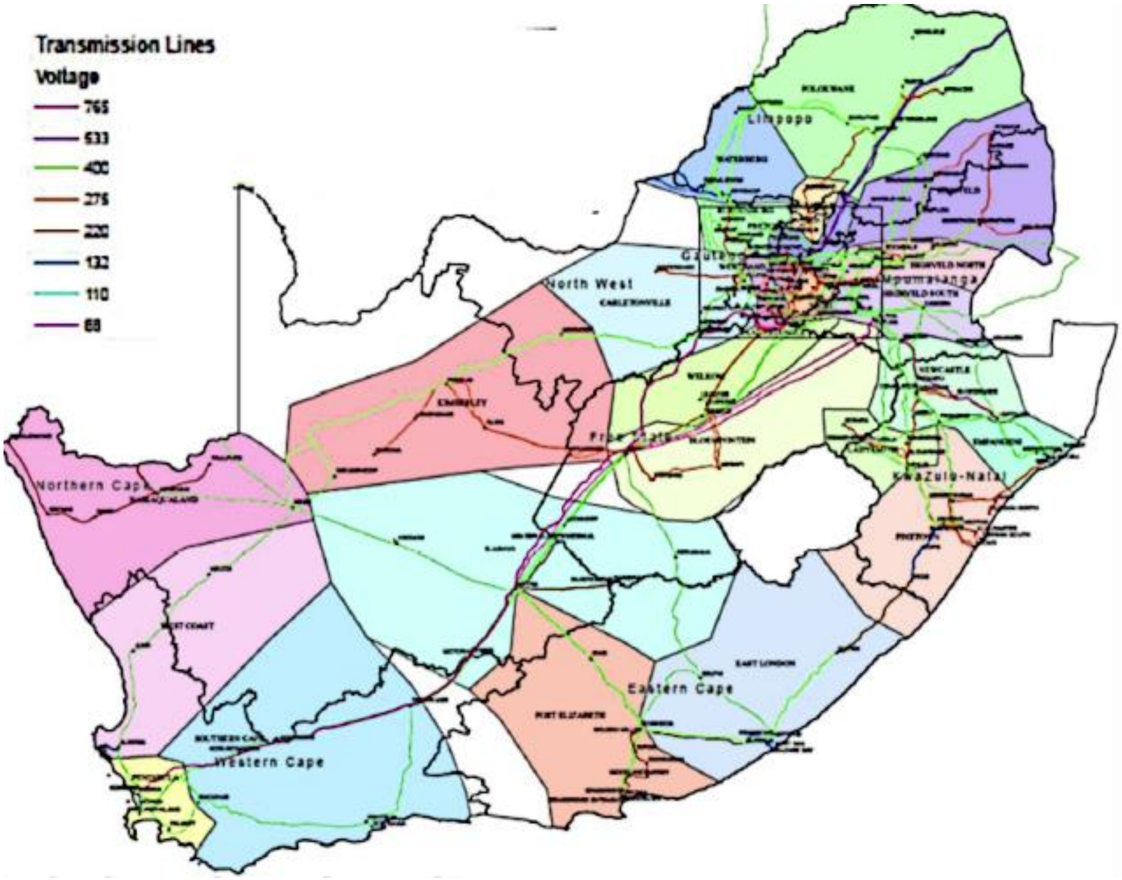


Figure 2.1: South Africa: Eskom main transmission system (World Wildlife Fund, 2014)

The transmission network shows that coal deposits are concentrated to a specific area. Meanwhile, renewable resources for example, wind and solar are more dispersed across the country. Given that most of solar and wind power plants would be best located in the eastern, northern and western Cape provinces, the existing infrastructure would need significant modification to cater for the renewable power plants (World Wildlife Fund, 2014).

The electrical system's ability to match the demand by controlling the generation units is dependent on the system frequency. While other international electrical systems run at 60 Hz, the nominal frequency of the electrical network in South Africa is 50 Hz. The grid standard frequency is used as an indication of demand. This means that if the frequency drops, the power generators must supply more and vice versa.

Eskom transmits alternating current which constantly changes direction. Frequency is a measure of how often the generator rotor and hence the current changes direction, between positive and negative, in a second.

Therefore, 50 Hz means the generator rotor turns 50 cycles per second. The allowable deviation from the standard frequency on the South African electricity grid is 0.5 Hz. Equation 2.1 and equation 2.2 are the governing formulae for synchronous speed (n) and horsepower (HP) of a three-phase motor or generator respectively.

$$n\ (rpm) = \frac{120 \times frequency\ (Hz)}{p} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ Equation 2.1}$$

$$P\ (watts) = \frac{\mathrm{n} \times torque}{9.54} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ Equation 2.2}$$

Where p represents the number of poles on a motor or generator and 5252 is the number of radians per second. Given that motors are constant torque machines, by applying the equation for horsepower, it can be observed that running for example 50 Hz rated machine at 60 Hz would produce 20 % more horsepower. To produce rated torque at a different frequency, the supply voltage would also need to be adjusted because the voltage to frequency ratio needs to remain constant. Hence the frequency tolerance needs to be adhered to.

Furthermore, grid frequency variations result in reduced system efficiency when generators are run outside their rated rotational frequency. When the frequency increases, because the generators assume demand has reduced and therefore, reduce their supply to meet the reduced demand. In this case the capacitances are reduced, and the inductances of the transmission electrical equipment increase. Therefore, if frequency is too low there is an increase in system losses. Consequently, reducing the efficiency transmission lines. According to Eskom Generation Communication (2017) in South Africa, if the frequency falls below a certain level, automatic load shedding will occur. Frequency is therefore, a vital consideration in the connection of power plants from intermittent sources to the grid as these technologies may result in variations in the system frequency.

Similarly, the control of system voltage levels has a significant role in maintaining the quality and security of supply. The aim is to maintain the system voltage as close as possible to the nominal values. Power fed in from distributed generation (DG) directly connected to the grid tends to increase voltage levels in a region.

2.1.3. Summary

The transmission network in South Africa was originally designed for a centralized electricity sector. However, to encourage efficient use of resources, where extra capacity is available connection of distributed generation must be encouraged. Network planning around the integration of new renewable generation capacity must be designed not only to increase the grid power supply but also to promote upgrade of infrastructure.

The electricity network infrastructure can be extended or reinforced to cater for the changes in demand and generation. To appropriate the existing network to the increasing demand and generation, network planning will often involve upgrading, refurbishment and decommission of some parts of the infrastructure. This report will investigate some of the current changes being made in the infrastructure through the Transmission Development Plan (TDP).

2.2. Demand-Supply Matching Strategies

In recent years, the Integrated Resource Plan (IRP), a long-term guide to the expansion of the electricity supply, has gained significance in the South African context. This is a result of its goals to improve security of energy supply and to prevent the continuously increasing carbon emissions and prices of fuel. The IRP 2010-30 is being revised by the Department of Energy, DOE in a move towards a more diverse electricity supply mix and reduced carbon emissions by introducing new power plant. In South Africa, demand has exceeded supply since 2008. Generation from renewable energy sources has been promoted through a competitive auction called the Renewable Independent Power Producers Procurement Programme (REIPPPP).

In the REIPPPP program, contractors from the private sector are invited to supply the national grid with electrical energy generated from renewable sources. This has resulted in South Africa getting renewable energy at some of the lowest tariffs in the world since the announcement of the first bid window in December 2011. The average tariff requested across all the technologies was 2.52 R/kWh initially. This had reduced significantly by the fourth bid window to 0.86 R/kWh by April 2016 (Department of Energy, 2016b; Portfolio Committee on Energy, 2018). Other countries, for example Germany, have recently also switched to a similar competitive bidding process (Federal Ministry for Economic Affairs and Energy, 2018).

According to World Wildlife Fund (2015), the bid windows 1 to 4 in REIPPPP have used up most of the extra grid capacity. In an effort to accommodate the increasing demand and new power plants being constructed across the country, approximately 5

000 km of transmission lines have been installed since 2005. This translates to about 24 000 MVA extra supply capacity to meet the ever-increasing electricity demand and consequently, accommodate Eskom's new power plants. Some of the newly built power plants by Eskom in the recent years are summarized in Table 2.2.

Table 2.2: New build projects (Eskom Generation Communication Department, 2013)

Project	Number of units	Fully synchronized commission target
Medupi (full commission 2020)	6	4 764 MW
Kusile (full commission 2022)	6	4 800 MW
Drakensberg pumped storage	4	1 000 MW
Ingula (full commission 2017)	4	1 332 MW

Since the commissioning of some of the units in Table 2.2, an improvement has been seen in the ability of South Africa's power generation to meet the demand. Figure 2.2 shows 33 % contribution expected from renewables compared to 29 % of new coal power plants.

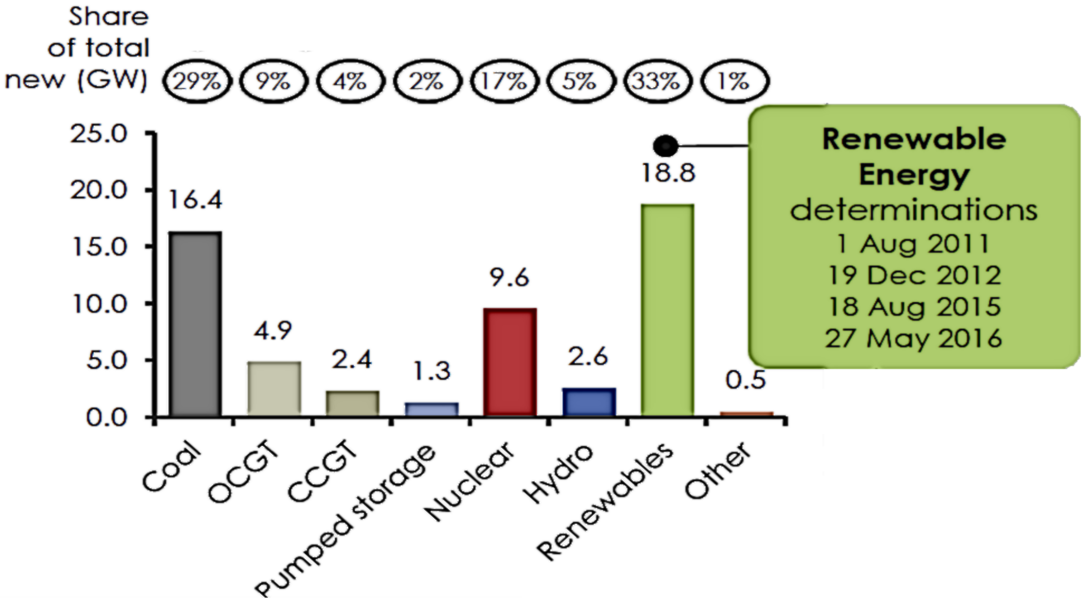


Figure 2.2: New builds in the diversified energy mix (Department of Energy, 2016b)

It can be observed from Figure 2.2 that a relatively high contribution to the energy mix is expected to be from nuclear. However, renewable energy was still expected to be the main contributor to the New Build Program for electricity supply by 2016. 9 600 MW new build for nuclear was approved in December 2015 (Prins, 2018). However, besides having minimal effect on the environment, technologies such as solar and wind are relatively favourable because they require a shorter construction period and the power plant designs can be more modular. According to Department of Energy (2016a), a diversified energy mix is one of the strategic objectives have been put in place to ensure energy security. The other objectives include increasing competition between IPPs in the energy sector and review and planning to expand electrical infrastructure.

It should be noted that the amount of solar and wind capacity allowed to be added in each year is limited (Department of Energy, 2016a). It is therefore, vital to uncover the reasons for these limits, whether they are economical or technical. This research focuses mainly on disclosing the technical hurdles, which may hinder the increase in penetration of renewable generation as part of the South African Electricity system.

2.3. Integration of Renewable Energy Systems

The main objective for the REIPPPP is to secure energy from the private sector. Therefore, alleviating the shortfall in electrical energy supply. The retail electricity market has been open to the private sector since 2009 to increase security of supply. On the supply side, plans have been put in place to procure additional renewable energy capacity and the decommission of the existing plants (Department of Energy, 2016b). However, for this report the discussion around the power plants that will be decommissioned or phased out was neglected. In the determining the new capacity for renewable energy power plants, it is vital to consider both the increasing demand and the decommissioning of the existing plants. The integrated resource plan will contain schedules for the decommissioning and commissioning of projects (Wright *et al.*, 2017). According to the IRP 2018 the wind capacity procured under the first bid window of REIPPPP will be decommissioned by 2015 and approximately 1 GW of solar PV by 2040 (Department of Energy, 2018).

While an unlimited capacity for renewable energy generation would be attractive for the increasing the renewable energy penetration in the electrical energy mix, it is more cost optimal for the increase to be a gradual process. When there is too much generation from solar and wind, there is a risk of running into curtailment. In such cases, storage becomes a plausible solution in integration of renewables to the electricity system.

A good example is CSP technology, which can be adapted to deliver dispatchable electricity when needed. It should be noted that CSP is comparable to base load power plants such as coal and nuclear fired plants provided spatial distribution and stable climate conditions are favourable to such deployment. CSP is a mature technology, however, South Africa its deployment is not yet fully established (Gauche, 2016; Hilton and Marquard, 2011).

During a fault condition, generators connected to the grid are required to support the grid and not disconnect (Eskom, 2012). Unfortunately, due to its intermittent nature, there is a high risk that generation from non-dispatchable renewable resource may not be able to support the grid in this way (Troester, 2009). Although the frequency of the electrical grid is controlled by balancing supply and demand, sudden changes in generation or demand can result in frequency fluctuations. During a frequency fluctuation event, the system frequency will initially change at a rate of change of frequency (ROCOF) which depends on the electrical grid's inertia. Inertia is a combined property of the spinning generation and load on the grid which limits these frequency fluctuations (Gonzalez-Longatt *et al*., 2013).

Spinning generators have a strong coupling between their rotational speed and electrical frequency. As a result, their kinetic energy (inertia) dampens the ROCOF. On the other hand, both wind and solar PV are interconnected with the grid through a power electronic interface. This interface electrically decouples the generator motion from grid frequency. Therefore, wind and solar PV do not have inherent inertia. Therefore, according to Wright *et al*. (2017) and Gonzalez-Longatt *et al*. (2013) grid integration, at high penetration levels, of solar PV or wind generation results in the displacement of conventional synchronous or spinning generators and consequently, reduces system inertia.

This means that adding a more diversified power system complicates the network control and management system. As a result, a new approach is required to network planning before the additional renewable plants can be connected.

2.4. Potential of Renewable Energy

2.4.1. Overview of the renewable energy resource

South Africa has high levels of the solar resource. Global horizontal irradiance (GHI) is the component required for solar photovoltaic (PV) projects, and direct normal irradiance (DNI) component is required for CSP. The north-western part of South Africa has an annual DNI level of approximately 3 000 kWh/m^2 while most of the country has values of more than 2 000 kWh/m^2. The wind resource in South Africa is dispersed geographically with high wind speeds around the western and eastern coastal areas. Wind speed variations are seasonal.

Based on the available resource, a study carried out by World Wildlife Fund (2015) determined some possible locations and limitations of utility scale renewable energy power plants in South Africa. The selection of areas shown in Figure 2.3 below was influenced mainly by abundance of renewable resource.

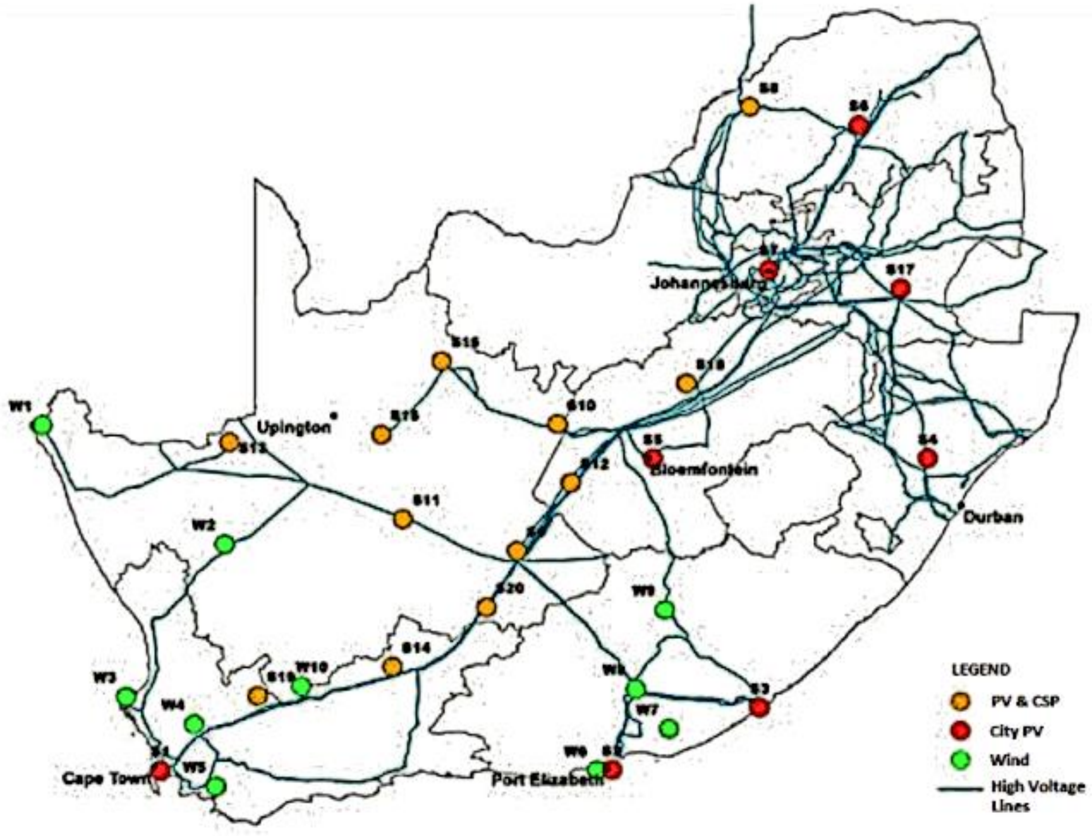


Figure 2.3: Solar and wind potentially suitable locations (World Wildlife Fund, 2015)

It can be observed in Figure 2.3 that the areas selected for most CSP and solar PV plants are between Upington and Bloemfontein, where the solar resource is more abundant in South Africa. Similarly, suitable areas for the wind plants are mostly on the coastal areas, around Cape Town and Port Elizabeth where it is relatively windy. Apart from the abundance of the renewable energy resource, potential locations were chosen near existing transmission lines close to existing Eskom substations. The main motivation for construction of a power plant near a transmission line is to reduce the costs of connecting the power plant to the grid (World Wildlife Fund, 2015) . Although the selected areas in Figure 2.3 are located close to existing Eskom substations, new capacity will still require additional substations and transmission lines.

2.4.2. Contribution of concentrated solar power to grid stability

Fluctuations in renewable resource due to events such as cloud movements or wind gusts can cause fluctuations in the local grid network. This can cause instantaneous mismatches between demand and generation. These issues can be resolved by either adjusting the design of the local transmission or distribution infrastructure or the design of the power plant. A carefully selected storage system, such as CSP thermal storage system, can also be used to correct the challenge of variability and intermittency. Concentrated solar power technology provides a flexible and fast response to energy demand (Boie *et al.,* 2016; Shultz, 2018).

CSP technology first converts solar energy to thermal energy and then finally to electrical energy. The inclusion of thermal storage enables this solar generation to be dispatch-capable instead of intermittent. Without thermal storage, a CSP generator has very little thermal inertia which lasts only several minutes (Gauche *et al.*, 2012; World Wildlife Fund, 2015). In this case it should be noted that storage is the major distinction there between photovoltaic and CSP. The main motivation for integrating storage would be for the production electricity on demand. Some studies also show that storage could resolve the challenge of reverse power flow from distributed generation (Crossland, 2014).

Although still in its early deployment stages, CSP is being implemented in South Africa with some projects designed by Eskom, for example the 100 MW plant in Upington, in the Northern Cape Province (Hilton and Marquad, 2011).

The use of a spinning synchronous generator turbine in CSP power plants adds inertia to the grid. This means, the utility is better able to manage system voltages and frequencies because CSP energy is dispatchable (Shultz, 2018). However, the dispatchability of CSP is relatively short term since it depends on thermal storage. Figure 2.4 shows results from tests carried out on a concentrated solar power plant in located Spain. The blue bar graph shows the planned output while the green bar graph shows the plant's actual output.

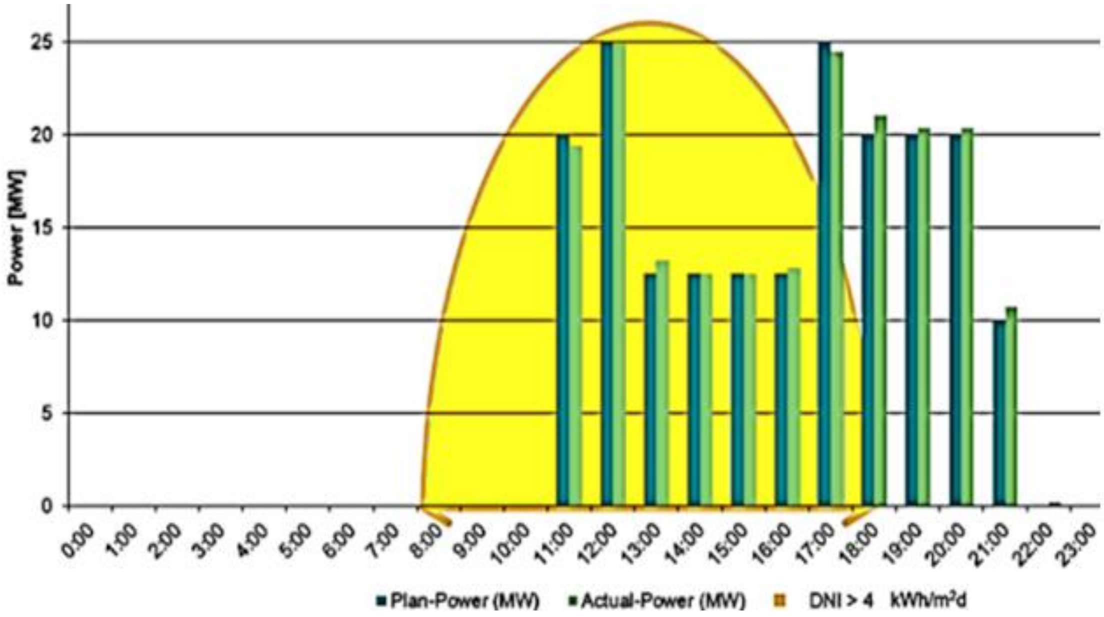


Figure 2.4: Dispatchability results for concentrated solar plant (Dinter and Mayorga, 2014)

It can be observed from Figure 2.4 that the actual power matches the planned power very closely. This can be attributed to the high responsiveness of CSP technology (Gauche *et al.*, 2012; Onwunta, 2014). During this test, ramp rates of approximately 6 MW/ min were observed. It was also observed that during daytime, up to approximately 6pm, the plant to operate on the DNI only without the use of storage (Dinter and Mayorga, 2014).

In South Africa, the REIPPPP was set up to give priority on to generation from renewable power plants. To project the potential benefits of CSP, the South African electricity system was modelled such that the electrical energy from renewable power systems is subtracted from the estimated demand value first. In this scenario, the aim is for the conventional power plants to then provide the balance of the required supply. Figure 2.5 show simulations carried out to show the effect on a conventional peaking plant of giving generation priority to wind, solar PV and CSP systems (Auret, 2015).

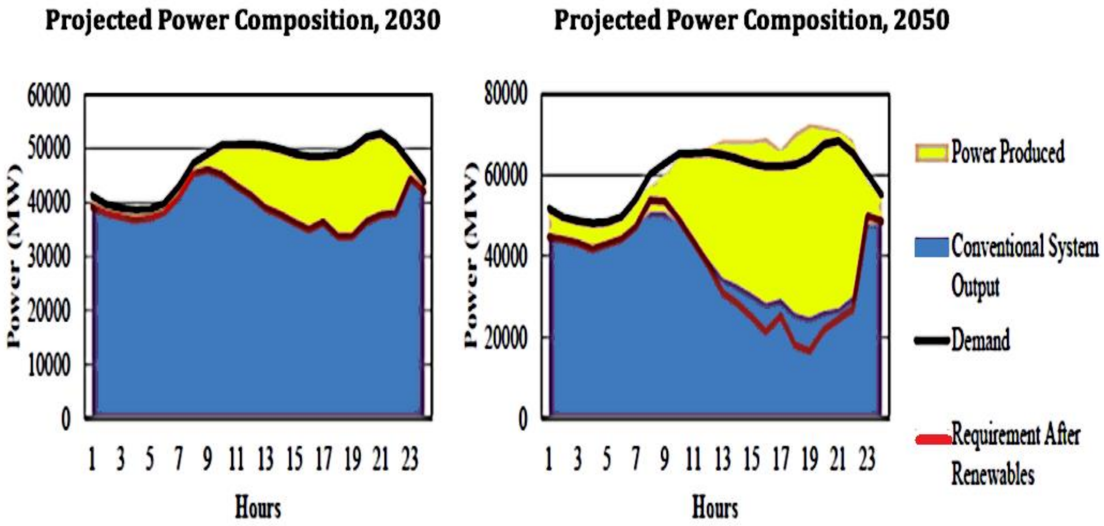


Figure 2.5: Effect on peaking plant using annual averaged demand curves by hour (Auret, 2015)

From Figure 2.5, it can be observed that by including the projected renewable capacity, on a priority basis, into the power supply composition, there is a large contribution from renewables between 3 pm and 10 pm. Between 9 pm and 12 am, the demand falls significantly as shown by the steep gradient. It can be observed that the CSP output ramps down very fast in a short period to match the supply to the demand. As a result, the requirements on conventional peaking power plants, to ramp up or ramp down output, are reduced by a significant amount.

In addition, giving priority to renewable power plants also results in conventional base load power plants running at a lower capacity factor. Generation from fossil fuels can therefore be used for matching demand to supply (Boie *et al.*, 2016). Therefore, from the perspective of the electricity network, the main benefits of CSP with storage are the following (Dinter and Mayorga, 2014):

- The supply challenge of intermittent generation is eliminated by the inclusion storage.
- Power generation can be shifted from periods of low demand to periods of peak demand.
- Power quality support is made possible using synchronous generators.
- Just like the typical fossil fuel generators, CSP plants can provide grid support for voltage or frequency by providing reactive power or reducing active power supply.

2.4.3. Benefits of wind and solar aggregation

In South Africa, solar and wind are the renewable energy sources with the largest potential. However, the intermittent nature of these sources may cause difficulties in the delivery of reliable electricity generation.

In the connection of wind generators into the electricity system, their power output affects the existing electrical network. As a result, before any new connection, advanced wind forecasting tools are necessary to determine the quality of the wind. Therefore, the location of wind power plant has potent influence on the power grid (Kolhe, 2017; Olakunle, 2018).

Aggregation of the outputs from distributed generation throughout the country will result a smooth output to the utility. It can be seen in Figure 2.6. below that increasing the number of wind farms installed (aggregation level), reduces short-term fluctuations. Hence, a more reliable output from these sources.

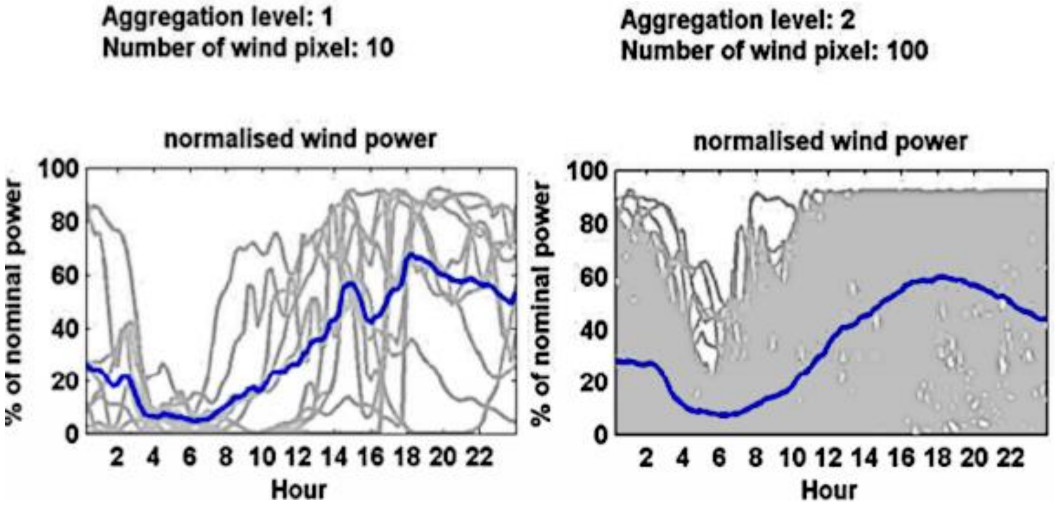


Figure 2.6: Smoothing effect from aggregation of wind farms (Bofinger *et al*., 2016)

The smoothing effect as a result aggregation is demonstrated at aggregation levels 1 and 2 in Figure 2.6. With only one wind power plant, the output fluctuates with availability of wind such that there is no power output between 5 am and 10 am. At aggregation level 1, with 10 wind farms installed, the resultant output is smoother and there is supply throughout the day. When the wind pixel is increased to 100, as shown on the graph with an aggregation level of 2, the fluctuations in the output are almost eliminated. This is a direct result of the geographical dispersion of several wind farms across the country. As a result, the net power on the grid will have minimal fluctuations.

Literature shows that the issue of seasonal variability of renewable energy sources can be addressed by geographical dispersion of several solar PV and wind farms across South Africa. Both solar PV and wind have very low seasonality in South Africa (Bofinger *et al.*, 2016; Calitz *et al.*, 2018). The climatic conditions are very diverse such that north-western part has a Desert climate, the south-western part a Mediterranean climate, while the northeast experiences a subtropical climatic condition.

2.4.4. Technical considerations for integrated resource plan 2018

The integrated resource plan 2010 to 2030 (IRP 2010-30) aimed to achieve a sustainable, affordable future energy supply with renewable comprising 18.8 GW of the new capacity. A common scheme which has been used internationally to attract the private sector is through Feed-in-tariffs, (FIT). FITs provide a warranty that that the utility will purchase the electricity at a guaranteed price (Boie, 2016; Department of Energy, 2016b; Oniemola, 2014). As a result of the IRP 2010-30, in a period of less than 2 years, the solar PV share of South Africa went up from 0 % to 2 % which is a faster pace than the United States of America -0.2 % to 0.4 %. Until recently the IRP 2010-30 remained the official plan for new generation capacity until its replacement by an updated plan which was released for public comment in August 2018.

The Integrated Energy Plan (IEP) shows that the potential to generate electricity from renewable energy is much greater than was initially planned. Although the IRP 2010-30 did not consider transmission network costs, the updated IRP aims to increase investment in the energy infrastructure (Department of Energy, 2018). This includes investments in new capacity and improvements in existing infrastructure. More specifically, the transmission network costs considered include transmission substations, collector stations and transmission lines connecting to the substations.

Having an abundant renewable energy resource in South Africa, great strides have been taken to encourage growth in renewable energy penetration into the power grid. According to the IRP 2018, in the plan up until 2030, there will be an increase in renewable energy generation. More specifically, wind will contribute 15 %, solar PV will make up 10 % and CSP will contribute 1 % (Department of Energy, 2018).

The IRP 2018 presents a least cost scenario with no limits on wind, solar PV and gas. Fortunately, regardless of the electrical grid in question, this means more renewable generation can be accommodated. According to Department of Energy (2018), the IRP 2018 neither considers the impact on transmission infrastructure for varying penetration levels per technology, nor the costs required for the system stability. However, the strength of the electrical infrastructure is of vital importance in an electrical system. While certain measures may be required to be taken for weaker grids to mitigate the negative impacts of intermittent generation on the electrical grids, the integration of wind and solar into stronger networks was found to improve the power quality of the network (Givaki, 2017; Matlokotsi, 2017).

A common wind turbine system is the doubly fed-induction generator (DFIG) wind turbine (Muhammad and Nasimullah, 2017). In a doubly-fed electrical turbine, the stator and rotor sides are separately connected to the grid as shown in Figure 2.7.

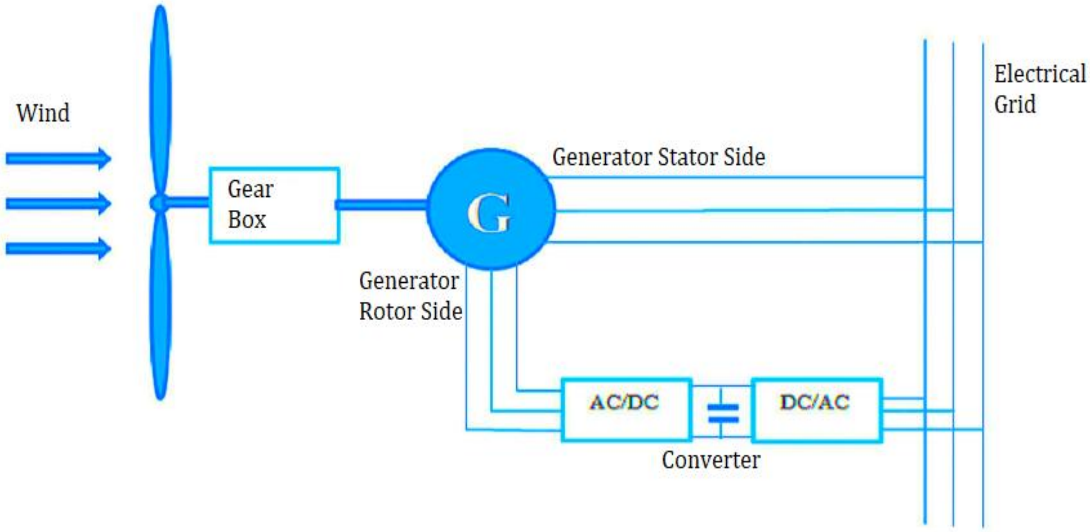


Figure 2.7: Schematic of a doubly-fed wind turbine system (Muhammad and Nasimullah, 2017)

The DFIG technology encompasses speed control which enables maximum wind energy capture and to better frequency control relative to solar PV. Figure 2.8 shows voltage magnitude improvement after connecting solar PV and DFIG wind turbine.

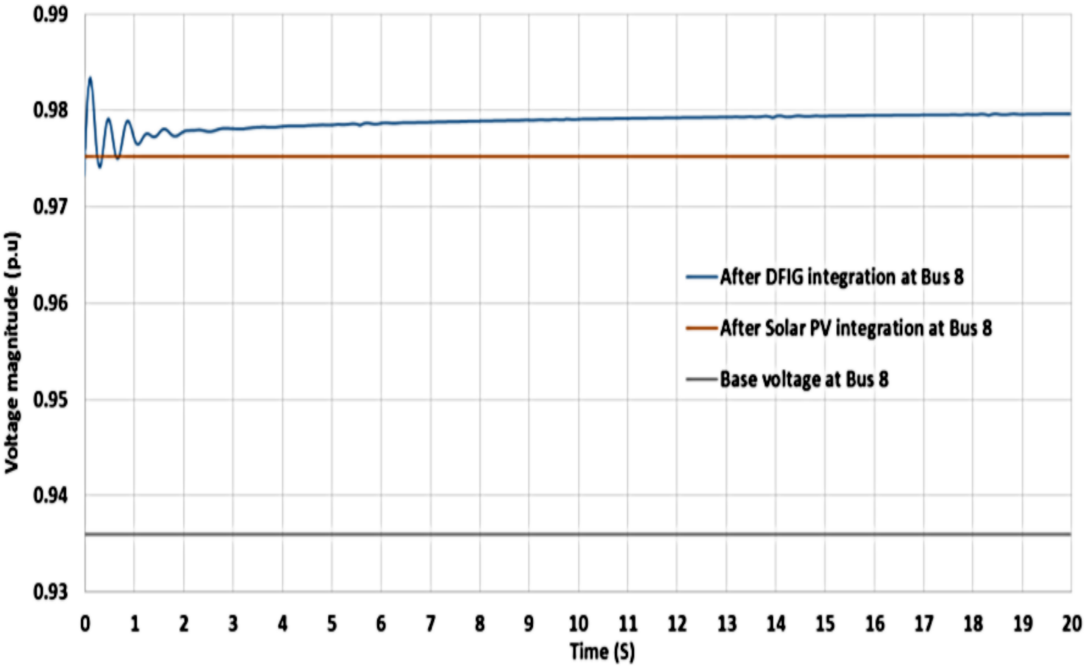


Figure 2.8: Voltage profiles on a bus after integration of solar and wind generators (Matlokotsi, 2017)

It can be observed from Figure 2.8, that the base voltage on the bus was improve by the integration of solar PV and DFIG-based wind turbine. Although solar PV improved the voltage magnitude by 3.95 %, and the wind turbine by 4.91 %, the results show that for the case study investigated by Matlokotsi (2017), integration of wind and solar improved the power quality on the bus. Therefore, in cases where there is reasonable extra capacity on the electricity network, renewable energy can be utilized to improve the quality of supply (Crossland, 2014).

2.5. Summary

In 2016, approximately 95 % electricity consumed in South Africa was generated from coal and gas (Calitz, 2017). Furthermore, according to the IRP 2018, coal will still contribute at least 65 % until the year 2013 (Department of Energy, 2018). The current procured and installed renewable energy capacity is just over 6 000 MW with a surplus peak of about 5 000 MW in the supply. In the recent past renewable energy is making major contributions to the electricity supply system with solar PV and wind being the most dominant RE technologies (Department of Energy, 2016b).

The extra available capacity on the current electrical network plan is being taken up by the new power plants builds through the REIPPPP. Therefore, to increase the penetration of renewable energy onto the national grid, investments should be made to build more substations and transmission lines (World Wildlife Fund, 2015).

While wind and solar have the greatest potential for addressing the challenges for electricity system, the intermittent nature of these sources needs to be addressed to ensure a reliable electricity supply. However, wind and solar can be used to improve the power quality of an electrical grid.

The work presented in this research will attempt to uncover the limitations in the further connection of renewables in South Africa and provide solutions on how these challenges can be overcome to ensure the 18 GW of solar PV and 37 GW of wind 2050 target can be met.

CHAPTER 3

3. THE CASE STUDY – GERMANY

3.1. The Electrical System – Germany

Germany has a decentralized electricity system which is both publicly and privately owned. The main energy regulator manages the overall grid connection access (Pinter, 2014). The electrical network in Germany comprises mostly of the low voltage lines. Table 3.1 summarizes the grid structure in Germany (Taylor, 2015).

Table 3.1: Operational voltages in Germany

Electricity system	Voltage Level	Network Length (km)
Transmission	220 kV – 380 kV	34 979
Distribution	110 kV	96 308
	10 -30 kV	509 866
	<400V	1 156 785

With a grid length of approximately 1.8 million kilometres, Germany has the most reliable electrical grid infrastructure in Europe (German-Swedish Chamber of Commerce, 2018). Network operators are under obligation to modify and reinforce their networks, bearing all costs, to accommodate new renewable energy builds. Unlike South Africa where the utility has the burden of managing the entire centralised electricity network, in Germany, network operators can afford to upgrade the electrical infrastructure as required through private investment. Network operators are under obligation to modify and reinforce their networks, bearing all costs to accommodate new renewable energy builds.

Germany offers financial incentives by simple credit checks (Oniemola, 2014). According to Boie (2016) the independent power producers, (IPPs), therefore only pay the cost for metering and for connecting to the closest grid connection point. On the other hand, in South Africa uses a different funding mechanism. When it is in the interest of both the utility and the IPP, the IPPs desiring to connect to a weak grid are approved for self-build for the required modification. Being a centralised system, the assets are then later handed over to the utility (Barday, 2016; Oniemola, 2014).

Over the years, by encouraging new builds for renewable energy and decommissioning the nuclear fleet, Germany's energy mix has evolved significantly (Kolhe, 2017). Figure 3.1 shows generation data captured on selected days in 2011 and 2012.

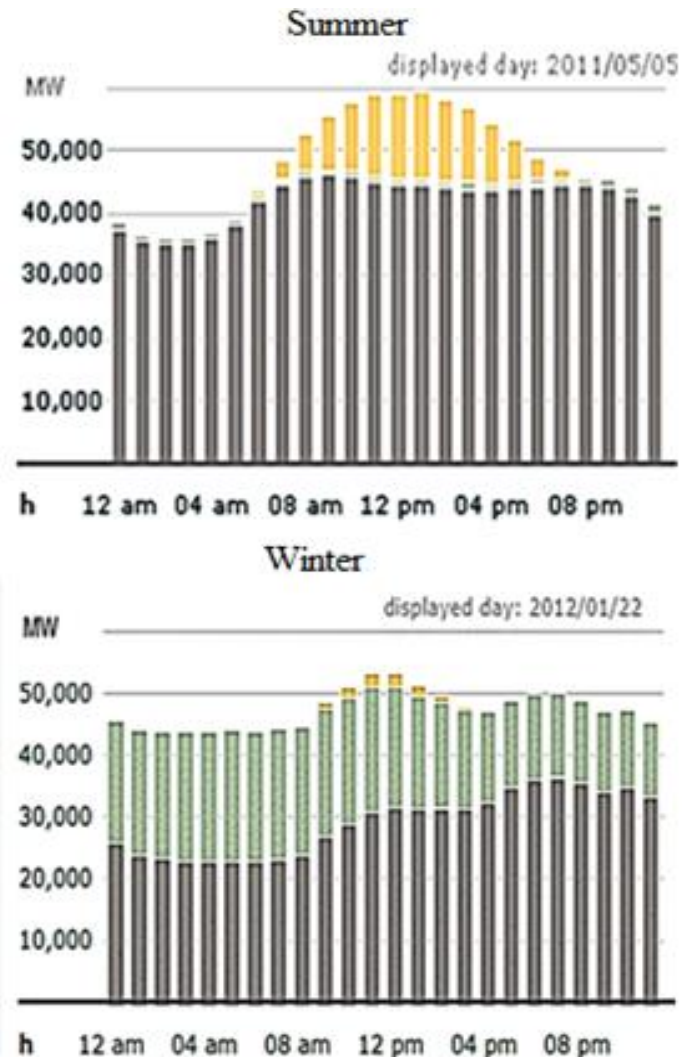


Figure 3.1: Germany energy mix: solar-yellow, wind-green and coal-grey (Simpson, 2012)

It can be observed from Figure 3.1 that because the utility no longer controls the power system in Germany, the energy regulators are able to adjust the energy supply mix to match the demand (Simpson, 2012). The flexibility of such a decentralised system enables renewable generation to be prioritized. Figure 3.2 shows that in 2017, renewable energy produced 33 % of the total generation.

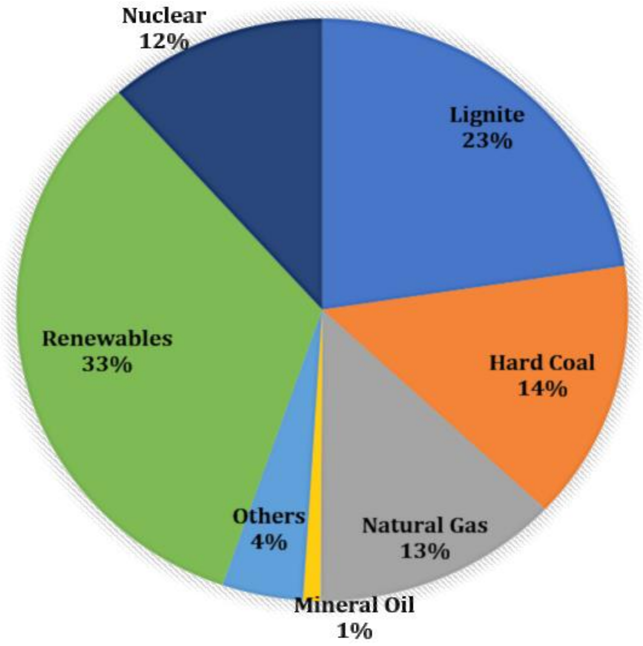


Figure 3.2: Share of energy sources in Germany power production in 2017 (Clean Energy Wire, 2018)

Evidently as observed from Figure 3.2, renewable energy electricity production in 2017 constituted more than 30 % compared to 2.9% in South Africa for the same period (Calitz *et al.*, 2018).

3.2. Strategies to Match Renewables to the Electricity System

3.2.1. Infrastructure development

Having realised at an early stage the need to decentralise the network, an investigation carried out showed 1 855 km additional length required to be built on the extra-high voltage line in Germany. The *Energiewende* is a plan that was put in place in Germany with the aim to reduce Germany's carbon footprint and to phase out nuclear generation (Clean Energy Wire, 2018). Figure 3.3 summarises the results of this plan in the recent years.

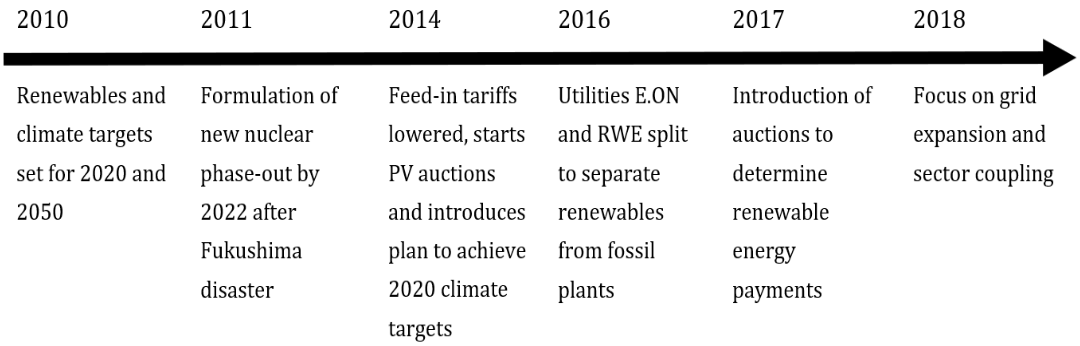


Figure 3.3: Share of energy sources (Clean Energy Wire, 2018)

It is evident from Figure 3.3 that the most recent object on Germany's energy plan is to expand the electrical grid and improve its management. The main reasons for this infrastructure development are to incorporate the decentralized electricity produced by PV. This extra length will not only enable Germany to harness more wind power from the north but also the additional capacity from the household photovoltaic in the south.

Earlier, in 2013, the distribution network also needed expansion measures mainly due to end of lifetime decommissioning of grid infrastructure. Figure 3.4 shows the planned extensions. The green indicates lines the project parts realized by early 2013, while the other colours show lines in various stages of planning (Justus, 2005; Merkel, 2014). The grid extensions were planned to be completed by 2022 with the decommissioning of the last nuclear plants.

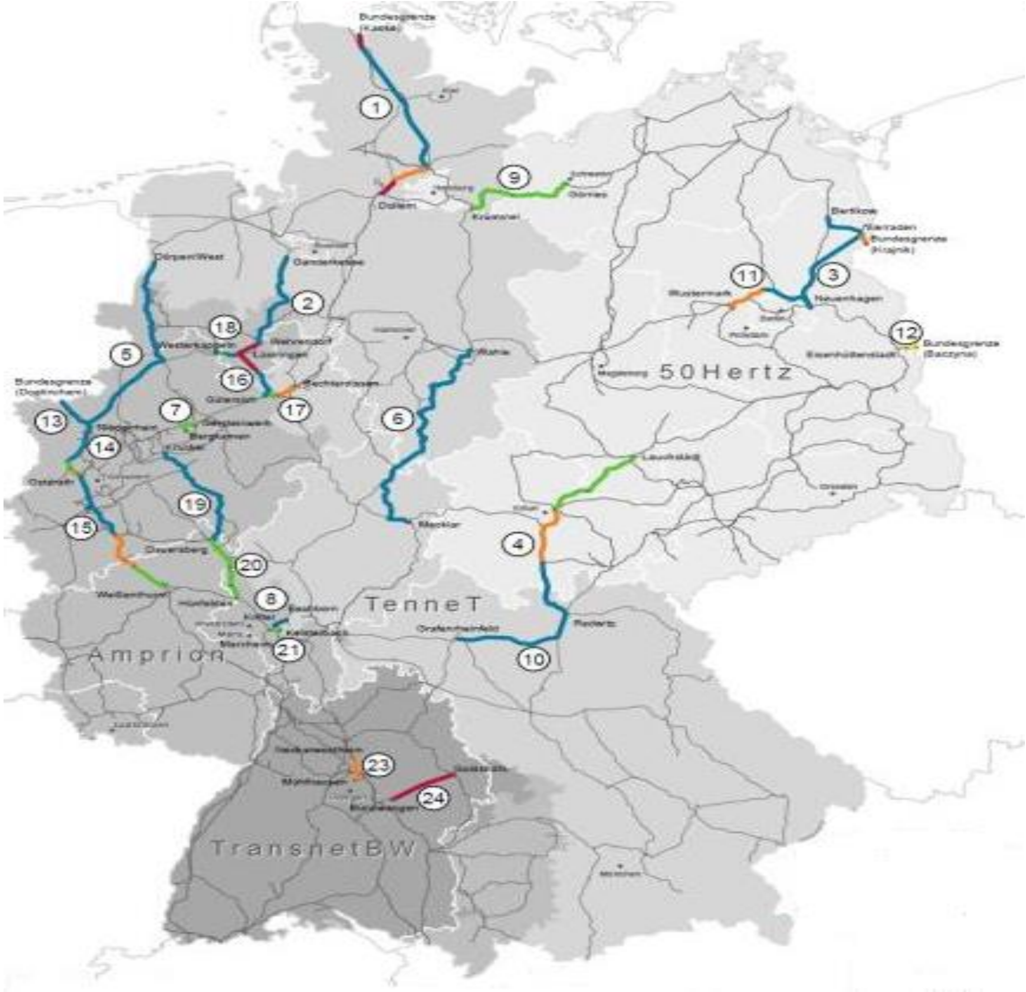


Figure 3.4: Grid extension power lines to achieve 2022 renewable energy target (Taylor, 2015)

Unfortunately, in recent years, there was public resistance to the electricity system expansion. As a result, progress has been delayed and only approximately 10 % of the target have been built (Agora Energiewende, 2018). Agora Energiewende (2018) recommends that in order to reach the planned targets, the revision of network expansion should be planned for 2050 rather than planning every two years.

Figure 3.5 shows part of the energy plan with overhead and underground electrical power lines planned for 2025. According to Agora Energiewende (2018), the network development plan for 2050 is already decided, but it eliminates new overhead lines.

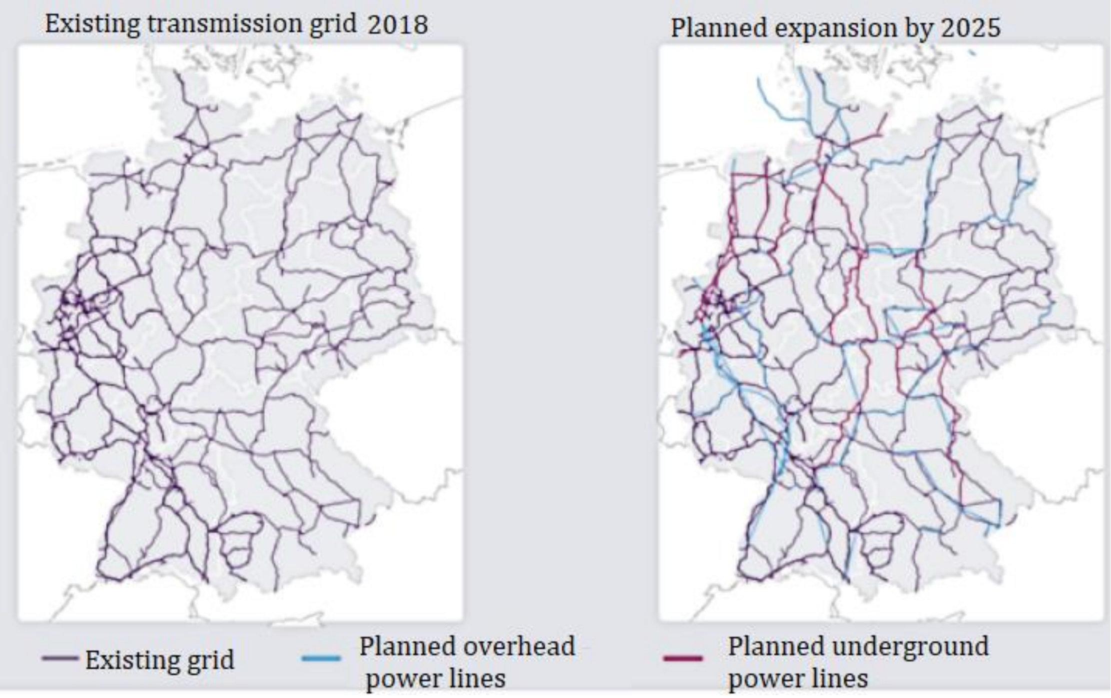


Figure 3.5: Existing grid 2018, and planned expansion by 2025 (Agora Energiewende, 2018)

The main aim of expanding grid infrastructure is to enable more renewable plants to be connected to the grid. However, smarter grids result in minimum upgrade requirements and consequently save on costs and reduce downtime (Agora Energiewende, 2018). As a result, research has been carried out which shows that by adjusting active power fed in by generating systems, the extent to which the grid needs to be reinforced can be reduced. Systems such as photovoltaic, (PV), with inductive reactive power consumption have potential to reduce voltage at the point of common coupling, (PCC). Figure 3.6 shows an example of a PV system with inductive power consumption.

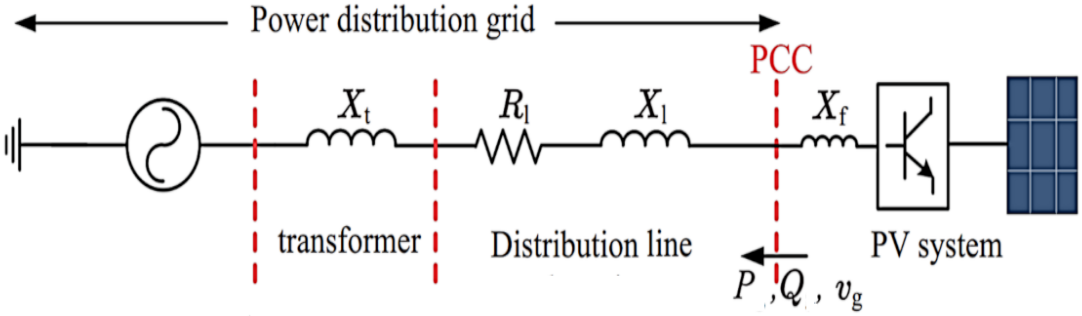


Figure 3.6: Simplified grid model connected with a photovoltaic system (Perera, 2013)

In Figure 3.6, X_f represents the PV system's inductive voltage controller, X_t is the transformer impedance, X_1 is the line impedance, R_1 is the line resistance. The active power supplied by the PV system is represented by P and the reactive power by Q. Finally, v_g is the voltage at the PCC due to the voltage controller of the PV system. According to Perera (2013), the resulting change in grid voltage is given by equation 3.1 .

$$\Delta V = \frac{P\,R_1 + Q\,(X_t + X_1)}{v_g} \qquad \text{Equation 3.1}$$

It is apparent that by increasing v_g at the PCC, the voltage rises on the grid are reduced, vice versa. Similarly, by reducing the active power, P injected at the PCC, voltage rises can be minimised. In Germany, active and reactive power control strategies such as the one illustrated in Figure 3.3 are used to limit the increase in voltage caused by PV. Various other methods are under research and in some cases, being implemented (Stetz *et al*., 2013). Such control systems imply that less upgrades will be required on the transmission and distributions line and substations.

3.2.2. Managing intermittent sources

The decentralisation of the network in Germany has resulted in low-cost renewable energy. This is because a highly distributed network allows dispatching of electricity on an intermittent basis. To resolve the issues associated with the intermittency of renewable generation, Germany uses baseload renewable sources. These include hydro power and biomass power plants whose net power generation in 2017 was 3.8 % and 8.6 % respectively (Burger, 2018).

3.2.3. Evolution of grid intelligence

Modern solutions are being implemented in Germany to transform the electrical infrastructure. At present, German utilities no longer control the electrical distribution and supply. Instead, it is managed by the grid operators. This market-based approach influences the times conventional generation capacities are switched on. On sunny and windy days, for example, the conventional power plants may be kept idling.

According to Agora Energiewende (2018), modern technologies have enabled the electricity system to coordinate demand and supply in real time. As a result, further digitalisation is one of the 2030 targets to enables a smarter and more integrated energy system in Germany (Agora Energiewende, 2018). Moreover, demand side management through artificial intelligence is expected to emerge in several countries to manage generation from intermittent sources (Olakunle, 2018). Appendix B summarises the main regulations currently influencing Germany's electricity system. Figure 3.7 shows the evolution in the energy mix between 1990 and 2012.

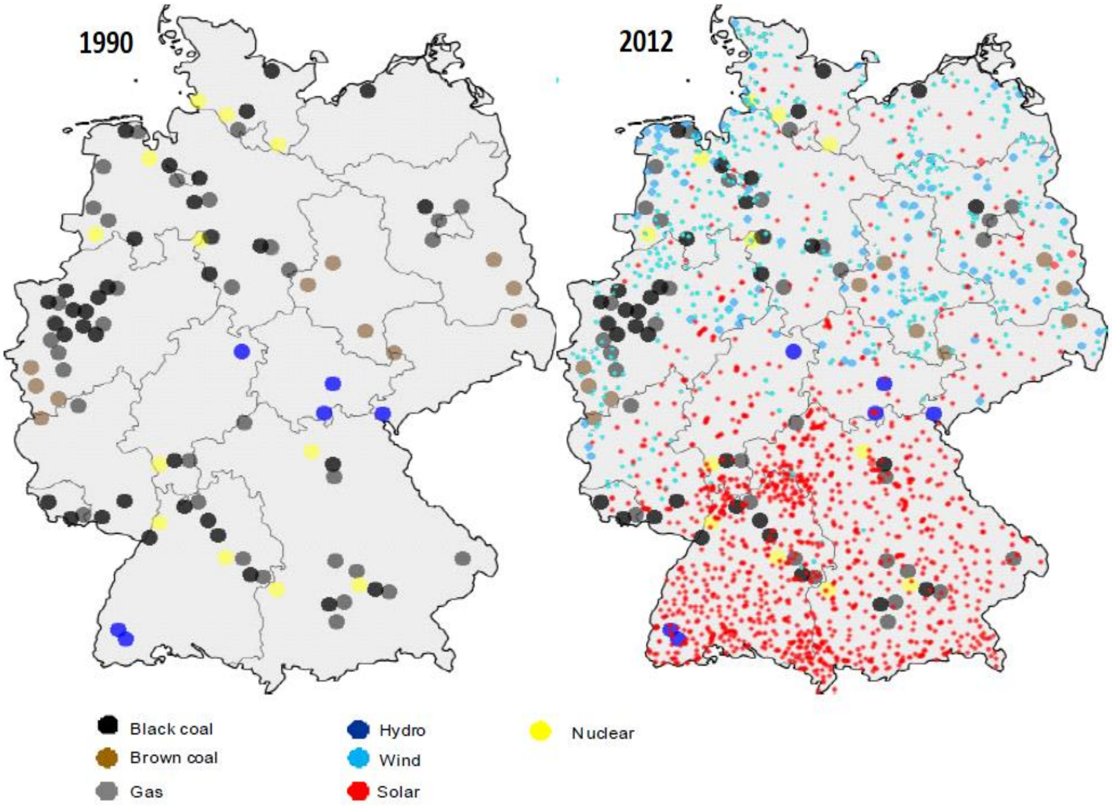


Figure 3.7: Germany's distributed power producers (Simpson, 2012)

It is observed that, the decentralisation of the electrical network has attracted a variety of new renewable energy technology investments on the grid (Dallinger *et al*., 2012). This has a major benefit of reducing peak demand and consequently peak pricing.

3.3. Electricity Product Flow

Most conventional power plants in Germany are owned by combinations of several companies. According to Taylor (2015), these companies, among others include EON, RWE and Vattenfall. While these companies are responsible for operating the power plants, four Transmission System Operators, (TSO) are responsible for operating the grid. As a result, it is the responsibility of the power plant operators to plan the utilization schedule of the plant and announce the schedule a day before the delivery day. Based on this, up to an hour before delivery, the local TSO is responsible for correcting imbalances in the network by trading electricity with other system operators (Simpson, 2012; Taylor, 2015).

Furthermore, renewable energy generators get priority to supply power to the grid over conventional power sources. As a result, by 2016, Germany had an installed capacity of approximately 40 GW for solar PV and 50 GW for wind as indicated in Figure 3.8 (Burger, 2018).

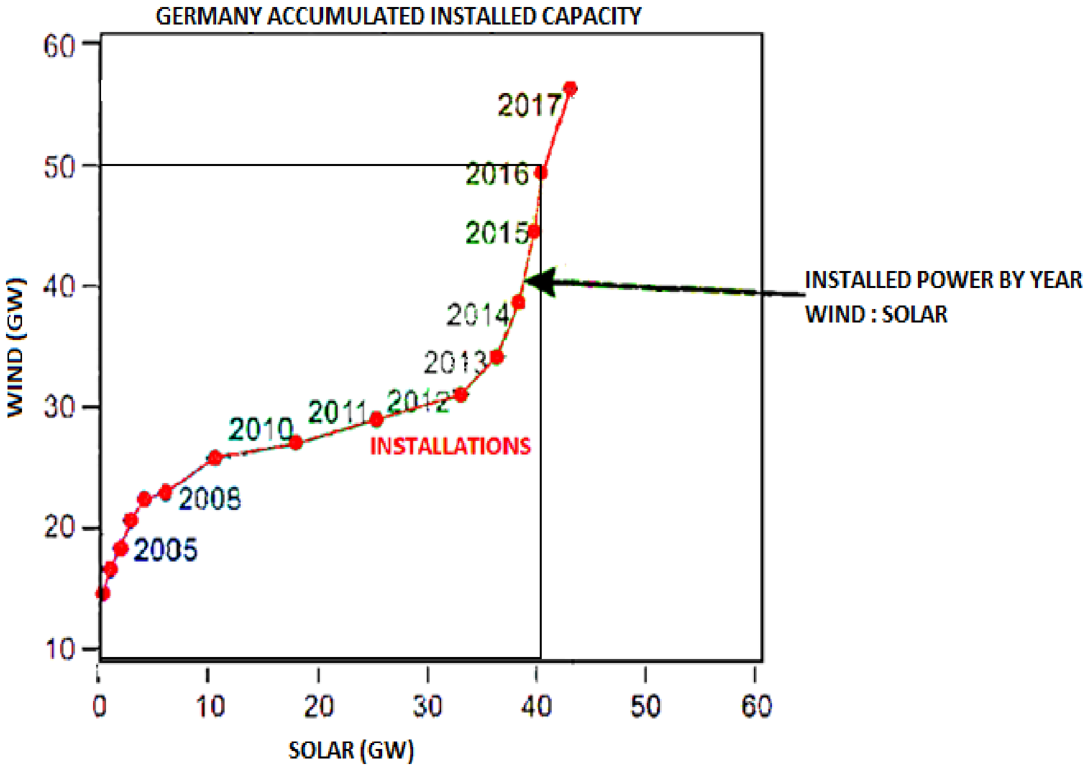


Figure 3.8: Germany installed capacity wind and solar (Burger, 2018).

Figure 3.8 shows that the generation from renewable energy under Feed-in Tariff, (FIT) was approximately 15 % higher in 2017 that the previous year. Carbon tax and the FIT are popular mechanisms in the European Union which have encouraged a shift from fossil fuel to renewable energy generation (Kang, 2016). Having instituted the initial steps of replacing a large percentage of its energy supply, the Germany government had to find ways to strengthen the growth of renewable energy production. According to Ferroni and Hopkirk (2016) this was achieved through favourable policy tools, such as the FIT.

The generation-based legislation for FIT gives priority for grid access to renewables to be the first to be fed into the electrical system (Boie, 2016; Oniemola, 2014). According to this tariff, anyone generating electricity from renewable sources such as wind, solar, biomass or hydro is entitled to fixed payment for every kilowatt-hour of electricity generated. This entitlement is guaranteed for twenty years, and utilities are required to connect wind generators and photovoltaic panels at no cost to the power producer.

However, for plant installations more than 750 kW wind and solar photovoltaic, the new Renewable Energies Act revision replaces the FIT mechanism (Federal Ministry for Economic Affairs and Energy, 2018). This implies that competitive prices determined by auctions now replace the fixed FIT previously set by the government. The main reason for introducing auctions was to give stakeholders a fair chance and encourage a more cost-efficient renewable energy system (Federal Ministry for Economic Affairs and Energy, 2018).

In the recent years, Germany's surplus power generation has continued to increase. Export surplus in 2017 was 53 TWh of which was exported 94% of the year. The electrical network is interconnected with countries such Switzerland, Sweden, Demark, France Poland and Austria. Depending on cross-border transfer capacities, to generate extra revenues, export of electricity is carried out when the market price of a neighbouring country is more expensive than in Germany (Boie, 2016b). According to Burger (2018), the average import cost in 2017 was € 38.31 / MWh, export cost was € 35.57 / MWh and the revenue generated from power trading was € 1.81 billion.

3.4. Summary

The case study acknowledges the challenges associated with high penetration of intermittent generating units into centralised grids. The study also provides strategies to overcome the technical and operational issues associated with the grid integration of renewables. However, it does not cover the economic performance of such electrical systems which vary depending on factors such as national policies, geographical location and weather

The following observations during the integration of renewable technologies to the grid emerge from the above case study:

- Extension of the electrical grid infrastructure are prerequisites to achieving high renewable energy integration.
- Instead of rebuilding the electrical grid to accommodate renewable technologies, the grid can be maintained smarter. This is because an electricity grid is a complicated and aging system which requires constant maintenance and would need many years to be rebuilt.

- Required grid modification and upgrades can be minimised by controlling the active power fed in to the grid at the connection point of the power plant. As a result, the potential number of connections to the grid can be increased.
- Advanced, intelligent technologies are available to enable power plants to interact with other power sources in the network. This enables plants to be run only when needed. Therefore, there is no need for power plants to run continuously.
- Intermittency issues of renewable technologies can be resolved by combining intermittent renewables technologies with flexible power plants such as concentrated solar power plants or energy storage plants. According to Ralon *et al.* (2017) German had approximately 150 MW of battery storage and 6 GW pumped hydro storage by mid-year in 2017.
- Grid access policies and requirements will vary for each region. Therefore, this imposes additional costs on the electrical generation technology because the technologies must be adapted to comply with local policies.
- Software simulation tool are available to model and investigate the strength of the electrical grid infrastructure. Weather prediction tools are also available to assist in the management of intermittent power sources.

When compared to static tariffs, competitive auctions promote a more cost-efficient renewable energy system because it enables power producers, as stakeholders, to contribute the economic structure of the power system.

CHAPTER 4

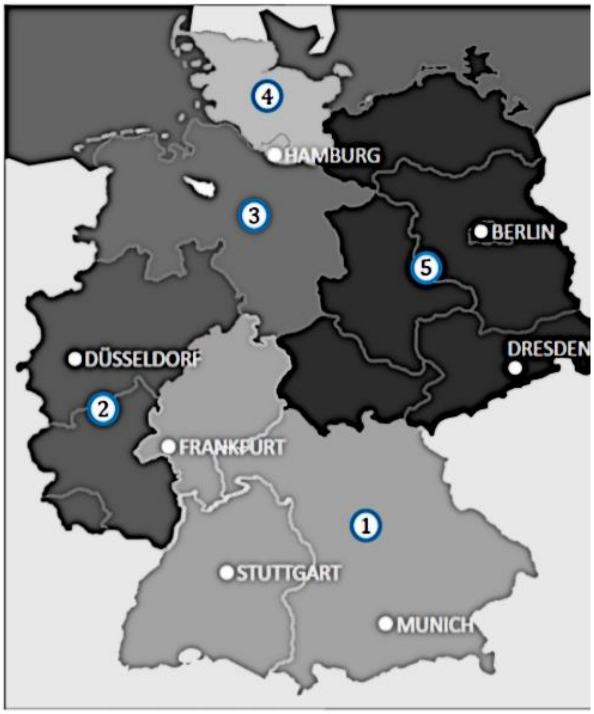
4. COMPARISON – GERMANY VS. SOUTH AFRICA'S ELECTRICITY SYSTEM

4.1. Electrical Infrastructure: Germany vs. South Africa

According to both German-Swedish Chamber of Commerce (2018) and Allianz Climate Solutions (2017), Germany has one of the world's most resilient electrical grid infrastructure. On the contrary, South Africa's ranks second highest among G20 countries in terms of requiring investment in electrical infrastructure (Allianz Climate Solutions, 2017). South Africa's development challenges may give the impression that the country is far from achieving the level of infrastructural advancement similar to Germany. However, the benefits of the experience in Germany has driven countries like South Africa to take strides towards the unconventional energy path (Tyler, 2012). This is evident in the IRP 2018 which now considers the cost of the transmission network, where previously the IRP 2010-30 did not explicitly include such factors (Department of Energy, 2018).

4.1.1. Decentralized vs. centralized

According to Heal (2016), the Germany's electric generation is also highly decentralized. The German government has also ensured that transmission system operators are able to expand their grids more quickly by creating the Electricity Grid Development Plan. The country is in the process of installing an ultra-high voltage grid that will be more efficient and smarter. This involves the use of super conductors for electricity transmission and incorporation of information technology to coordinate electricity grids, electricity generation and consumption (Sinn, 2017). In 2016, Germany started a Schaufenster *intelligente Energie – Digitale Agenda für die Energiewende* (SINTEG). The main focuses of SINTEG are the grid integration wind power projects in the north and solar power generation in the south (German-Swedish Chamber of Commerce, 2018). The project was planned over five years and consists of five sub-projects as summarized in Figure 4.1.



1. Interconnected, regional energy systems with cellular structure and focus on PV integration that balance each other
2. Decentralized renewable power supplied flexibly to urban and industrial load centres
3. Stabilizing the grid by improved measurement and data analysis coupled with new market mechanisms
4. Maximizing the efficient use of regional wind power overproduction by flexible demand response and inter-regional trade in electricity
5. Sectors electricity, heat, and mobility are integrated to flexibly accommodate fluctuating regional wind power

Figure 4.1: Smart energy program 2016 – 2020 (German-Swedish Chamber of Commerce, 2018)

On the other hand, the South African grid differs from the German one in that it is still largely centralized. Electric production is still mainly the purview of the government, through Eskom. The biggest hurdles that face South Africa’s renewable energy, (RE) production are the current government regulations that govern the generation licensing (Department of Energy, 2015).

4.1.2. Local vs. import technology

Another difference is that while Germany can manufacture its own RE technology components, South Africa currently produces a small percentage of these components and must rely on imports. Research and development of RE is still low in the country. For example, exploring opportunities such as the use of superconductors is still in its infancy.

4.1.3. Community engagement

Several companies and individuals are producing the majority of their own electricity consumption through rooftop solar and consequently influencing the electricity system (Department of Energy, 2018). The IRP 2018 states that the electricity demand projected in the IRP 2010-30 for South Africa was not realised due to changes on the demand side (Department of Energy, 2018). Similarly, due to resistance from the citizens, Germany has managed to build only 850 km of additional transmission and distribution lines out of the 2025 target of 7 700 km (Agora Energiewende, 2018).

According to Agora Energiewende (2018) an energy transition requires major infrastructural changes which affect many people's lives. For example, new transmission lines, wind turbines in agricultural land and solar farms create more interaction between people and the electrical system infrastructure. As a result, 'democracy' is one of the targets for shaping the energy system, outlined in the 2018 Germany *Energiewende* (Agora Energiewende, 2018).

On the contrary, an issue that was identified by Department of Energy (2015) is that South Africa has not yet managed to engage most of its citizens in the planning in the energy development and transition plan. This results in inaccurate projections and therefore, an inability to reach the energy targets. However, steps are being taken in South Africa to encourage citizens contributions as was seen with the update process for IRP 2018 which included a release for public comment (Department of Energy, 2018).

4.2. Renewable Electricity Generation: Germany vs. South Africa

4.2.1. *Energiewende* 2030 vs integrated resource plan 2018

The *Energiewende* 2030 outlines Germany's energy and emissions targets to be achieved by 2030 and proposes strategies to integrate various energy systems. The integrated resource plan (IRP 2018) is similar to the *Energiewende* in that it uses analytical calculated models to determine energy supply targets at minimal cost and reduced emissions (Agora Energiewende, 2018). Of relevance to this research is the fact that both policies do not include additional nuclear capacity but consider wind and solar as the least expensive and the primary renewable technologies for the future targets (Agora Energiewende, 2018; Department of Energy, 2018).

According to Agora Energiewende (2018), the greatest challenge will be the transformation of the electricity system being used up due to the increase in the integration of renewables. The IRP 2018 also acknowledges that the required electrical infrastructure, which includes power plants and power lines, is expensive and requires a long time to build (Department of energy, 2018). As a result, South Africa's IRP 2018 is comparable to Germany's *Energiewende*.

4.2.2. Fixed feed-in tariff vs. competitive auction

Although recently Germany has introduced competitive auctions for selected technologies with capacity more than 750 kW, Germany predominantly uses the feed-in tariffs (FIT) mechanism. FIT is a mechanism which provides economic incentives to promote generation of electricity from renewable sources (Burger, 2018; Trainer, 2014). FIT is a mature strategy which has been used in the renewable industry for many years. Under FIT, a tariff is set for a generation technology and is maintained for several years. The main advantage of FIT is that it is a long-term plan with no batch allocations and no limit to how much renewable energy can be connected to the grid. Therefore, FIT attracts investors (Boie 2016). However, the main shortfall of FIT is that it does not drive towards meeting renewable energy targets (Winkler, 2005).

South Africa uses a competitive bidding process which not only provides economic incentive but is also focused on meeting the renewable energy targets. According to Allianz Climate Solutions (2017), in the recent past, South Africa has had one of the fastest growing renewable energy industries. The successful projects from foreign and local independent entities allow power producers to supply electricity to Eskom under a power purchase agreement valid for twenty years (World Wildlife Fund, 2017). As a result, according to World Wildlife Fund (2017), the systems suffer a setback because Eskom as the utility then controls more than one stage in the bidding process. Unlike the FIT system used in Germany, South Africa's bidding process, both the tariff and the quantity of integrated renewable electricity are ministerial decisions by Department of Energy.

4.2.3. 38 % vs. 2.9 % renewable electricity production

According to Burger (2018), in 2017, approximately 38.4 TWh of electricity from photovoltaic arrays was fed into the German electric grid. The monthly electric production of solar photovoltaic, (PV), system was 5.8 TWh which was higher than the 4.7 TWh produced by hard coal power plants. Wind energy in the country produced approximately 104 TWh in the same year. This was a 32 % increase in energy production from 2016. Onshore wind farms produced about 85 TWh, while offshore wind farms produced 17.4 TWh during this year. Both wind and solar power plants contributed 142 TWh of energy higher that the amount produced by nuclear plants, brown coal and hard coal. Hydropower in the country produced 20.5 TWh and Biomass producing 47.5 TWh in the same period. The total amount of electricity produced from renewable sources in Germany in 2017 was 210 TWh. According to Burger (2018), renewables made up 38 % of the total public net power supply in Germany in 2017.

In South Africa on the other hand, Calitz (2017) notes that at the end of 2016, solar PV produced a total of 2.6 TWh to the total electric grid comprising 1.6 % of the total energy produced. Concentrated Solar Power (CSP) in the same period was 0.5 TWh for the whole year. Wind energy contributed 3.7 TWh to the total grid, about 1.65 of the total electricity produced by the country. In 2016, the total renewable energy, wind, solar PV and CSP, produced in South Africa was 6.9 TWh, supplying 2.9 % of the countries system load.

4.3. Germany's Dependence on Renewables and South Africa's Dependence on Coal

The objective of this section is to highlight the extent to which South Africa is lagging when compared to strides taken in Germany. In 2015, two rural states in Germany Mecklenburg-Vorpommern and Schleswig-Holstein generated at 130 % and 100 % net electricity from renewables (Marks, 2016). With Germany in some instances like having achieved 100 % renewable electricity generation in some states, South Africa is still largely dependent on coal for electricity generation. In a study carried out by Sinn (2017), the green energy revolution was found to have been going on for the past two decades. It was, however, in the time following the Fukushima accident in 2011 that Germany accelerated its energy revolution and decided to decommission all its nuclear power stations. By the end of 2015, nine nuclear power stations had been already decommissioned, with a phase-out of the rest being scheduled for 2022. After replacing nuclear plants, the country began investigating the possibility of eliminating electric power generation from fossil fuels and non-renewable fossil waste. These systems combined to 58 % of the country's electric power generation.

Trainer (2014) also studied the steps taken by Germany to improve RE production and reports that during this same period, Germany installed buffers to smooth out the volatility issues of both wind and solar power production. For example, during periods where the solar radiation and wind are minimal, a biomass gas electricity plant of equal capacity is used to supply the electricity shortfall from the wind and solar plants. Germany also engages its citizens in setting up policies and systems to improve RE production. Policies were set-up to reduce the cost of solar panels and to ensure that individual dwellings could contribute any excess energy to the national grid (Federal Ministries of Economic Affairs and Energy, 2015). According to Ralon *et al.* (2017), policy support for distributed, behind-the-meter, battery storage was the main reason approximately 68 MW small-scale battery storage systems were deployed in 2017.

In South Africa, several factors hinder RE production. According to Amigun and Brent (2011) barriers to production can be grouped into several categories: infrastructural, research and development, human resources, economic and financial factor, and regulatory. Renewable energy capital return on investment is relatively unpredictable. As a result, this often limits the financial investments for the renewable electricity technologies (Pegels, 2010). In Germany for example the FIT requires utilities to purchase electricity from independent power producers. This provides investors a guaranteed return on investment for the renewable power plants (Winkler, 2005).

In South Africa, the low tariffs available for renewable electricity make it difficult to justify such investment from a financial perspective (GreenCape, 2017). According to SAWEA (2018), the reason Eskom was unable to sign the power purchase agreements which were due in April 2016 was due to risk of being unable to recover financially. The main uncertainty was as a result of the regulated tariffs at which they can sell electricity.

Edkins *et al*. (2010) also found out that there are too many agencies involved in RE integration process in the country. The regulatory requirements from these agencies are usually contradictory thus creating several hurdles to developers willing to generate RE. Apart from Eskom, Table 4.1 shows the departments which each have a role in the process (World Wildlife Fund, 2017).

Table 4.1: Main contributors to the renewable integration process (World Wildlife Fund, 2017)

Governmental Institution	Responsibility
Department of Economic Development	Focuses on the socio-economic policies for the power producers
Department of Energy (DoE)	Planning for the energy industry which inclusive of renewable energy generation
National Energy Regulator of South Africa (NERSA)	Mainly processes the licensing of new power plant and grid installations
Department of Environmental Affairs (DEA)	Grants authorisations relating to sustainable development and the integrity of the environment
National Treasury	Manages the government procurement of projects and investments
Department of Trade and Industry (DTI)	Promotes local manufacture and development of the required technologies buy attracting foreign investment
Department of Public Enterprises (DPE)	Plays a main role in the power purchasing contracts
Provincial governance	Regulate distributed generation by enforcing the relevant policies. This includes generation from renewable sources

While South Africa has plans to increase renewable energy penetration on the electrical grid, the country still lacks sufficient infrastructure, manpower and research and development tools to be on par with countries such as Germany. According to GreenCape (2017) RE technologies continue to fall in prices thus creating a huge opportunity for advancement of renewable energy production in the country at utility scale.

4.4. Lessons Learnt from Germany

The intent here is to determine strategies which have been applied in Germany which can be adopted into the South African electricity system. From the studies in this research so far, the following are the actions South Africa needs to adopt from Germany's way of doing things:

- Adopting favourable governmental policies that encourage RE power generation. At present, South Africa has no approved regulations to govern small scale, grid connected renewable generation (NERSA, 2015). Unfortunately, this means RE policies such as the grid code currently do not distinguish between utility scale and small scale grid connected RE.
- Germany's feed-in policy would be particularly effective in the country because it does not limit the amount of renewable energy that can be procured. A competitive auction will only be more successful if policies are set in place to ensure there are no delays or changes made in the process once bidding has started. Such delays were experienced in South Africa when it took approximately two years for power purchase agreements, from bid windows 3.5 and 4, to be signed (SAWEA, 2018).
- Decentralization of power supply. This will allow private companies to set up alternatives for both RE and non-RE generation facilities which can later be integrated into the national grid.
- Increase in penetration of renewable energy does not need to be preceded installation storage. Power trading and demand side management are cost effective alternatives to storage systems (Ralon *et al.*, 2017).
- Engaging the public. This will prevent unnecessary delays such as the protests experienced in Germany over power line expansions (Agora Energiewende, 2018). Moreover, including the citizens in the decision making process will allow for a democratic decision making system. Engaging the public will also encourage interest in the field of renewable energy ultimately adding skilled professionals into the market. Finally, this also encourages private investment in the field allowing the government more flexibility to use its budget to tackle other state problems.

4.5. Summary

South Africa is on the right track with regards to planning for renewable electricity integration. Although the country has only focused on this field in the last 10 years, it is still ranked among the top ten countries in the world with ideal renewable energy investment conditions (Allianz Climate Solutions, 2017).

The main problem facing the country's efforts is that government policies are still lagging the drive to achieve high RE penetration to produce electricity. Looking at the strides taken by Germany, South Africa seemingly still has a long way to go in establishing adequate RE policies as shown in Figure 4.2.

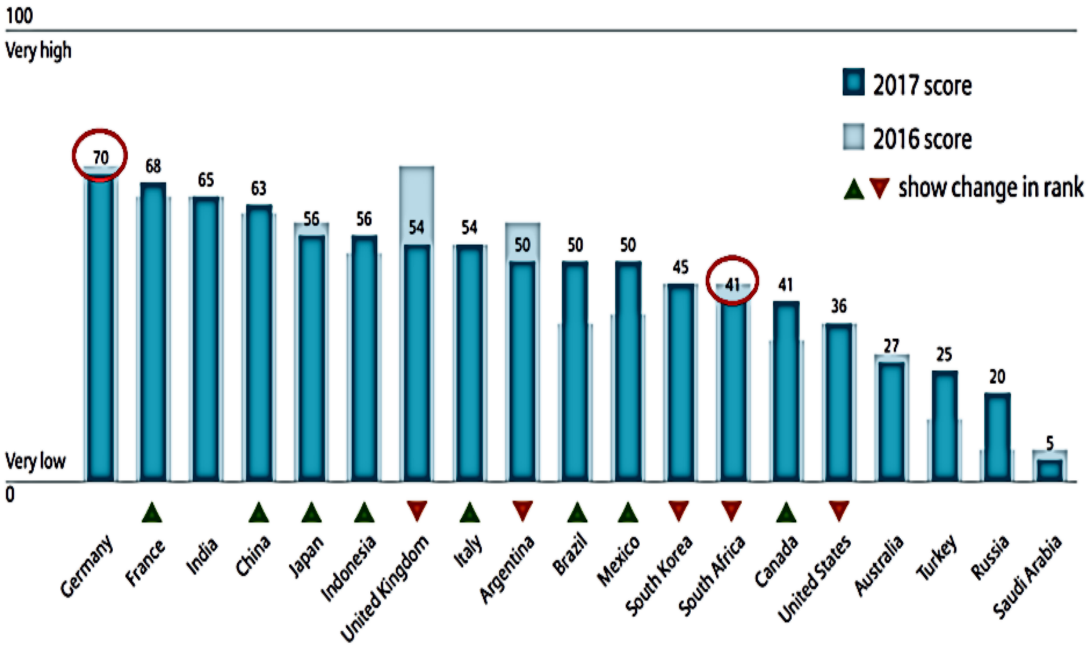


Figure 4.2: Renewable electricity production policy-adequacy (Allianz Climate Solutions, 2017).

Figure 4.2 shows that Germany's policies which support electricity generation from renewable are about 70 % effective in the long-term transition for the electricity system. However, South Africa shows a policy adequacy of 41 %. This is because South Africa is one of the countries with policies in place but their long-term measures to eliminate fossil fuels from the grid are not apparent (Allianz Climate Solutions, 2017).

However, policies are currently being revised, for example the integrated resource plan (IRP) (Wright *et al.*, 2017). Appendix B summarizes some of the other regulatory policies which are in place for renewable generation integration in South Africa.

CHAPTER 5

5. THE GRID CODE

5.1. Overview of South Africa's Grid Code

Operational strategies are necessary to promote the successful connection of renewable energy technologies to the national grid. Wind farms for example can have either fixed speed or variable speed wind turbine generator systems. However, the dependence of fixed speed generators on reactive power increases the risk on grid stability should this technology be integrated to the electrical network. As a result, the acceptable power system performance of renewable technologies has been defined, and before any physical connections can be authorized, rigorous testing and simulations are carried out on the generation technology design.

The grid code is the set of laws, which serve as a technical guideline to supply and demand matching for Renewable Power Plants (RPP). In South Africa, RPPs are grouped into the three categories summarized in Table 5.1.

Table 5.1: Categories of renewable power plants in South Africa (Craib, 2013; Eskom, 2012)

Unit Type	**Categories**	**Connection Voltage**	**Plant capacity**
All RPPs (solar, wind, hydro, biogas, biomass, landfill gas)	A1	LV (<1 kV)	0 < X ≤ 13.8 kVA
	A2		13.8 kVA < X < 100 kVA
	A3		100 kVA ≤ X < 1 MVA
	B	MV (1 kV- 44 kV)	0 < X < 1 MVA
	B	n/a	1 MVA ≤ X < 20 MVA
	C		≥20 MVA

It can be observed from Table 5.1 that the power plant categories are dependent on the plants rated capacity, and where indicated, the acceptable voltage at the point of connection (POC). In this case, connection refers to the physical interface between the power plant and the national electricity grid as illustrated in Figure 5.1.

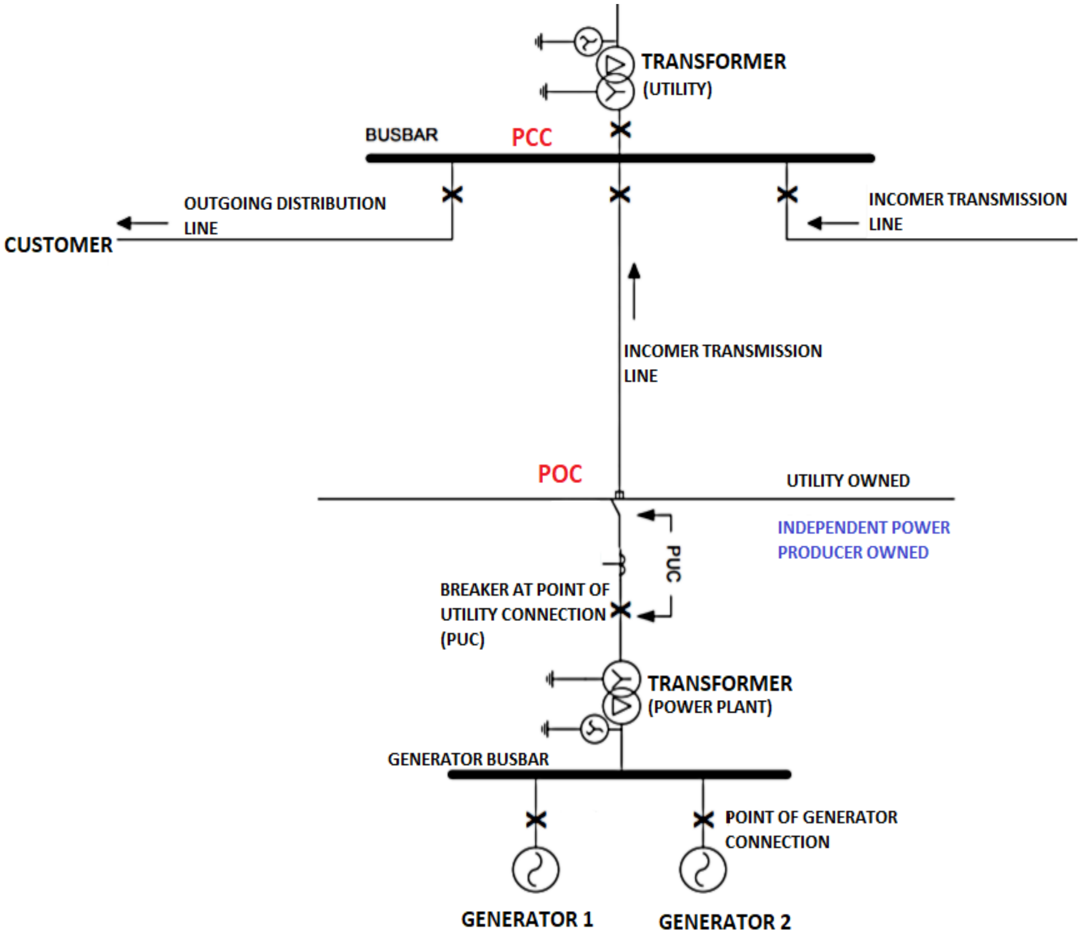


Figure 5.1: Layout of electrical network to explain some terms used (Craib, 2013)

Figure 5.1 shows the difference between the point of common coupling (PCC) and the POC. In general, PCC refers to the point where the multiple power plants and customers connect to the grid. This point is required to be accessible to the utility, the RPP and the customer (Craib, 2013). POC refers to the physical point where a power plant or individual generator injects into the grid. It should be noted that the point of utility connection (PUC) which contains the main protection and disconnection system between the utility and the RPP can be located near the PUC. Alternatively, as shown in Figure 5.1, the PUC can be connected within the RPP between the POC and the generator point of connection.

The major technical requirements for Grid Connection of Renewable Power Plant, RPPs are summarized below:

- **Synchronization**: Allowed only after a certain minimum time i.e. 60 seconds for category A and 3 seconds for categories B and C.
- **Voltage range:** RPPs can operate at a voltage in the range -15 % to +10 % around nominal voltage. Specifically, category A RPPs can operate within the voltage range of -15 % to +10 %, while categories B and C must operate between -10 % to 10 % on the nominal voltage
- **Frequency range**: Allowed frequency is within the range of 49.0 Hz and 50.2 Hz to the utility.
- **Frequency control**: Requires high frequencies exceeding 50.5 Hz to be controlled by reducing active power as a function of the change in frequency. Disconnecting of RPP is required once either the frequency is more than 52Hz for a minimum specified time 4 seconds or the frequency is less than 47 Hz for more than 200 ms.
- **Frequency variation**: The requirement is that the RPP must remain connected rate of change of frequency (ROCOF) of magnitudes not more than 1.5 Hz per second, if the network frequency is still within the desired range.
- **Power quality**: Voltage jumps, phase jumps and harmonics are required to be maintained within the desired range. As a result, the RPP must be able to withstand sudden phase jumps of up to 40° at the POC without disconnecting or reducing its output. After conditions at the POC have reverted to normal, the maximum allowed settling period to resume normal operation is 5 seconds.
- **Voltage ride through:** The requirements for category A3 RPPs and larger is that in the event of a voltage drop to zero, the connection must be maintained for at least 0.15 seconds. For voltage jumps up to 120 % of the nominal voltage, the RPP should stay on line for a period of at least 2 seconds.
- **Active or reactive power control:** Requires categories A and C RPPs to supply rated power between power factor 0.95 leading and 0.95 lagging. For category B RPPs this the requirement differs slightly in that rated power should be maintained between 0.975 leading and 0.975 lagging.
- **Power factor control**: This function controls the ratio between active and reactive power. If a power factor set point is changed by the network service provider or the utility, the RPP is required to respond to the new set point within 30 seconds and remain with $\pm$ 0.02 of the set point.

5.2. Constraints on Renewable Energy Technologies for Grid Connection

As penetration of renewable energy power increases, it becomes vital to monitor the power quality issues of RPPs to ensure they meet the grid code standards. The intermittence of most renewable sources such as wind and solar implies that there may be supply surges on the grid and the conventional coal generators will need to start and stop frequently. The requirement in the event of major network disturbances is that the

RPP must disconnect itself. Alternatively, the RPP must assist in the restoration of the nominal conditions in the minimum possible times. This has resulted in several technologies and in some cases, integration of technologies being implemented to achieve this (Muyeen *et al*., 2010).

Other renewable technologies such as CSP make use of thermal storage systems to counter any disturbances due to the intermittence of the solar resource. Therefore, power quality management and control are no longer a constraint in the matching renewable energy to the South African Electricity supply. However, the greatest challenge is the high cost of such control technologies and storage.

Currently, due to the high capital costs of importing the required technologies into South Africa, most renewable energy projects are not financially feasible at the tariffs available for grid connection (Matthews, 2010; De Jongh *et al*., 2014). As a result, justifying grid connection of more renewable technologies especially on a small scale is at present relatively difficult.

5.3. Comparison of Grid Codes Worldwide

The technical requirements and procedures which govern the integration of renewable power plants to the grid are adapted from one country to another. Several countries worldwide, such as China, United States and Germany are increasingly transitioning towards renewable power as a sustainable and affordable energy solution. By considering the total capacity installed, Table 5.2 summarises the rankings of the top countries by capacity and generation technology.

Table 5.2: Top countries by total capacity at the end of 2017 (REN21 Secretariat, 2018)

	1	**2**	**3**	**4**
Renewable power (excluding hydro)	China	United States	Germany	India
Solar PV capacity	China	United States	Japan	Germany
Concentrated solar power (CSP)	Spain	United States	South Africa	India
Wind capacity	China	United States	Germany	India

The countries shown in Table 5.2 each have grid codes which have played a pivotal role in the successful integration of renewable energy (Ackermann *et al.*, 2016). The intention of a grid code is to define both the steady state and dynamic behavioural requirements of power plants during fault conditions. Dynamic requirements include grid support and fault ride-through events. These requirements are commonly defined at the PCC, where the power plant connects to the grid. However, for smaller systems, the requirements can be defined at the POC where a single generator or turbine connects to the grid.

Table 5.3 shows a summary of some of the specifications in the various grid codes. It should be noted that, a requirement that is not checked may still be considered by the country but there are no direct specifications available in the grid code.

Table 5.3: Comparison of most relevant specifications in grid codes (Arias, 2006)

Requirement	**USA**	**Germany**	**Denmark**	**South Africa**
Transmission system stability	X	X	X	X
Grid fault backup protection		X	X	X
Isolation	X	X	X	
Frequency control	X	X	X	
High frequency response		X	X	X
Harmonic distortion	X			
Voltage control	X	X	X	
Automatic voltage regulation				X
Criterion n-1		X	X	X
Operational communication	X	X	X	

For a successfully integrated electricity system, the technological, operational and regulatory requirements of the system need to be considered. According to Ackermann *et al.* (2016), to enforce the technical requirements outlined in grid codes, it is necessary to establish verification methods which corroborate compliance. Prior to the approval of a new connection to the grid by the national energy regulator of South Africa (NERSA) and Eskom or the local municipality, the independent power producer is required to conduct network studies or tests (NERSA, 2012). The studies which are typically carried out using specialized computer software packages such as PowerFactory aim to evaluate possible changes to the network because of this new connection and to determine whether there are any network planning criteria exceeded.

The acceptable power system performances of renewable technologies have been pre-defined in the grid code, and before any physical connections can be authorized, rigorous testing and simulations must be demonstrated on the generation technology design. Where the construction of the plant has already commenced, examples of such verification methods include on-site inspection and certification systems.

Europe has a network code which contains many common grid interconnection requirements for 35-member countries as can be seen in Table 5.2 for Germany and Denmark. The detailed specifications are currently being implemented on a national level with an expected completion date of 2018. Germany, for example has recently enforced a positive sequence grid voltage support (Addalla *et al.* 2015). This involves injection of positive sequence reactive short-circuit current to grid support during unbalanced faults. Among some of the recent changes are requirements for consecutive grid faults, fault ride-through and grid voltage support for both low voltage and high voltage ride-through capabilities, i.e. LVRT and HVRT respectively.

System protection requirements are enforced to prevent damage on the transmission system components due to faults. For example, according to Arias (2006), frequency range is a requirement for continuous operation. Each grid code defines a frequency range within which power generators should stay on line. As a result, frequency is included in all the grid codes. Allowable transmission voltage variations are typically 10%. However, Germany’s grid code is the only one where voltage variation is allowed up to 11% (Arias, 2006).

China’s grid code developments typically follow those of Europe (ABB, 2016). While the HVRT requirements are typically at power plant level, this is a requirement for individual turbines and generators in China. Much the same as South Africa’s smaller category A1 and A2 power plants where the allowable peak voltage at the POC is 120 % and the withstand time 0.16 seconds, the generating unit in China must stay connected if there is a temporary voltage surge up to 130 % for a minimum of 0.2 seconds (Wenzhong *et al*., 2016).

It is interesting to note that there is no grid code applicable to North America. However, in the rest of the United States, (USA), the specified requirements include low voltage ride-through, voltage regulation, dynamic reactive power control and reactive power requirements. In both USA and South Africa, the local utility or network service provider may specify its own interconnection requirements. Unlike South Africa, where new coal power plants are currently under construction, the recent trend in the United States has been to decommission coal-fired power plants and install more renewable generation like wind and solar. According to DOE Act (2016) coal fired power plants made up 80% of the decommissioned electricity generation in 2015. Consequently, energy storage technologies are under evaluation to provide frequency regulation on the grid.

Evidently, no two Grid Codes are exactly alike. This is because national electrical networks and the type of generation technology may vary from one place to another.

In some cases, for example the United States the requirements include more indicators, such as frequency range and climate specific requirements. In other cases, such as China’s requirements for voltage deviation and active power control, the standards are less demanding. Therefore, grid codes must be complied with to ensure local stability and reliability of the electricity system stability and reliability (Wenzhong Gao *et al*., 2016).

The development of international grid codes and standards for the connection of RPPs has led to the advancement of renewable energy technologies. These advancements make renewable technologies stable and safe for grid operation. While it may be necessary to adjust the performance of a technology depending on location, it is evident that any technical challenges can be resolved using appropriate power system analysis tools such as DigSilent’s PowerFactory.

5.4. DigSILENT Power Factory

Digital Simulation and Electrical Network Power Factory (PowerFactory) is an analysis software program used for dynamic performance simulation and monitoring of power generation, transmission and distribution systems (DigSilent, 2018a). This licensed software has been developed since 1985 by a private company called DigSilent GmbH located in Gomaringen in Germany.

PowerFactory provides modelling features for interconnected power systems and hence enables non-dispatchable generation to be accommodated in a reliable manner. This high-profile power systems analysis software has become a package of choice for most power utilities around the world including Eskom Distribution (DigSilent News, 2003). Figure 5.2 shows project examples, for diverse applications, available in PowerFactory.

Example of a low-voltage distribution network. Please press the button to import the project.

Base Model

Introduction to the base model used in all LV distribution network example study cases.

LV Load Flow Calculation

Probabilistic load flow calculation considering coincidence of low-voltage loads.

Feeder Load Scaling

Loads connected to a feeder are scaled according to measurements taken at the start of the feeder.

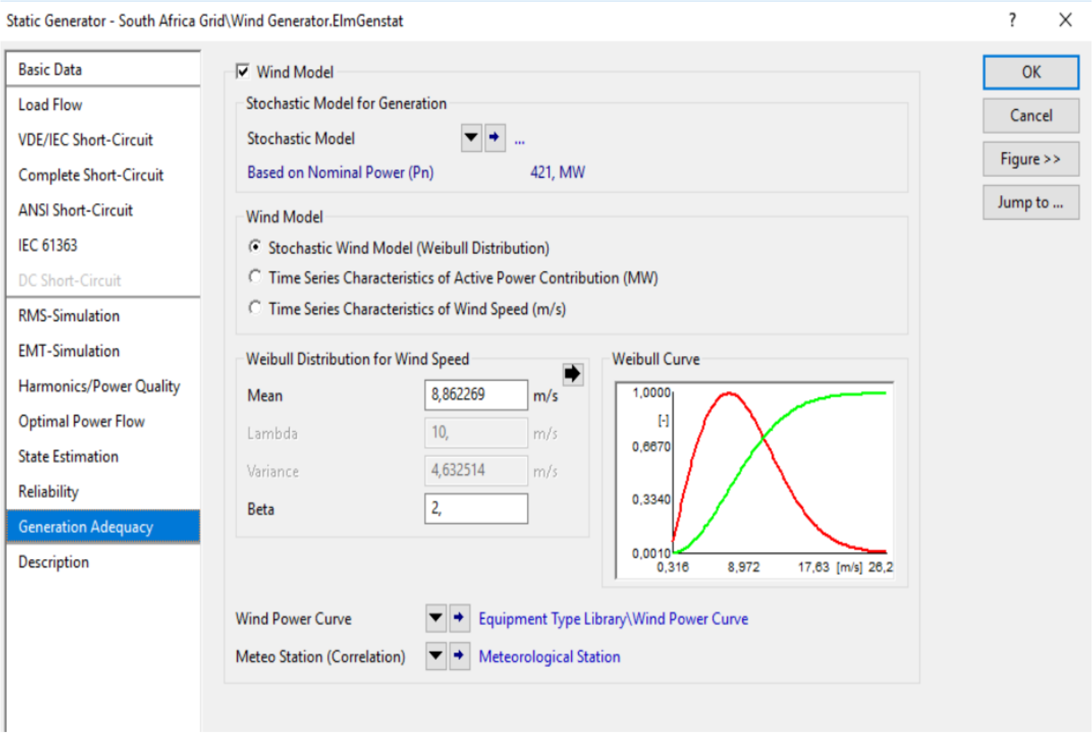
Quasi-Dynamic Simulation

The quasi-dynamic simulation is used to analyse a time series (e.g. of a day, a week or a year) taking load and generation profiles into account.

Figure 5.2: Example projects available in PowerFactory (DigSilent, 2017)

From Figure 5.2, there are wind farm examples available. These examples evidently show that the complex functions required for simulating the connection of renewable generation into the transmission and distribution networks are readily available in PowerFactory. Figure A.1 and Figure A.2, in Appendix A, are extracts from the technical documentation outlining the main features available for wind and solar power systems.

Some studies (Hansen *et al.*, 2006) use the software to simulate the dynamic performance of wind power because PowerFactory includes models of wind gusts and turbulences for grid connection studies. This is because PowerFactory not only enables modelling of the power system but also the influencing factors such as wind speed as shown in Figure 5.3.



Static Generator - South Africa Grid\Wind Generator.ElmGenstat

☑ Wind Model

Stochastic Model for Generation

Stochastic Model ...

Based on Nominal Power (Pn) 421, MW

Wind Model

● Stochastic Wind Model (Weibull Distribution)

○ Time Series Characteristics of Active Power Contribution (MW)

○ Time Series Characteristics of Wind Speed (m/s)

Weibull Distribution for Wind Speed

Mean 8,862269 m/s

Lambda 10, m/s

Variance 4,632514 m/s

Beta 2,

Wind Power Curve → Equipment Type Library\Wind Power Curve

Meteo Station (Correlation) → Meteorological Station

Figure 5.3: Modelling a wind generator in PowerFactory

Figure 5.3 shows how the required generator parameters and meteorological data can be set when modelling a wind power plant. Other studies have used the PowerFactory to compare network performance in the case of no CSP power plant connection and cases with CSP integrated into the electrical grid at different points of connection (Addalla *et al.* 2015). PowerFactory is therefore an ideal and flexible analysis package for electricity network systems. It covers a diverse range of power system applications and enable simultaneous analysis of electrical network features.

CHAPTER 6

6. EFFECT OF RENEWABLES ON ELECTRICITY SYSTEM

6.1. System Model Definition

In this section, a generic simplified model representing the South African Electricity system was created with the purpose of illustrating how the electricity system responds to the generation connected to it. Figure 6.1 shows a typical generation, transmission and distribution system.

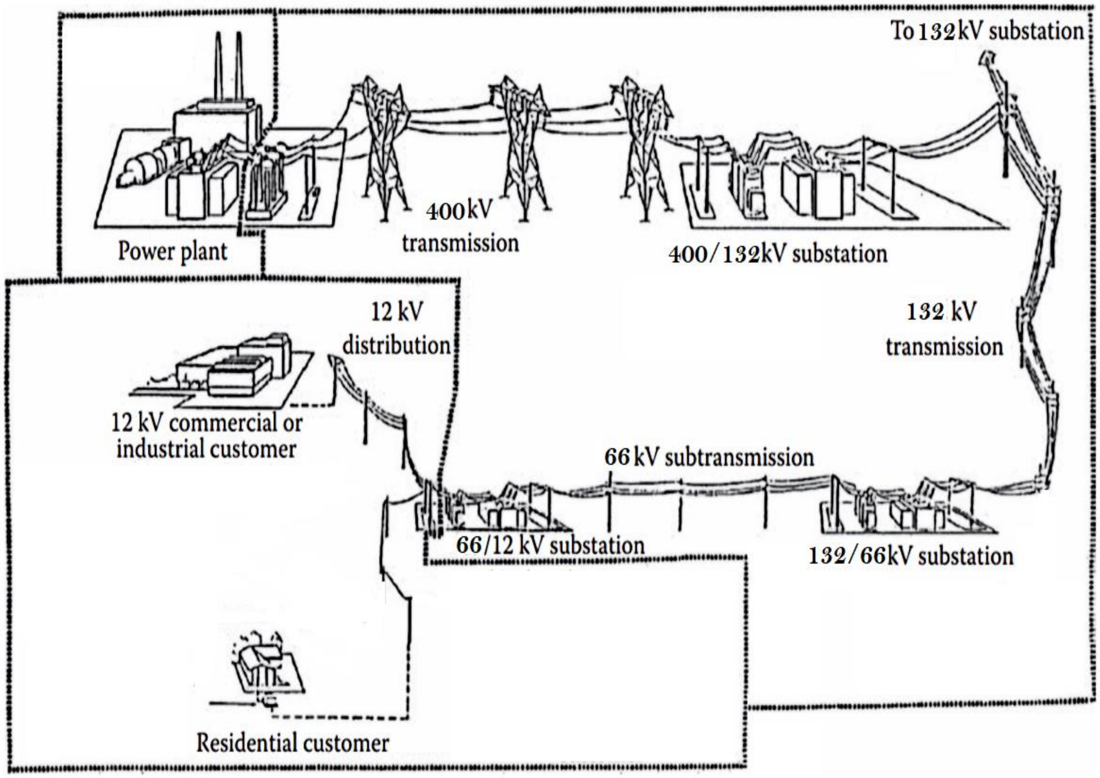


Figure 6.1: The concept of an electricity generation and transmission system (Grigsby, 2012)

The power plant will include a step-up transformer which steps up the generator voltage to a voltage suitable for transmission. In Figure 6.1, the power plant transformer steps up to 400 kV which is transmitted through various substations until it reaches the customer at the correct voltage. A substation links two transmission or distribution lines, typically by terminating the lines on busbars. The substation also consists of an

electrical transformer, switch gear and protection system (Grigsby, 2012). Transmission and distribution substations are typically utility owned, and their main purpose is to convert between two voltage levels.
The simulations carried out in section 6.2.1 were carried out to determine the effect on the electricity system when demand and generation are not matched. Given that South Africa has a centralised electrical system, Figure 6.2 shows how new generation is typically introduced into such a system. The broken connection lines indicate the new transmission or distribution lines often required to connect the new distributed power plants.

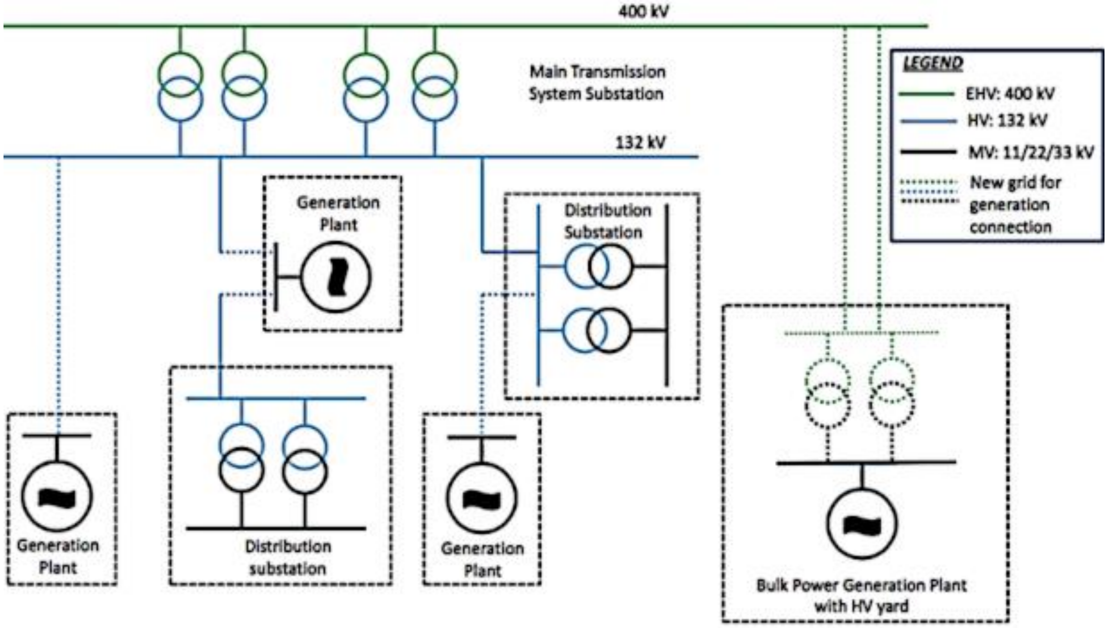


Figure 6.2: Integration of distributed generation in a centralised system (Wright *et al*., 2017)

From the illustration in Figure 6.2 the power plants are connected directly to substations in the electrical network. The aim of the simulations carried out section 6.2.2 was to validate the reason for physically connecting the generators or power plant to a substation instead of along a transmission or distributed line.

In section 6.2.3 simulations were carried out to confirm that integration of renewable generators such as wind and solar photovoltaic (PV), influence power quality. Similarly, the simulations carried out in section 6.3 are to validate that concentrated solar power (CSP), can be used to balance the system power quality. This is because CSP technology uses a steam turbine generator like the conventional coal fired power plants. The CSP power plants are represented by the synchronous generators in Figure 6.3. These provide system stability through synchronous coupling of their physical inertia to the grid which asynchronous and static machines like wind and solar PV are unable to provide (Gonzalez-Longatt *et al*., 2013).

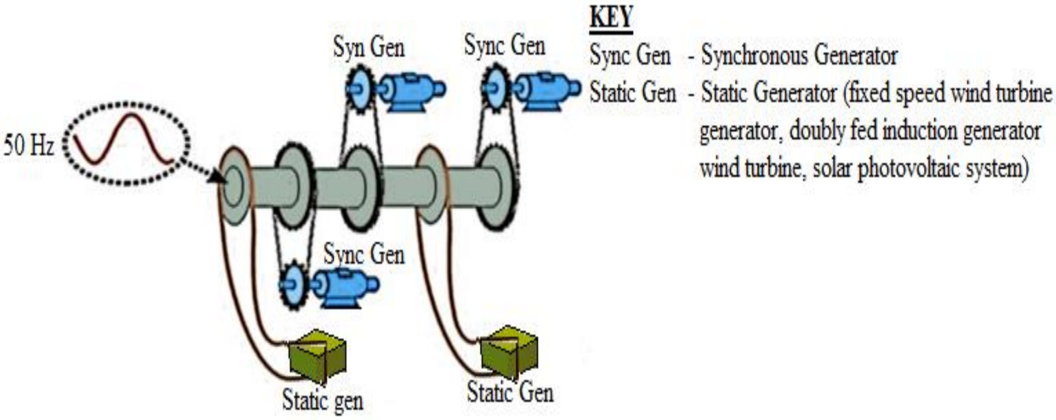
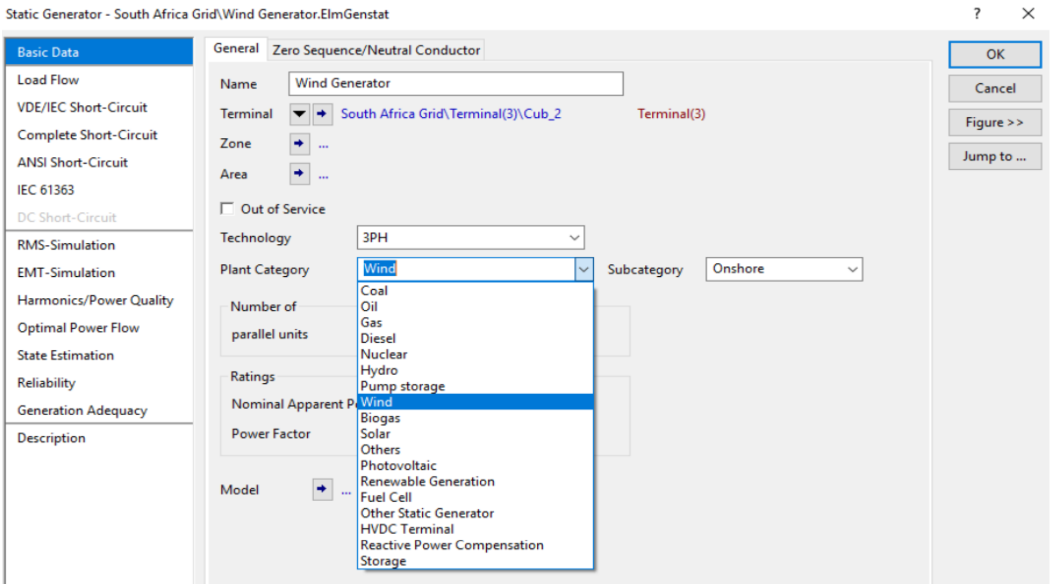


Figure 6.3: Frequency control by using synchronous Generator (Wright *et al*., 2017)

Figure 6.3 illustrates how CSP plants (blue) can be used to balance out power quality instabilities which may be a result of other renewable generators (green) connected to the electrical grid. The PowerFactory version 2017 software package was used for the simulations (DigSilent, 2018a). The wind and solar generators were represented by static generators. Detailed models for both generators are also readily available in the simulation package as shown in Figure 6.4.


Static Generator - South Africa Grid\Wind Generator.ElmGenstat

Name: Wind Generator

Terminal: South Africa Grid\Terminal(3)\Cub_2 Terminal(3)

☐ Out of Service

Technology: 3PH

Plant Category: Wind

Subcategory: Onshore

Figure 6.4: Selecting static generator model in PowerFactory

As shown in Figure 6.4, the solar or wind power plants can be characterised by selecting the relevant plant category. The capacity values and connection voltages used for the simplified model were derived from the major power plants in the Western Cape Province. The data used in the simulation model is shown in Table 6.1.

Generation	Type	Project name	Capacity (MW)	Connection Voltage (kV)
Nuclear	Base load	Koeberg	1860	400
Gas, Pumped storage	Peaking	Acacia, Gourikwa, Ankerlig, Palmiet	2643	400
Wind	Eskom Renewables	Sere, Darling	105	132
Wind	Renewables *	Dassiesklip, West Coast 1, Gouda, Hopefield	316	132
PV	Renewables *	SlimSun Swartland, Touwrivier Project, Aurora, Electra Capital	125	132
PV	Renewables *	Vrendal	9	66
Main Grid			42 000	400
*Commissioned under Renewable Energy Independent Power Producers Procurement Program REIPPPP				

The electricity demand on the network is represented by single customer load models connected at each of the three connection voltages shown in Table 6.1. For the simulation model, the chosen maximum demand values used were 300 MW, 600 MW and 3 700 MW connected to 66 kV, 132 kV and 400 kV respectively. These estimate values were derived from the load forecast for the Western Cape by Eskom (2017). The demand value was derived from the forecast shown in Figure C.1 in Appendix C. Table C.1 in Appendix C. shows the generation profile used for the simulations. The simulation model is shown in Figure 6.5.

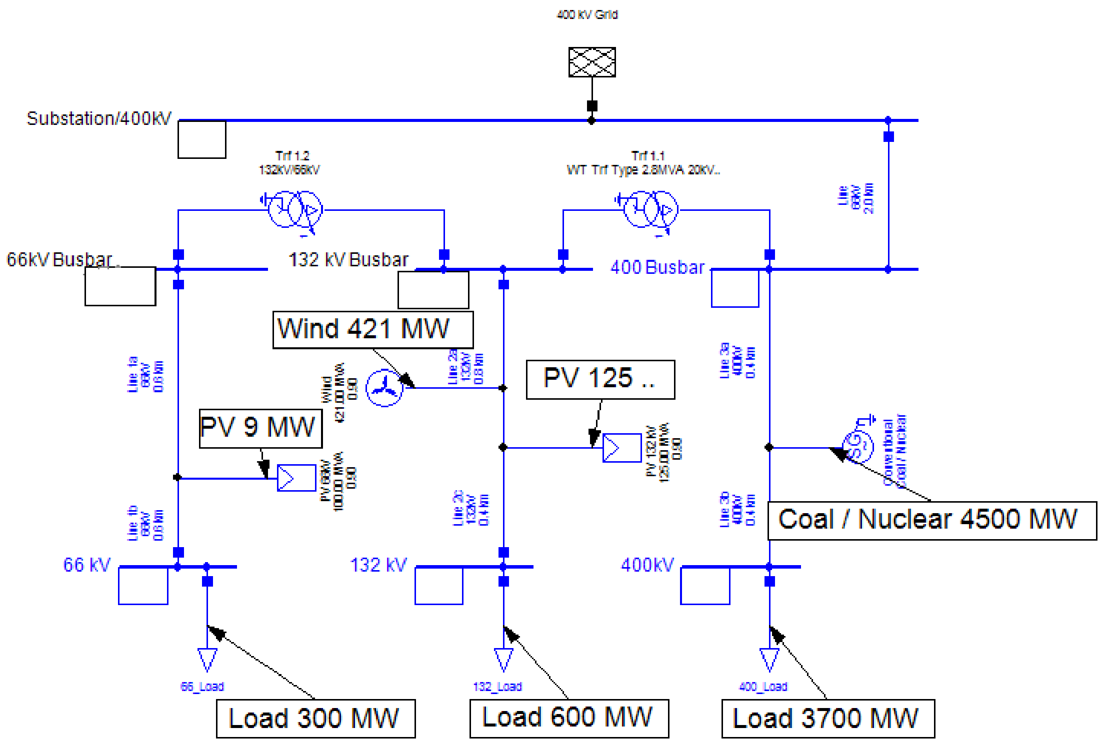


Figure 6.5: Simplified grid model for South African electricity system

From Figure 6.5, it can be observed that the renewable energy generators are linked to the grid by a transmission line. This is because the POC, is typically nearest to the generator. The substations are represented by busbars and transformers. The demand model assumed the electrical loads only requires active power. The nominal frequency for the South African electricity system should always be kept at 50 Hz.

Load flow analysis is a vital tool in the planning and designing of electricity systems. Based on load flow calculations, results such as line losses, transformer loading, line loading and allowable voltage ranges can be predicted. The boundary conditions of the modelled generators are defined by setting the maximum output in the PowerFactory application. To allow for the line limits to be determined, no generator boundary conditions are set for the transmission line.

Since South Africa's installed capacity already includes some renewable energy capacity to the grid, the initial simplified model already included wind and solar PV generators. The behaviour of the electrical network components in the electrical system was determined using load flow calculations. Power system load flow calculations calculate the voltage magnitude, phase angles and power flow at an instant and assume there are no faults at the period of observation. Figure 6.6 shows a load flow simulation carried out at an instant when the wind and conventional generators are delivering maximum allowable capacity and the photovoltaic generators are only delivering a fraction of their rated capacities.

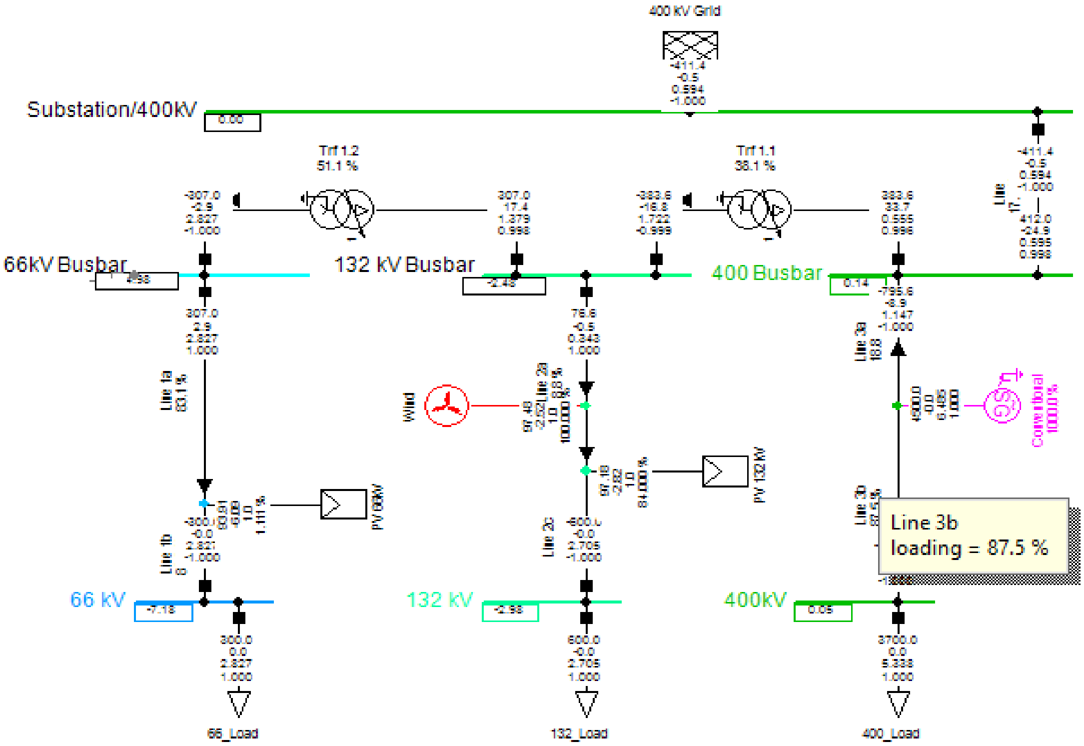


Figure 6.6: Load flow simulation of simplified grid model

Figure 6.6 shows that some of the network components such as the 400 kV transmission line 3b, are already operating close their design limits, i.e. at 87.5 %. Assuming the system was initially sized correctly with no renewable power integration, then the integration of wind and PV plants pushes the limits of an adequately sized system (De Sisternes, 2014). This implies that, there is a limit to the amount of extra generation capacity or demand that can continue be added to this electricity network.

6.2. System Response

6.2.1. System response to variation in generation

In this section simulations were carried out to determine how the electricity network responds at instances when there is more generation that demand or vice versa. For the case in Figure 6.7 it was assumed that the excess generation output, i.e. the difference between the total generation and demand, will vary throughout the day as shown by the line graph. In this case a generic 24-hour demand profile was used and varied as indicated in Appendix C, Table C.1. The behaviour of the transmission line loading this simulation are shown by the bar graph.

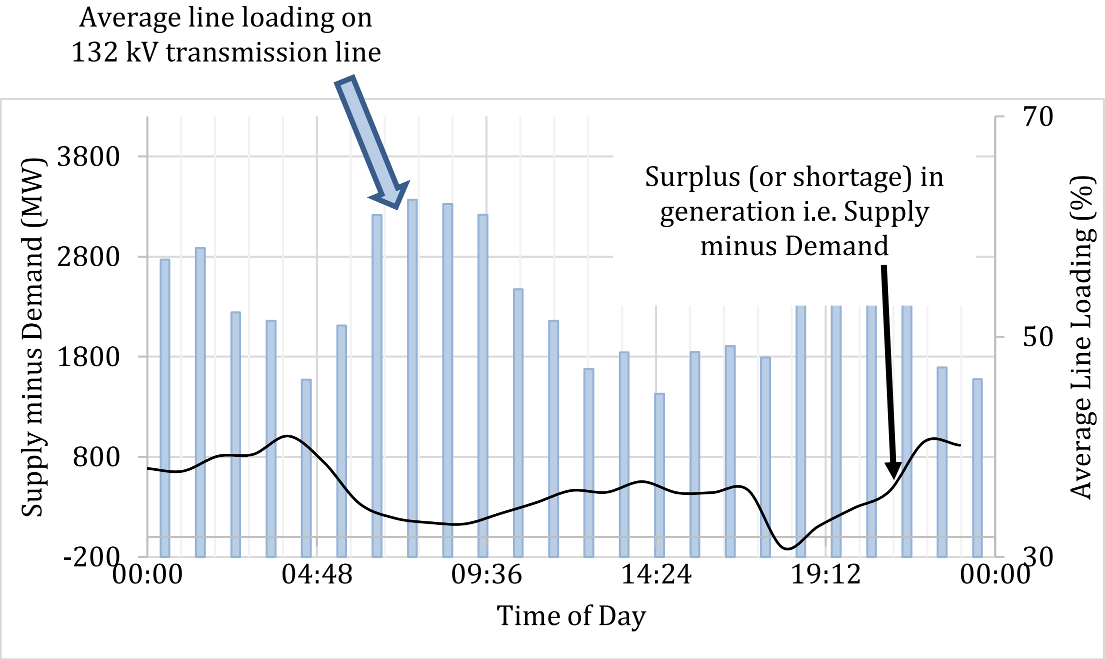


Figure 6.7: Variation of 132 kV line loading with excess generation

From Figure 6.7, it can be observed that the transmission line loading appears to be inversely related to the difference between generation and demand. The line loading is high in the morning and evening peaks and around midnight when the demand is low, but generation is high. For this simulation model, the average line loading is approximately 55 %. This is an example of an adequately designed part of the electrical network which designed to carry more capacity than it currently handles. Morocco is an example of such a transmission grid (Boie *et al.*, 2016). However, this is not the case with most countries, including South Africa. This is evident from Figure 6.8 that in the year 2017 the projected demand for Mpumalanga province is approximately 21 % higher that the grid capacity in the province.

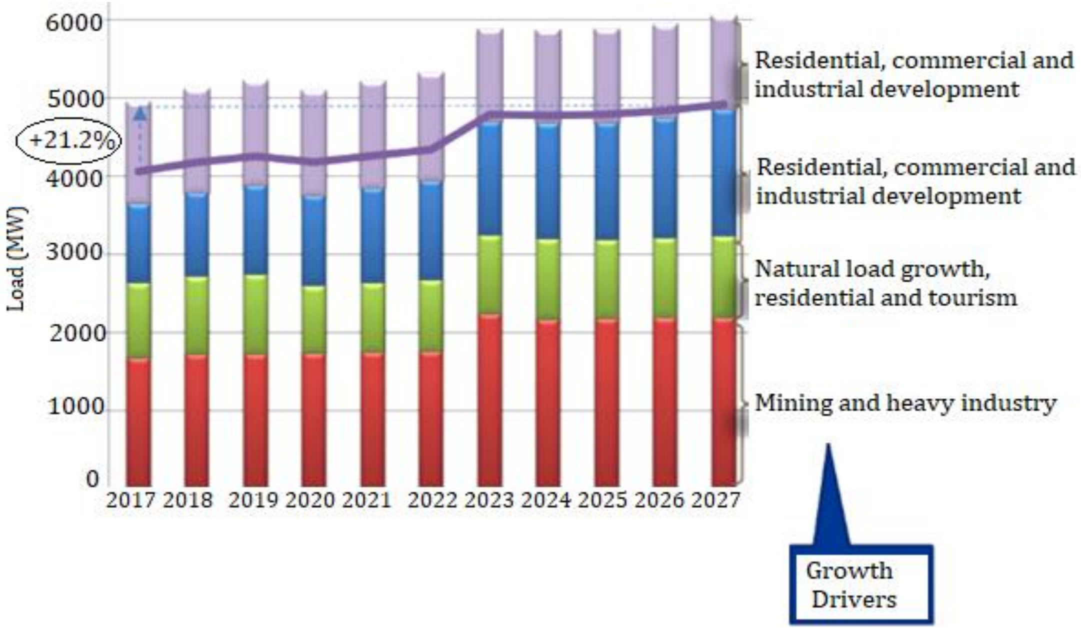


Figure 6.8: Mpumalanga load forecast (Eskom, 2017)

According to Eskom (2017), beyond the REIPPPP bid window 4B, most of the transmission and distribution loading will be exhausted as shown in Figure 6.8. However, to match the system to match the grid capacity and to the demand, a Transmission Development Plan (TDP 2017) has been put in place to modify the electrical grid in South Africa.

From Figure 6.7, it was observed that both the demand and generation will affect the loading on the electrical infrastructure. Figure 6.9 shows a similar relationship between the line loading and the demand. The demand is shown by the line graph and the line loading by the bar graph. As expected, the line loading is high during the peak times when there is increased power flow.

Similarly, the loading is high after midnight when the wind generation is high, but demand is low. This implies that the electrical network will experience the most strain where there is a general imbalance between supply and load. This is because an excess in demand results in a voltage drop on the grid which reduces power available for consumption by the loads. As a result, the grid also tries to act as a backup electricity source to match the excessive demand. Similarly, an excess in generation results in over-voltage which results in an overflow of power to the loads Therefore, the grid must absorb the excess generation (Thopil et al., 2018).

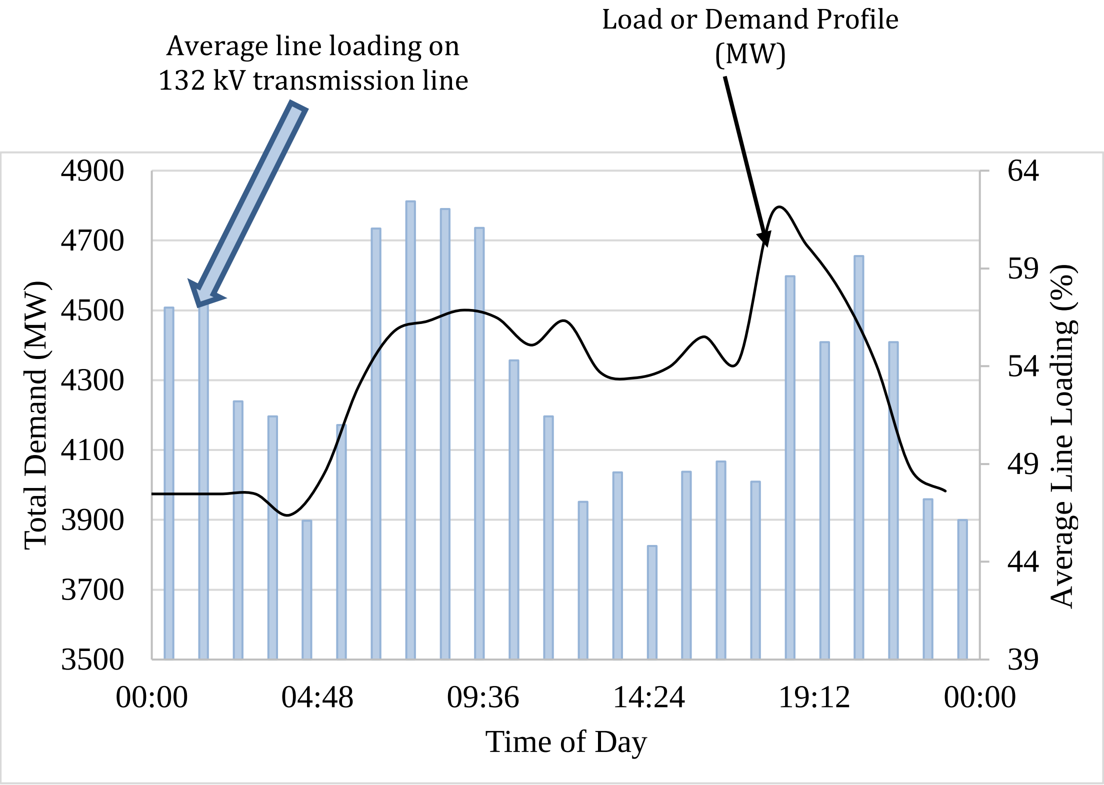


Figure 6.9: Relationship between daily demand profile and line loading

In general, it can be observed from Figures 6.7 and 6.9 that the loading on the network components responds both to variation in generation output and to changes in demand. However, it is evident that the line loading is higher when the generation capacity in increased and during times of relatively low load i.e. between 12 am and 4 am. A study carried out by Ramdhin (2014) also confirms that component loadings increase more during low demand periods where the generators are operating at 100 % capacity. The above simulations validate the fact that it is vital to determine optimal ways to integrate more renewable generation into the already strained South African grid.

6.2.2. System response to point of connection

As previously discussed on integration of distributed generators in a centralized system, Eskom (2017) also states that developments by independent power producers tend to be near Eskom substations. In this section, simulations were carried out to achieve a clearer understanding of how the connection point of the renewable generation is influenced by the local network in electricity system.

The main aim of this section was to determine which physical POC, imposes the least strain on the local electricity network. According to Onwunta (2014) and Van der Walt (2016), given the correct power plant output rating, the distance of the POC will not affect the network voltage conditions significantly. Based on this, the connection points were randomly selected for this simulation. It is assumed that this system model has there are no constraints on costs. At the maximum simulation load, the simulations were carried out for the following scenarios:

Scenario 1 doubles the capacity of both the photovoltaic and the wind generation connected to the 132 kV transmission line.
Scenario 2 is like Scenario 1 in that it includes doubled renewable energy capacity. However, the additional capacity is connected to the 132 kV substation/ busbar. Figure 6.10 shows that simulation for Scenario 2.
Scenario 3 is simulated using the simplified system model described in Section 6.1.

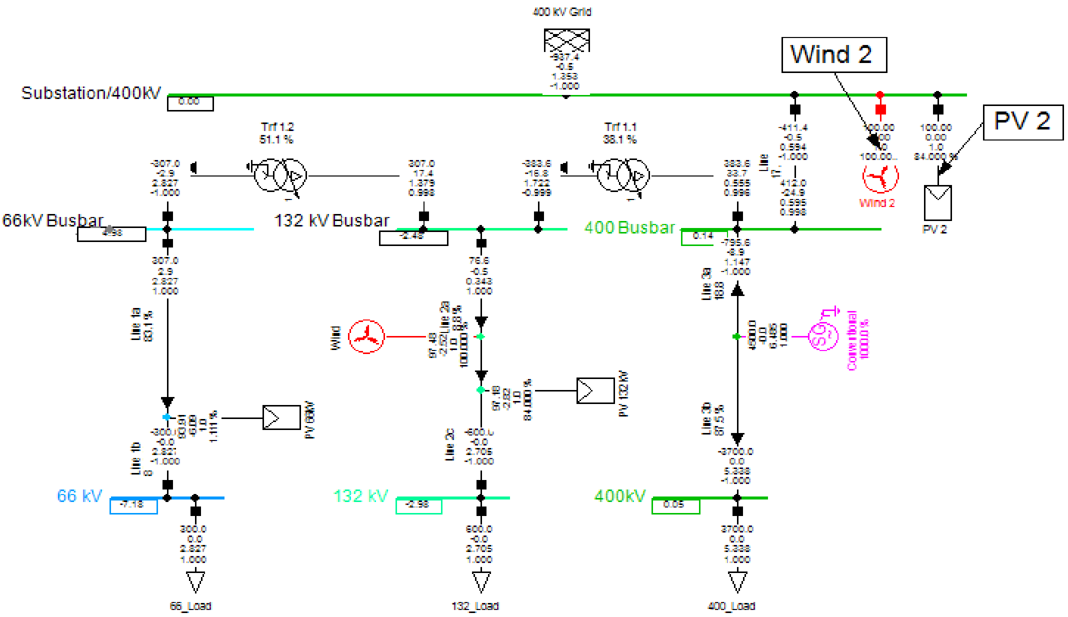


Figure 6.10: Additional renewable generation capacity on 400 kV substation

The results from the simulation are shown in Table C.2 in Appendix C. It was observed that connecting new generation capacity onto any point in the network will impact all the components in the entire grid to an extent. This is a result of the grid compensating for excess demand or trying to absorb excess generation. Moreover, the integration of distributed generators results in bidirectional power flow through the electrical network, which can also lead to technical complications on power quality (Thopil *et al.*, 2018). Figure 6.11 shows the combined percentage loading on the 132 kV transmission line.

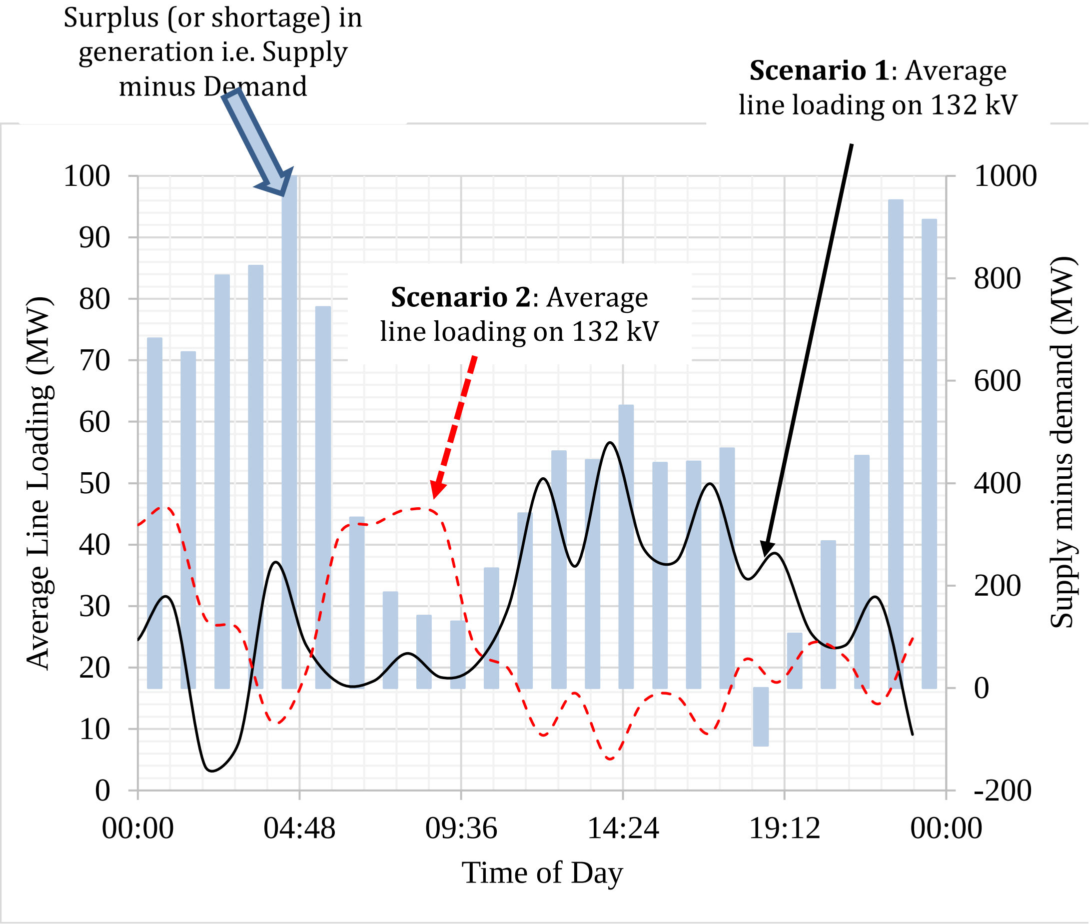


Figure 6.11: Hourly variation of line loading at different connection points

In scenario 2, the additional capacity is connected to directly to the 132 kV substation. As can be seen, majority of the time, the line loading in scenario 2 is lower that loading in scenario 1. Based on Figure 6.11, Scenarios 1, which involves connecting additional generation capacity to existing transmission lines, will impose the most strain on the network.

Scenario 2 shows that connecting additional renewable generation capacity directly to the substation will have relatively less impact on the transmission line loading when compared to a direct connection to the transmission line. This is because the ability of the network to accept more generation capacity reduces as the length of the incomer transmission line from the generator or power plant increases (Gill *et al*., 2014). The correlation between distance of the POC from the substation and network strain is further explained in Figure 6.12.

In Figure 6.12 the loading on the network is measured by the capacity availability, i.e. the fraction of time when the electrical network can accept the rated capacity of the power plant (Gill *et al*., 2014). A capacity availability of 1 means that the system can still accept 100 % of the average rated power plant capacity of 7 MW. On the other hand, a capacity availability of value 0 means the network is already 100 % loaded and can no longer accept any extra generation.

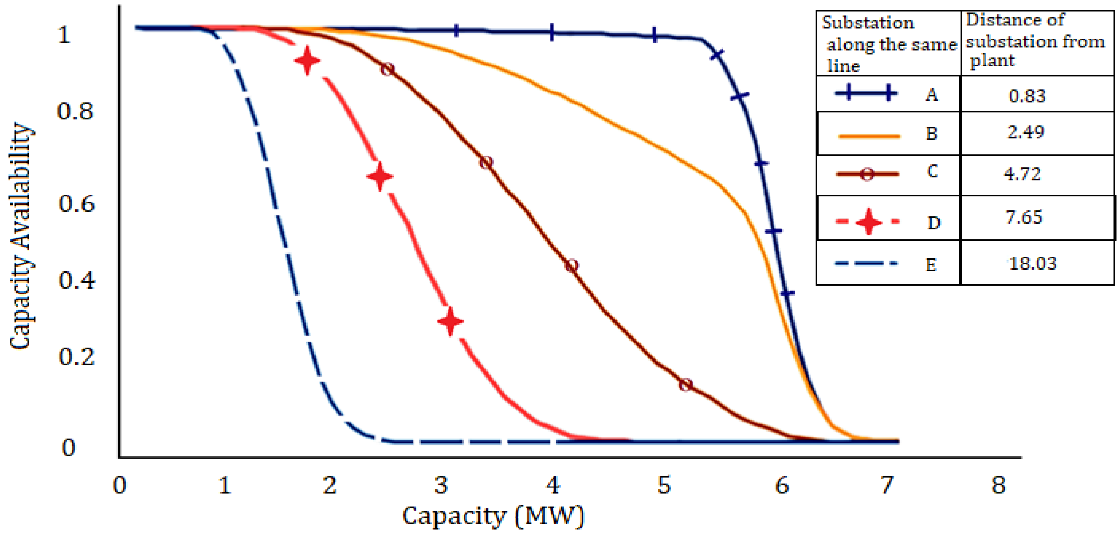


Figure 6.12: Network capacity availability at five substations (Gill *et al*., 2014)

Figure 6.12 shows the results of a particular power plant connected along the same line to several substations at distances ranging from 0.83 km to 18.03 km, relative to the plant's location. The capacity availability increases from left to right. It can be observed from Figure 6.12 that substation which is closest to the power plant has a capacity availability of 1 for a larger capacity range. This implies that substation A is able to accept 5 MW, majority of the time, which close to the rated capacity of the power plant.

When considering overall effect on all components in the modelled system, the results are shown in Figure 6.13. The simulation model used to determine the POC is shown in Figure C.2 in Appendix C

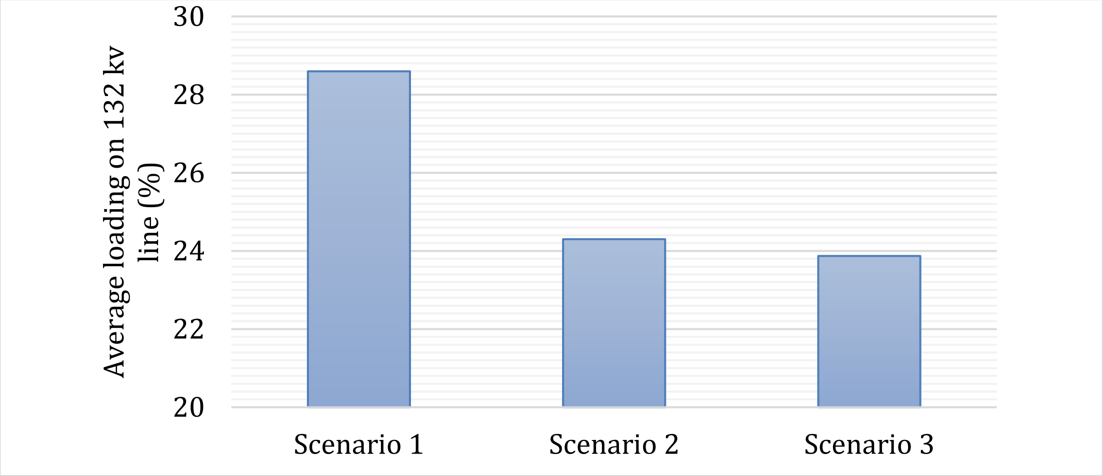


Figure 6.13: Effect of point of connection on local electricity network

It can be seen from Figure 6.13 that any addition of extra capacity to the grid will increase the loading on the transmission lines. However, neglecting the distances and costs involved, increasing penetration by connecting new renewable plants to directly a substation or via separate transmission lines may be ideal way to incorporate new renewable generation into the South African Electricity system.

6.2.3. System voltage response to variations in generation output

In this section, voltage regulation and power control, as an operational requirement provided in the grid code for South Africa will be investigated. Power plants connected to the South African electricity system are required to operate in the range of 85 % to 110 % of the nominal voltage. Figure 6.14 and Figure 6.15 show simulation results carried out for the simplified model.

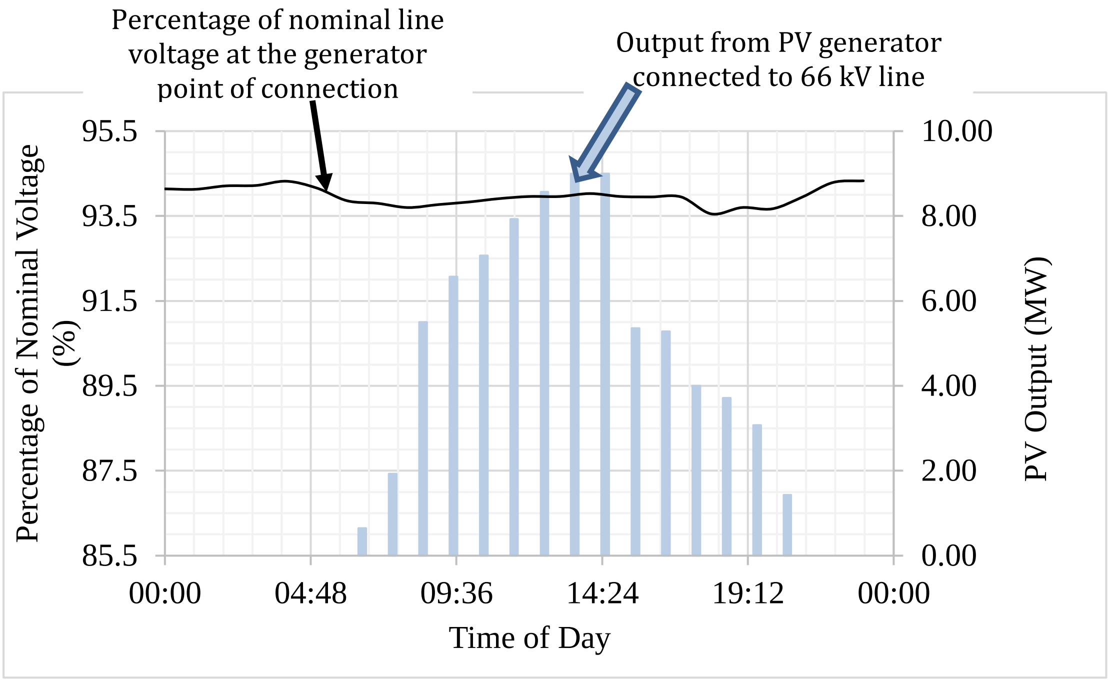


Figure 6.14: Voltage variation at photovoltaic plant point of connection

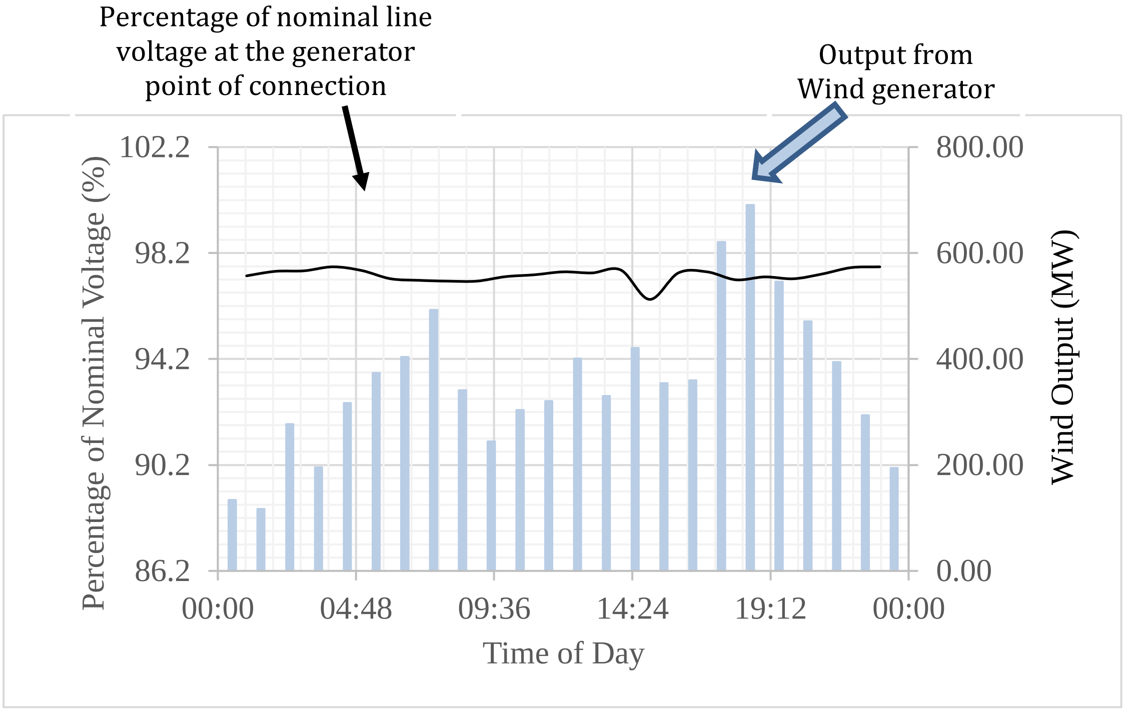


Figure 6.15: Voltage variation at wind plant point of connection

It can be observed from Figure 6.14 that the deviation in voltage at the POC of the photovoltaic plant is relatively higher when generation or demand are at their peaks. However, while the simulation model's voltage remains within the required range of 85 % to 110 %, both Figure 6.14 and Figure 6.15 show that grid intelligence is necessary to smooth the voltage at the POC of the renewable generators. As is the case for the (TDP) in South Africa outlined in Eskom (2017), using transmission lines of a higher voltage rating will resolve the challenge of over-voltage or under-voltage on transmission or distribution lines with high RE penetration levels. According to van der Walt (2016), decreasing the distance of the POC from the substation also results in a reduced voltage at the POC. However, distance of the POC is beyond the scope of this research.

Active damping of voltage fluctuations is another possible method to improve system stability (Givaki, 2017). Moreover, as observed for countries with high renewable energy penetration, artificial intelligence through smart grid systems will also enable renewable power plants to interact not only with each other but also match power quality levels with the grid's (Crossland, 2014; Stetz *et al.*, 2013; Tonkoski *et al.*, 2010). The advanced grid intelligence in Germany is evident from the following grid code requirements (German-Swedish Chamber of Commerce, 2018; Rangarajan *et el.*, 2018):

- **Voltage Range:** In Germany, renewable power plants can operate at a voltage in the range -20 % to +15 %. This is more liberal compared to South Africa's range of -15 % to +10 %. The implication in this case is that the control systems in the grid can handle large voltage variations to prevent them from overloading the infrastructure.
- **Frequency Control:** For the same disconnection time requirements, renewable power plants in Germany must operate within a frequency range of range 47.5 Hz and 50.2 Hz. This is a relatively narrower range compared to South Africa's 47.0 Hz and 50.5 Hz. Since frequency depends on the balance between supply and demand on the electrical grid, a narrow range means high-speed technology is available to manage generation and demand side. Hence, the frequency is expected to be 50 Hz virtually all the time.

To introduce basic grid intelligence to the system model, inductive-capacitive shunt controllers (LC) were incorporated into the simulation model to regulate the system voltage. Using the generation profile data as described for Figure 6.13 and Figure 6.14, the model with controllers is shown in Figure 6.16.

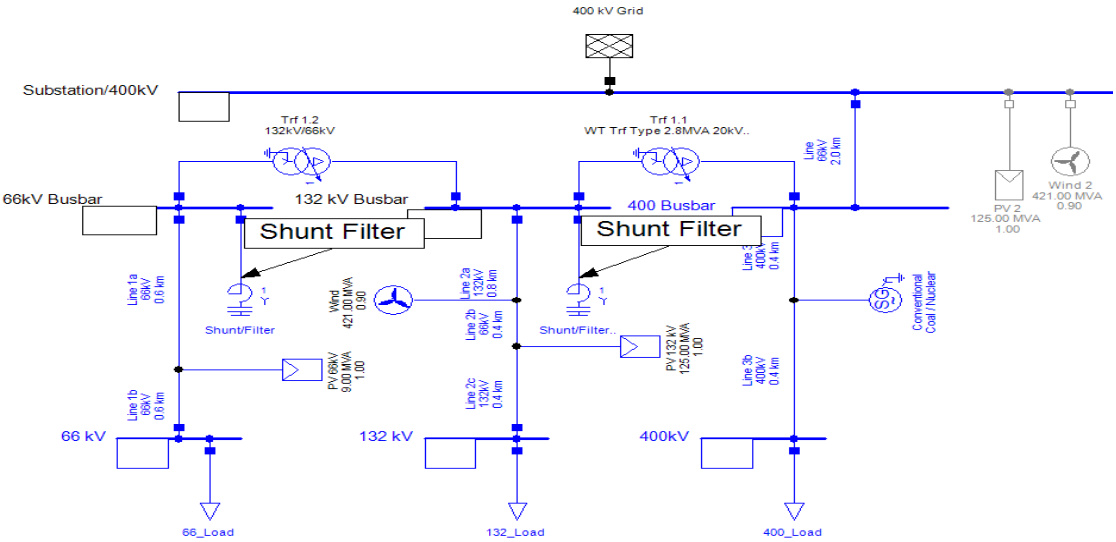


Figure 6.16: Grid model with shunt filter

The shunt filters in Figure 6.16 regulate the bus voltage by supplying or absorbing reactance power. This principle of power quality control is largely acceptable in several countries including Germany, Denmark and South Africa for the suppression of electrical system disturbances at the grid end. The control systems, however become more complicated in grid-connected photovoltaic systems which have non-linear loads (Mohamed *et al.*, 2017; Onwunta, 2014). The resulting voltage profile is shown in Figure 6.17.

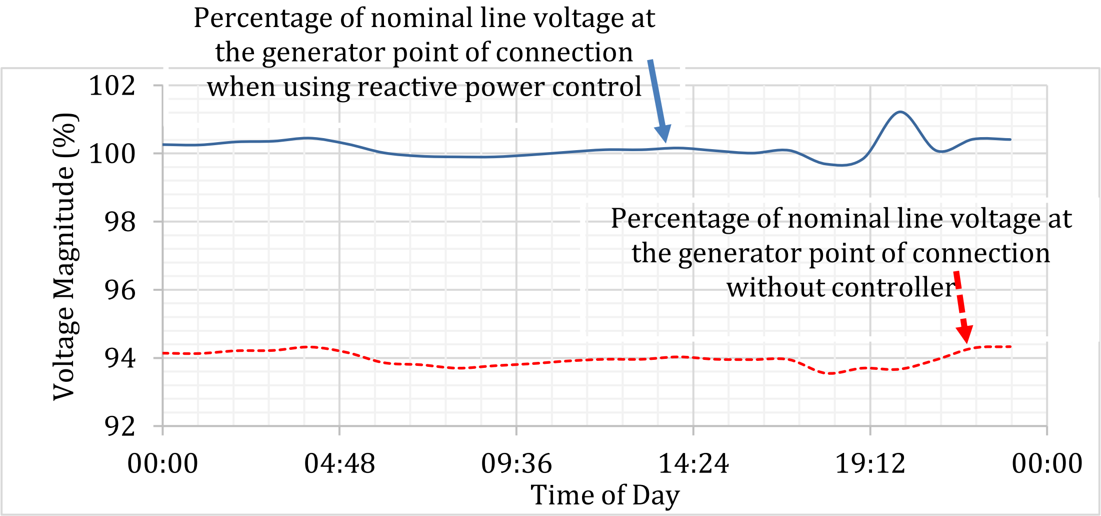


Figure 6.17: Transmission line voltage improvement with LC shunt filter

It should be noted from Figure 6.17 that before including the LC filter, the system voltage was compliant with the requirements of the grid code as shown by the bottom line graph. However, the improvement in the voltage towards the nominal value because of the filter shows that there are technologies available which can be used to match renewable generation to the electrical network. The simulation results are given n in Table C.3 in Appendix C.

6.3. Grid Support with Concentrated Solar Power

From the simulations carried out in this report to this point, it is evident that depending on the physical point of connection, the sizing of the generation capacity and support from control technologies, renewable power does not have a negative impact on the electricity network. More specifically, concentrated solar power plants, CSP have proven to be effective as merit-load or base load due to their dispatchability (Auret, 2015). In addition, studies have shown that in South Africa, this dispatchability is possible throughout the year (Onwunta, 2014). In this section, simulations were carried out to validate that CSP can be used to improve grid power dispatchability without compromising power quality. As explained in section 2.4.2 CSP power plants have impressive ramping rates on the output. The studies carried out in this section aim to use the fast response rates of CSP technology to regulate voltage, and consequently power quality of the electricity system by controlling the active power injected from the CSP plant. The simulation model used is shown in Figure 6.18.

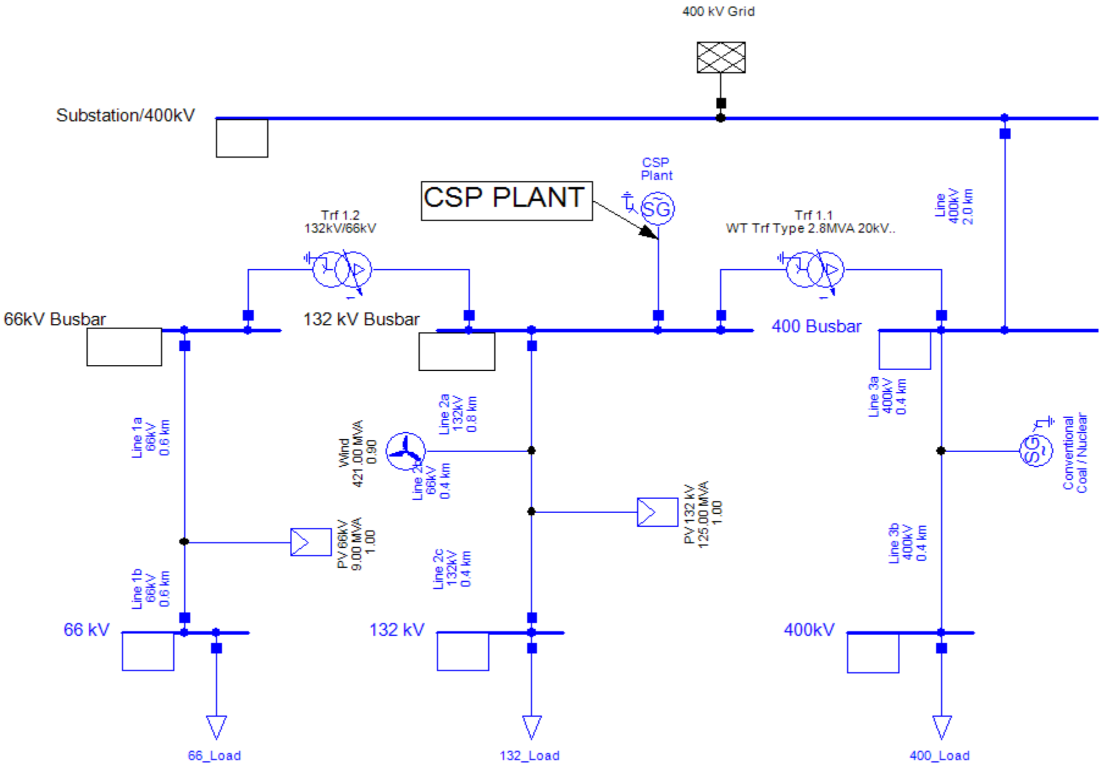


Figure 6.18: Concentrated solar plant connection

The CSP plant is modelled using a synchronous generator model which is also readily available in PowerFactory. As a result, when integrated to the grid, the characteristics of the power output are the same properties as a typical synchronous generator (Onwunta, 2014; Ntlahla, 2014). Unlike wind power plants, the South African grid code does not give special requirements exclusive to CSP. Therefore, CSP power plants are only required to comply to the same requirements applicable to all renewable power plants (Eskom, 2012).

The bar graphs in Figure 6.19 show the generation in the simulation model, while the line graph shows the demand. The graph shows the case described in section 6.1 where the renewable contribution is from both wind and the photovoltaic plant connected to the 132 kV and 66 kV transmission lines.

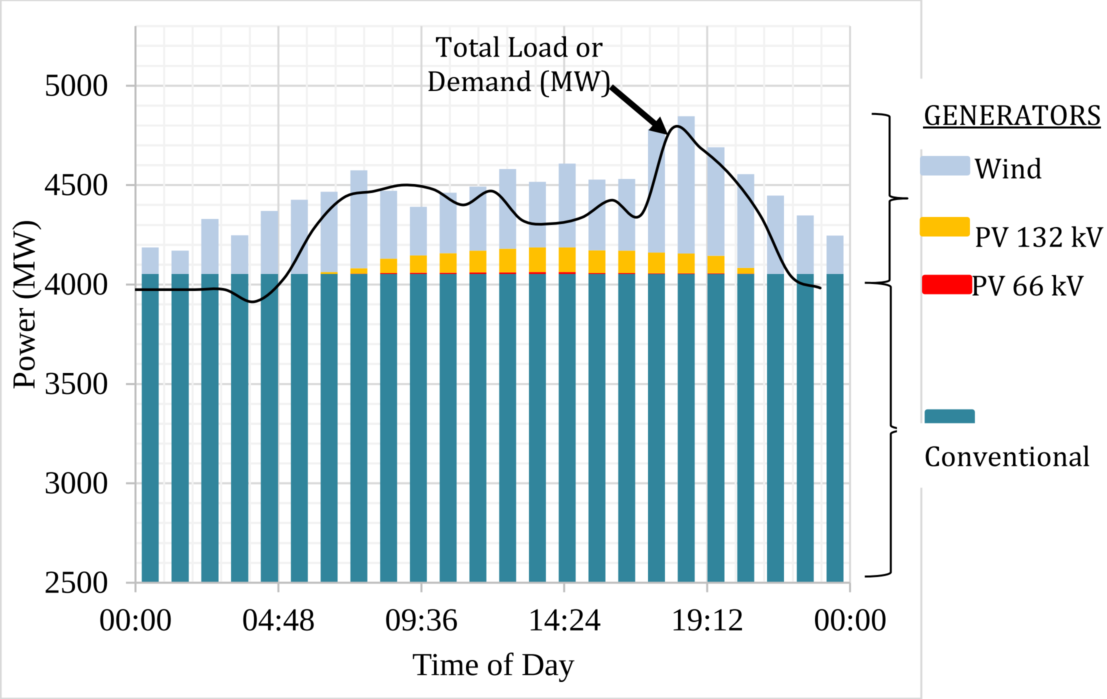


Figure 6.19: Simulation generation profiles using wind and photovoltaic to supply excess demand

It can be observed from Figure 6.19 that the profile of renewable generation throughout the day does not match the demand. The simulated data was designed to match the morning and evening peak demand. However, the mis-match between demand and supply throughout the day enabled the observed results to show how the intermittent nature of solar and wind affect the results. Even though there is a lot of wasted energy especially between 12 pm and 4 pm, the renewable energy is still unable to completely supply the required extra generation for the evening peak demand.

It can be observed from Figure 6.19 that the availability of the wind and solar resources are extremely unpredictable. Even when the capacity is over sized, their contributions cannot be guaranteed especially during peak times (De Sisternes, 2014). By replacing the wind and PV power plant with a concentrated solar power, renewable generation can be shifted from periods of low demands to peak demand hours. Figure 6.20 shows a case where the renewable contribution is from CSP only.

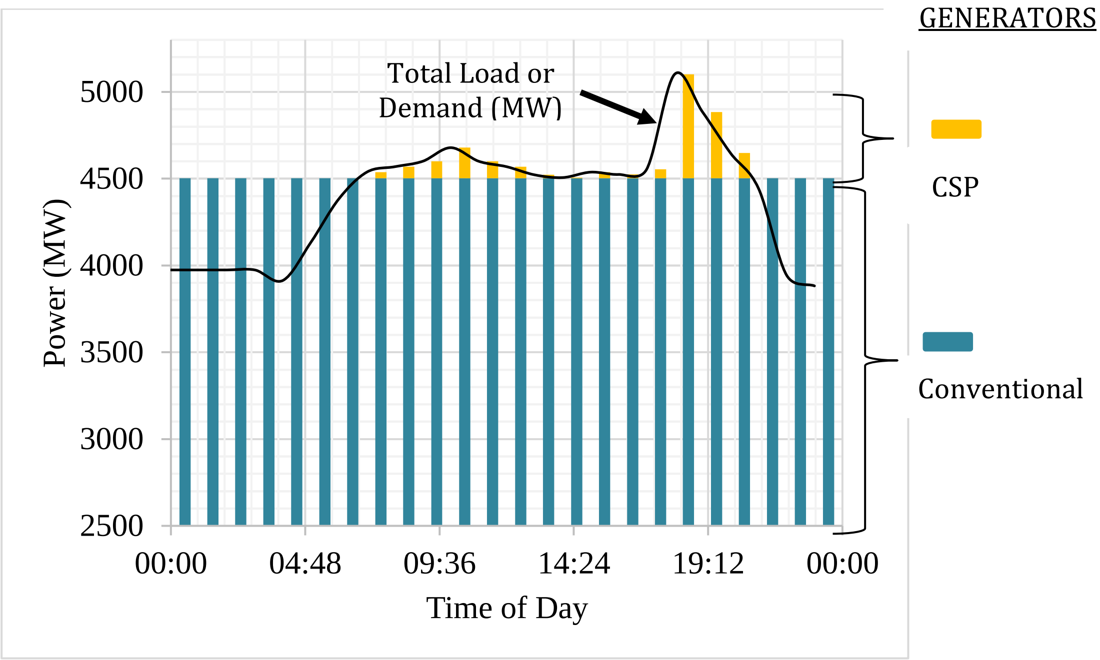


Figure 6.20: Simulation generation profiles using concentrated solar power to supply excess demand

CSP plants operate similar to other steam turbines which can all manifest some form of uncertainty sometimes. Consequently, can be seen from Figure 6.20 that CSP can be used to match renewable generation to the demand more accurately than wind and solar PV.

Using the similar data to Figure 6.16, the simulation model was modified to include CSP power output at the 132 kV substation, without a shunt controller on the bus. Given that high ramp up rates are possible, the CSP plant is set to provide power on demand at a power factor of 0.8. During the period when there is no active power required from the CSP plant, the plant supplies constant reactive power. Figure 6.21 shows the deviation of the bus voltage from the nominal for simulations where CSP was the only renewable generation and where there was no CSP generation, i.e. only wind and photovoltaic for renewable contribution.

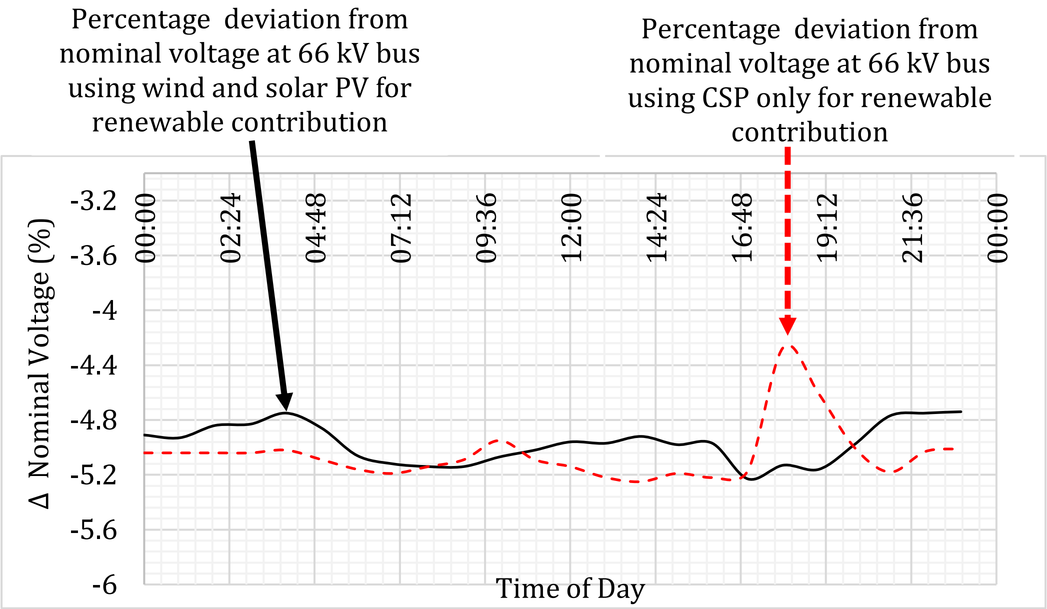


Figure 6.21: Deviation from 66 kV bus voltage for a system with renewable generation

The red line graph in Figure 6.21 shows the deviation of the voltage profile for the case with CSP. It can be observed that during the morning and evening peak times, the CSP voltage profile is much closer to the nominal than the case for wind and solar. This is because CSP plants dispatch on demand, therefore not overloading the system. For the times when the is no generation required from CSP, for example between 12 am and 4 am, CSP generators can be used to provide reactive power support to the electrical grid. However, for this simulation model, this was not necessary since the voltage is still with the acceptable range of – 15 % to + 10 %. The simulation results are given n in Table C.4 in Appendix C.

The simulation therefore, validates that the synchronous turbine generators and thermal storage enable CSP to contribute to grid stability. Fundamentally, CSP power plants can be used to support renewable energy integration by offering reactive power, voltage and frequency control without requiring any spinning reserve in the electricity system,

In Europe, the CSP system with thermal energy storage also generates income from the heat market. Consequently, a study by Fursch *et al.*, (2013) shows that in these combined heating and power systems such as CSP, the overall costs in the electricity system costs are reduced. This is because there is less electricity demand from the heat market.

This implies that if industries with high heating requirements could be located near CSP plants or vice versa, the loading on the electrical network could be reduced significantly. This is because, processes which normally require electrical energy to produce heat will be able to acquire heat directly from the power plant. Therefore, reducing the electrical energy demand on the grid.

6.4. Summary

Matching distributed generation to any electricity system can be realized only if technical feasibility studies are carried out on the grid. While the demand and supply requirements for every electrical network is unique, the following strategies obtained from the simulations carried out in this report, can be useful for integrating more renewable generation to the South African electricity system.

- The impact of the renewable energy generator on the electrical network is dependent on, among other factors, the penetration level and strength of the electrical infrastructure
- Matching the output of the generators to demand is essential to minimise loading on the electrical network.
- Relative to a direct connection to the transmission line, the physical point of connection points for new power plants to the grid will have the least strain on the transmission or distribution network components if located at the substation.
- The hybrid structure of CSP plants, synchronous generators with thermal storage not only enables provision of active power on demand but also complements the grid by providing reactive power support during periods of reduced demand.
- CSP power stations have potential to reduce loading on the electrical network by supplying heat directly to industries which normally use electrical energy for heating systems

CHAPTER 7

7. CONCLUSIONS

7.1. Motivation for Research

In the last years Germany achieved 100 % renewable electricity generation in some areas. On the contrary, South Africa increased coal electricity generation because there was not enough electrical power generation to reliably support all Eskom's customers in South Africa. To promote renewable generation, the Renewable Independent Power Producers Procurement Program (REIPPPP) was setup with the purpose of increasing the generation capacity on the grid.

Unfortunately, the inherently intermittent nature of these sources has resulted in some limiting regulatory requirements to protect the electrical grid infrastructure. For example, because solar power is not guaranteed to be available during the evening demand peak when its most needed the grid code specifies the regulatory requirements to ensure that integrity of the grid is not compromised. Therefore, indirectly encouraging fossil fuel electricity generation.

On the other hand, the South African electricity grid was originally largely constructed around the coal mines. The challenge here is that the renewable energy resource is more geographically dispersed to regions where the electrical infrastructure is weak. Therefore, the amount of renewable generation which can be incorporated into the current electricity system is limited.

The main motivation for this research was to determine how renewable energy can be incorporated reliably given the current South African electrical network infrastructure. Therefore, by referring to countries with high renewable energy penetration, determine the best possible grid connection strategies to increase the penetration for wind and solar power plants.

By considering strategies applied in a country with high renewable energy penetration, the aim was to recommend some of these strategies for the South African electricity system. The aim of the simulations carried out was to validate some of the challenges, derived from literature, associated with the integration of renewable generation onto the electrical grid.

7.2. Key Findings

The main significance of this project was to provide South Africans with a framework in which reliable electrical power while reducing the reliance on fossil fuels such as diesel and coal can be achieved. The main research question was:
'How does renewable energy affect the electricity system?'

Power system analysis tools like PowerFactory make it possible to investigate such research questions. By utilizing PowerFactory's highly flexible applications, different connection strategies under different penetration levels could be compared and the limitations of the electrical infrastructure illustrated. Matching renewable energy with Eskom's electricity transmission and distribution is necessary to ensure that the new power plants will be integrated to the electrical grid at the correct voltage and frequency and match the demand of electricity.

This research was necessary to determine a solution for the areas where the existing electricity infrastructure has been detrimental to the increase in renewable energy penetration. Based on the results, it was found that from a technical perspective, renewable energy can be matched to the electricity system by correctly calculating the points of connection and the sizes of the system. However, although the socio-economic factors were beyond the scope of this research, the study showed that it was found that a decentralised system is more financially manageable for the utilities. Without too much modification to the current infrastructure or taking any customers off grid, decentralisation can help to better manage the grid stability and reliability.

While the technical challenges associated with connecting renewables on to the grid are not unique to South Africa, South Africa unfortunately does not manufacture most of the associated technologies locally.

The keys findings derived from this report are summarized below:

- The generation connection capacity assessment which is made possible by PowerFactory is pivotal in understanding the available grid capacity to connect distributed generation. However, only when this understanding is coupled with a more decentralized electricity system does the system encourage private entities and the public to contribute freely to the renewable energy integration.
- The grid code is put in place to protect the electrical infrastructure and maintain the integrity of all electricity systems. However, a decentralized electricity network offers more unprejudiced regulatory requirements. Therefore, renewable energy programs such as the REIPPPP may need to be revised as penetration levels increase and intelligent control and analysis systems become available.

In addition, in matching renewables to the South African electricity system, the following steps which have already been taken, should be highlighted:

- While the electricity supply system is still centralized, the independent power producer (IPP) programs have been established to attract investments from private companies.
- In terms of adopting favourable government policies, a transmission development plan, (TDP) is updated annually and has been put in place to expand and maintain the electrical network. The need for IPPs to connect to a substation in a centralized system means that new substations are required in regions where new power plants are being built. The new power plants investments have been attracted by the REIPPPP and the coal baseload IPP procurement program.
- Engaging the public through for example, the new integrated resource plan, which was released for public comment in August 2018, has promoted local research on technologies and favourable strategies in the integration of renewable technologies to the electricity system.

7.3. Recommendations for Future Work

The research presented in this report can be further expanded by investigating the socio-economic factors which affect the integration of renewables on to the electrical grid. The main focus can be on other developing countries such as Zimbabwe, Mozambique and Nigeria which have an indisputable energy deficit but an abundance of renewable energy resource. The future work can also be extended to other renewable energy sources apart from wind and solar.

It is also necessary to analyse the policies which influence renewable power generation in South Africa. Of particular interest would be an investigation of the total capacity of off-grid renewable projects (large scale and small scale) and the policies which have restrained these projects from being connected to the grid.

REFERENCES

ABB (2016). *Standards and grid codes – the latest developments and trends.* ABB Conversations. Available at: https://www.abb-conversations.com/2016/10/standards-and-grid-codes-the-latest-developments-and-trends/. [Accessed 21 January 2019].

Ackermann, T., Martensen, N., Brown, T., Schierhorn, P., Boshell, F., Gafaro, F., Ayuso, M (2016). *Scaling up variable renewable power: The role of grid codes*. Abu Dhabi: International Renewable Energy Agency, IRENA.

Agora Energiewende (2018). *Energiewende 2030: The Big Picture. Megatrends, targets, strategies and a 10-point agenda for the second phase of Germany's energy transition*. Berlin, April 2018. Germany: Agora Energiewende.

Allianz Climate Solutions (2017). *Assessing the needs and attractiveness of low-carbon investments in G20 countries.* Allianz climate and energy monitor 2017. Germany: Allianz Climate Solutions GmbH.

Arias, I. M. I. (2006). *Grid codes comparison*. Masters in Electric Power Engineering. Sweden: Chalmers University of Technology.

Addalla, O. H., Al-Badwawi, R., Al-Hadi, H., Al-Riyami, H., Al-Nadabi, A. (2015). *Steady-state and transient performances of Oman transmission system with 200MW concentrated solar power plant*. Oman: Oman Electricity Transmission Company.

Amigun, B., Brent, A. (2011). *Sustainable electricity generation technologies in South Africa: Initiatives, challenges and policy implications*. Energy and Environmental Research, 1(2011), 124-138.

Auret, C. (2015). *Scenario modelling for short to long term rollout of concentrating solar power in South Africa*. Master of Engineering in Mechatronics. South Africa: Stellenbosch University.

Banks, D. I., Schäffler, B. (2006). *The potential contribution of renewable energy in South Africa, 2nd Ed.* RAPS Consulting & Nano Energy, prepared for SECCP, Earthlife Africa Johannesburg.

Barday, M. (2016). Controlled Disclosure. *Standard for MV/LV self-build customer projects in distribution*, 240-99376650, Revision 1, South Africa: Eskom.

Bofinger, S., Zimmermann, B., Gerlach, A., Bischof-Niemz, T., Mushwana, C. (2016). *Wind and solar PV resource aggregation study for South Africa*, South Africa: Fraunhofer IWES and CSIR.

Boie, I, (2016). *Determinants for the market diffusion of renewable energy technologies: An analysis of the framework conditions for non-residential photovoltaic and onshore wind energy deployment in Germany, Spain and the UK*. Doctor of Philosophy in Geography. United Kingdom: University of Exeter.

Boie, I., Kost, C., Bohn, S., Agsten, M., Bretschneider, P., Snigovyi, O., Pudlik, M., Ragwitz, Ma., Schlegl, T., Westermann, D. (2016b). Renewable energy. *Opportunities and challenges of high renewable energy deployment and electricity exchange for north Africa and Europe scenarios for power sector and transmission infrastructure in 2030 and 2050*, 87 (2016), Pt.1, 130-144.

Burger, B. (2018). *Power Generation in Germany: Assessment of 2017*. Berlin: Fraunhofer Institute for Solar Energy Systems.

Calitz, J. (2017). *Statistics of utility-scale solar PV, wind and CSP in South Africa in 2016*. Available at: https://www.csir.co.za/sites/default/files/Documents/Statistics%20of%20Wind%20and%20Solar%20PV%20in%20SA%20in%202016%20-%20CSIR%20-%20PUBLISHED.pdf [Accessed 24 July 2018].

Calitz, J., Mushwana, C., Bischof-Niemz, T. (2018). *Statistics of utility-scale solar PV, wind and CSP in South Africa in 2016*. 1st ed. South Africa: CSIR Energy Centre.

Clean Energy Wire (2018). *A reporter's guide to the Energiewende*, Volume 5, 2018, Germany: CLEW.

Chovatia, C. M., Gupta, N. P., Gupta, P. N. (2018). International journal of emerging technology and advanced engineering. *Harmonic mitigation using shunt active filter at utility end in grid connected to renewable source of energy*, Volume 2, Issue 8, August 2012, 230 - 235.

Craib, A. (2013). S*tandard for the interconnection of embedded generation*, 240-61268576, Revision 1, South Africa: Eskom.

Crossland, A. F. (2014). *Application of stochastic and evolutionary methods to plan for the installation of energy storage in voltage constrained LV networks*. Doctor of Philosophy School of Engineering and Computer Science. United Kingdom: Durham University.

Dallinger D. Schubert G., Wietschel M. (2012). Integration of intermittent power supply using grid-connected vehicles. *A 2030 case study for California and Germany*, Fraunhofer ISE: Working Paper Sustainability and Innovation, No. S 4/2012, 17 - 18.

Department of Energy (2015). *State of renewable energy in South Africa*. South Africa: DOE.

Department of Energy (2016a). *Integrated resource plan update: assumptions, base case results and observations*, Revision 1, South Africa: DOE.

Department of Energy (2016b). *Independent power producer's procurement program (IPPP) –An Overview*, South Africa: DOE.

Department of Energy (2018). *Integrated resource 2018, Final Draft_22/8/2018 for public input*, South Africa: DOE.

de Jongh, D., Ghoorah, D., Makina, A. (2014). Journal of Energy in Southern Africa. *South African renewable energy investment barriers: An investor perspective*, Volume 25, Issue 2, pp. 15 - 27.

de Sisternes, F. J. (2014). *Risk implications of the deployment of renewables for investments in electricity generation*. Doctor of Philosophy. USA: Massachusetts Institute of Technology.

DigSilent (2016). *PowerFactory: Licensing & Software Editions*. Available at: http://digsilent.ir/wp-content/uploads/2016/08/PowerFactory_LicenceTypes_SoftwareEditions.pdf [Accessed 16 August 2018].

DigSilent (2017). *Digsilent Powerfactory 2017: User manual*. Version 2017. Germany: DigSILENT.

DigSilent (2018a). *Integrated power system analysis software for transmission / distribution / industry / generation / integration of renewables*. Powerfactory 2018. Germany: DigSILENT.

DigSilent (2018b). *Integrated power system analysis software. Digsilent powerfactory for wind power applications*. Powerfactory 2018. Germany: DigSILENT.

DigSilent (2018c). *Integrated power system analysis software. Digsilent powerfactory for solar power applications*. Powerfactory 2018. Germany: DigSILENT.

DigSilent News (2003). *Eskom distribution chooses Digsilent powerfactory*. Available at: http://80.156.202.82/index.php/company-news-detail/items /eskom-distribution-chooses-digsilents-powerfactory.html. [Accessed 16 August 2018].

Dinter, F., Mayorga Gonzalez, D. (2014). Operability, reliability and economic benefits of CSP with thermal energy storage: first year of operation of ANDASOL 3. *In SolarPaces 2013*. USA, 17 - 20 September 2013. Germany: Energy Procedia. 2472 – 2481.

DOE Act (2016). *Grid resiliency pricing rule. Notice of proposed rulemaking*. Department of Energy Organization Act: Docket Number RM17-3-000, 18 CFR Part 35. Available at: https://www.energy.gov/sites/prod/files/2017/09/f 37/Notice%20of%20Proposed%20Rulemaking%20.pdf [Accessed 25 August 2018].

Edkins, M. Marquard, A., Winkler, H. (2010). *Assessing the effectiveness of national solar and wind energy policies in South Africa*. Available at: https://www.erc.uct.ac.za/.../10Edkinesetal-Solar_and_wind_policies.pdf [Accessed 24 July 2018].

Eskom (2012). *Grid connection code for renewable power plants (RPPs) connected to the electricity transmission system (TS) or the distribution system (DS) in South Africa*, Version 2.6, South Africa: National Energy Regulator of South Africa (NERSA).

Eskom (2017). *The Eskom Transmission Development Plan 2018 to 2027 (TDP 2017): Public Forum.* South Africa: Eskom.

Eskom, Generation Communication Department (2013). *Eskom power stations*, February 2013.

Eskom, Generation Communication Department (2017). *Fact sheet. The roles of voltage and frequency in the transmission of electricity*, November 2017. TD 0004 Revision 6.

Federal Ministries of Economic Affairs and Energy, (2015). *Making a success of the energy transition*. Germany: Federal Ministries of Economic Affairs and Energy.

Federal Ministry for Economic Affairs and Energy, (2018). 2017 Revision of the renewable energy sources Act. *Key points of the decision by the German Bundestag of 8 July 2016*. Available at: https://www.bmwi.de/Redaktion /EN/Downloads/2017-revision-of-the-renewable-energy.pdf?__blob= publicationFile&v=2 [Accessed 20 June 2018].

Ferroni, F., Hopkirk, R.J., (2016). *Energy return on energy invested (ERoEI) for photovoltaic solar systems in regions of moderate isolation*. Energy Policy, Volume 94, pp. 336–344

Fursch, M., Hagspiel, S., Jagemann, C., Nagl, S., Lindenberger, D., Troster, E. (2013). Applied Energy. *The role of grid extensions in a cost-efficient transformation of the European electricity system until 2050*. Volume: 104, Issue C, pp. 642-652.

Gauche, P. (2016). *Spatial-temporal model to evaluate the system potential of concentrating solar power towers in South Africa*. Doctor of Philosophy in Engineering. South Africa: Stellenbosch University.

Gauche, P., Pfenniger, S., Meyer, A. J., von Backstrom, T. W., Brent, A. C. (2012). Modelling dispatchability potential of CSP in South Africa. *In southern Africa, solar energy conference*. South Africa, 21-23 May 2012. South Africa: SASEC. Pp. 1 - 2.

German-Swedish Chamber of Commerce, (2018). *Smart grid market analysis: Germany*. Sweden: Swedish smart grid.

Gill, S., Plecas, M., Kockar, I. (2014). *Distributed generation on 11kV voltage constrained feeders*. Report produced by University of Strathclyde for the Accelerating Renewables Connection Project. United Kingdom: University of Strathclyde.

Givaki, K. (2017). *Integration of large wind farms to weak power grids*. Doctor of Philosophy. United Kingdom: University of Strathclyde.

Gonzalez-Longatt, F., Chikuni, E., Rashayi, E. (2013). *Effects of the Synthetic Inertia from Wind Power on the Total System Inertia after a Frequency Disturbance*. 2013 IEEE International Conference on Industrial Technology (ICIT), 978-1-4673-4569-9, 826 - 832.

Govender, T. (2017). *Transmission development plan 2018-2027 (TDP 2017)*, South Africa: Eskom.

GreenCape, (2017). *Utility-Scale Renewable Energy: 2017 Market Intelligence Report*. South Africa: GreenCape.

Grigsby, L. L. (2012). *The electric power engineering handbook: Electric power generation, transmission and distribution.* 3rd ed. USA: CRC Press, Taylor and Francis group.

Hansen, A. D., Sorensen, P., Iov, F., Blaabjerg, F., 2006. Renewable Energy (RENEW ENERG). *Centralised power control of wind farm with doubly fed induction generators*, Volume 31, Issue 7, pp. 935-951.

Heal, G. (2016). *Notes on the economics of energy storage*. NBER Working Paper 22752.

Hilton, T., Marquard, A. (2011). *Prospects for Renewable Energy in South Africa*. South Africa: Heinrich Böll Stiftung.

Justus, D. (2005). *International energy technology collaboration and climate change mitigation. Case Study 5: Wind power integration into electricity systems*, France: Organization for Economic Co-operation and Development, OECD.

Kang, H. (2016). *Establishing a new guideline for south Korea's renewable portfolio standard*. Master of Science in Engineering and Management. USA: Massachusetts Institute of Technology.

Kolhe, P. T. (2017). *TeleLab for decentralized hybrid power system with renewables*. Doctor of Philosophy. United Kingdom: University of Bolton.

Kost, C., Friebertshäuser, C., Hartmann, N., Fluri, T., Nitz, P. (2017). *The role of CSP in the electricity system of South Africa – Technical operation, grid constraints, market structure and economics.* In 22nd SolarPACES Conference. United Arab Emirates, 11-14 October 2016. Germany: Fraunhofer ISE. pp. 6.

Marks, J. (2016). *Two German states that reached 100 % renewable electricity*. Available at: https://inhabitat.com/two-german-states-reach-100-renewable-electricity/. [Accessed 23 August 2018].

Matlokotsi, T. (2017). *Power quality enhancement in electricity networks using grid-connected solar and wind based DGs*. Master of Science degree in Electrical Engineering. South Africa: University of Cape Town.

Mathews, J. A., Kidney, S., Mallon, K., Hughes, M. (2010). Energy Policy. *Mobilizing private finance to drive an energy industrial revolution*, Volume 38. Issue 37, pp. 3263–3265.

Merkel, M, (2014). *Integration of renewable energies into distribution grids – A case example from Germany*. In Integration of renewable energies into distribution grids: Innovation and comparative views. Germany, 27 March 2014. Germany: EWE NETZ GmbH.

Muhammad, A., Nasimullah (2017). Renewable Energy. *Performance comparison of wind turbine based doubly fed induction generator system using fault tolerant fractional and integer order controllers*, Volume 116, 2018, pp. 244 - 264.

Mohamed, J. M., Rasul, A., Khang, H. V., Kohle, M. (2017). Harmonic mitigation of a grid-connected photovoltaic system using shunt active filter. *In 2017 20th International Conference on Electrical Machines and Systems (ICEMS)*. Australia, 11-14 August 2017. Australia: IEEE.

Mushwana, C. (2014). *Generation connection capacity assessment of the 2016 transmission network*, Revision 2, South Africa: Eskom.

Muyeen, S. M., Takahashi, R., Murata, T., Tamura, J., 2010. IEEE transactions on power systems. *A variable speed wind turbine control strategy to meet wind farm grid code requirements*, Volume 25, Issue 1, pp. 331 - 340.

NERSA (2015). *Consultation Paper. Small-Scale Embedded Generation: Regulatory Rules*. Available at: http://www.nersa.org.za/Admin/Document/Editor/file/Consultation%20Paper%20on%20Small%20Scale%20Embedded%20Generation.pdf [Accessed 26 August 2018].

Ntlahla, N, (2014). *Impact of large scale grid-connected concentrated solar power and photovoltaic power on small signal and transient stability of the power system*. Bachelor of Science in Electrical Engineering. South Africa: University of Cape Town.

Olakunle, A. O. (2018). *Integration of renewable energy into Nigerian power systems*. Doctor of Philosophy. South Africa: University of Cape Town.

Oniemola, P. K. (2014). *Developing a legal framework for promoting investment in renewable energy in the Nigerian power sector: an analysis of the design and implementation challenges*. Doctor of Philosophy in law. Scotland: University of Aberdeen.

Onwunta, O. E. K. (2014). *Modelling and simulation of the impacts of distributed generation integration into the smart grid*. Doctor of Technology in Electrical Engineering. South Africa: Cape Peninsula University of Technology.

Pegels, A. (2010). *Renewable energy in South Africa: Potentials, barriers, and options for support*. Energy Policy, Volume 38. pp. 4945 – 4954.

Perera, B. K., Ciufo, P., Perera, S. (2013). *Point of common coupling (PCC) voltage control of a grid-connected solar photovoltaic (PV) system*. In IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society. Vienna, 10 -13 November 2013. Austria: IEEE.

Pinter, G, (2014). *A comparative analysis of the electricity and telecommunications regulations of the UK and Germany - cross country and cross sectoral lessons*. Doctor of Philosophy. England: University of East Anglia.

Portfolio Committee on Energy, (2018). *Presentation on the independent power producer procurement programme.* Parliament, Cape Town. Available at: https://sawea.org.za/wp-content/uploads/2018/04/Presentation-to-PCE-on-IPP_06-March-2018.pdf [Accessed 7 August 2018].

Prins, N. (2018). *South Africa's nuclear new build program :The domestic requirements for nuclear energy procurement and public finance implications*. South Africa: WWF South Africa.

Ralon, P., Taylor, M., Ilas, A., Diaz-Bone, H., Kairies, K., (2017). *Electricity storage and renewables: costs and markets to 2030*. Abu Dhabi: International Renewable Energy Agency, IRENA.

Ramdhin, A. (2014). *Grid integration of distributed and renewable energy sources: A network planning perspective*. Master of Science degree in Electrical Engineering. South Africa: University of Cape Town.

Rangarajan, S. S., Collins, E. R., Fox, J. C., Kothari, D., P. (2018). Journal of Energy Technology Research. *Consolidated compendium of PV interconnection standards and guidelines across the globe in a smart grid*, 2 (113).

REN21 Secretariat (2018). *Renewables 2018 global status report*. In renewable energy policy network for the 21st century. Paris: REN21. 24 -26.

SAWEA (2018). *Renewable energy power procurement: Why Eskom should finalise outstanding agreements*. Briefing note by South African Wind Energy Association, March 2018. Available at: https://sawea.org.za/wp-content/uploads/2018/03/SAWEA-Briefing-Note-on-Eskom-Agreements-Mar-2018.pdf [Accessed 24 August 2018].

Shultz, A. (2018). Office of energy efficiency & renewable energy. *concentrating solar power could provide the flexibility and reliability the U.S. electric grid needs*. Available at: https://www.energy.gov/eere/articles/concentrating-solar-power-could-provide-flexibility-and-reliability-us-electric-grid. [Accessed 20 June 2018].

Simpson, A. (2012). National assembly for wales: Documents. *Case study: Germany at the forefront*. Available at: http://www.senedd.assembly.wales/documents/s34101/Paper%201.pdf [Accessed 20 June 2018].

Sinn, H-W. (2017). *Buffering volatility: A study on the limits of Germany's energy revolution*. European Economic Review, Volume 99, 2017. pp. 130-150

Stetz, T., Marten, F., Braun, M. (2013). Improved low voltage grid-integration of photovoltaic systems in Germany. *IEEE Transactions on Sustainable Energy*, Volume 4. Issue 2. pp. 534 -542.

Taylor, S. (2015). *Germany's wind and solar deployment 1991 – 2015: Facts and lessons learnt*, Germany: EWI.

Thopil, M. S., Bansala, R.C., Zhanga, L., Sharmab G. (2018). Energy Strategy Reviews. *A review of grid connected distributed generation using renewable energy sources in South Africa*, Volume 21, 2018. pp. 88 -97.

Tonkoski, R., Lopes, L. A. C., El-Fouly, T. H. M. (2010). *Coordinated active power curtailment of grid connected PV inverters for overvoltage prevention.* In IEEE transactions on sustainable energy. Canada, 10 December 2010. Canada: IEEE. pp. 139 - 147.

Trainer, T. (2014). *Some inconvenient theses*. Energy Policy, Volume 64, January 2014. pp. 168–174.

Troester, E, (2009). *New German grid codes for connecting PV systems to the medium voltage power grid.* In 2nd international workshop on concentration photovoltaic power plants. Germany, 9 - 10 March 2009.

Tyler, E. (2012). *Germany's Transition to Renewable Energy – A Model for South Africa?* South Africa: Heinrich Böll Stiftung - Southern Africa.

van der Walt, H. L. R. (2016). *Photovoltaic based distributed generation power system protection.* Master of Engineering in Electrical Engineering. South Africa: University of Pretoria.

Wenzhong Gao, D., Muljadi, E., Tian, T., Miller, M., Wang W., (2016). *Comparison of standards and technical requirements of grid connected wind power plants in China and the United States*, USA: National Renewable Energy Laboratory, NREL.

Winkler, H. (2005). Energy Policy. *Renewable energy policy in South Africa: Policy options for renewable electricity*, 33 (2005), 27 - 38.

World Wildlife Fund (2014). *Climate change and energy: renewable energy vision 2030*, South Africa: WWF-SA.

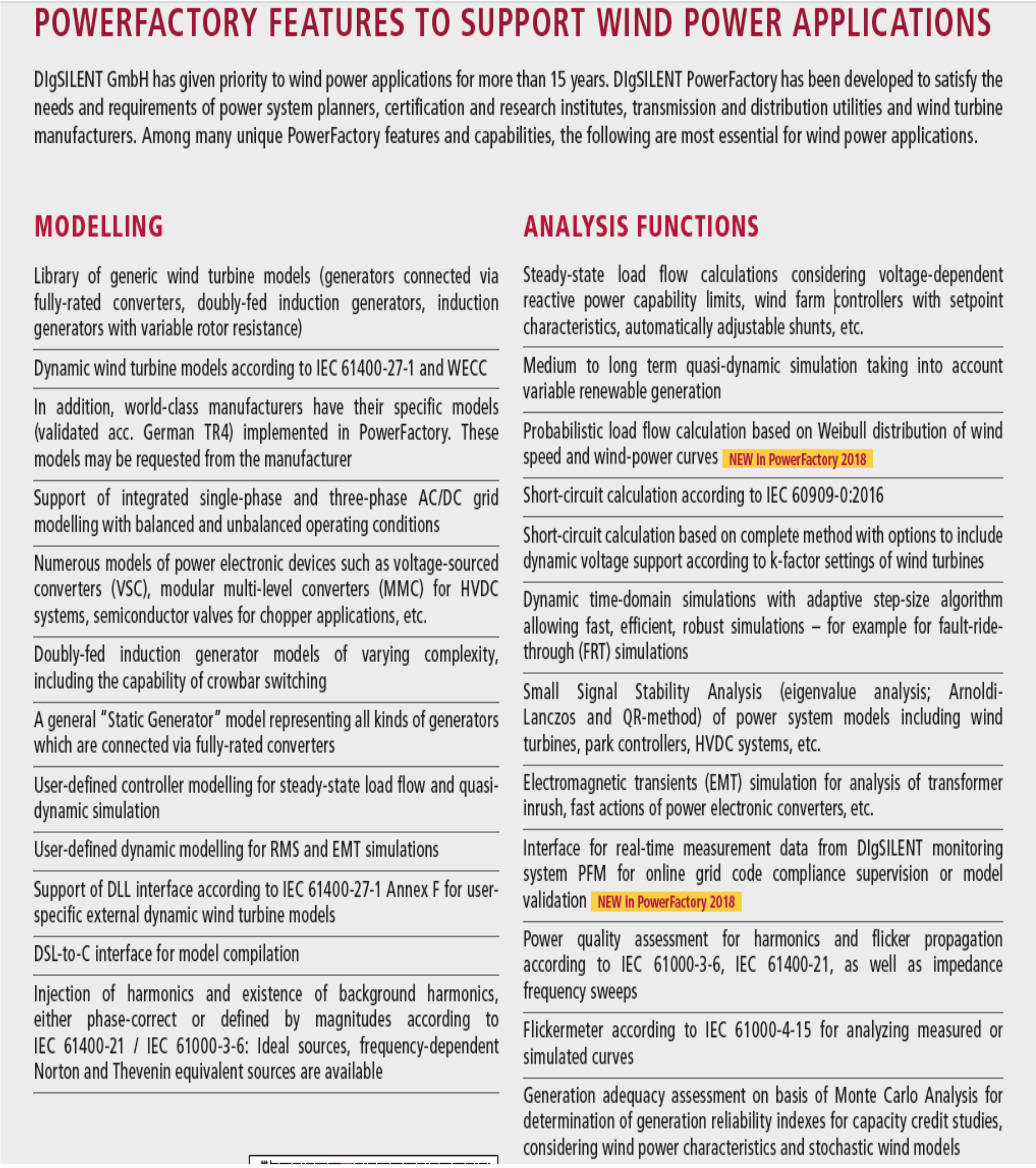
World Wildlife Fund (2015). *Energy: Feasibility of the renewable energy vision 2030- A spacial temporal analysis*, South Africa: WWF-SA.

World Wildlife Fund (2017). *Energy: Renewable energy: Facts and futures*. *The energy future we want*, South Africa: WWF-SA.

Wright, J. G., Dr Bischof-Niemz, T., Calitz, J., Mushwana, C., van Heerden, R., Senatla, M. (2017). *Formal comments on the Integrated Resource Plan (IRP) Update Assumptions, Base Case and Observations 2016*, South Africa: CSIR Energy Centre.

APPENDIX A:

A. DIGSILENT POWERFACTORY MODELS



POWERFACTORY FEATURES TO SUPPORT WIND POWER APPLICATIONS

DIgSILENT GmbH has given priority to wind power applications for more than 15 years. DIgSILENT PowerFactory has been developed to satisfy the needs and requirements of power system planners, certification and research institutes, transmission and distribution utilities and wind turbine manufacturers. Among many unique PowerFactory features and capabilities, the following are most essential for wind power applications.

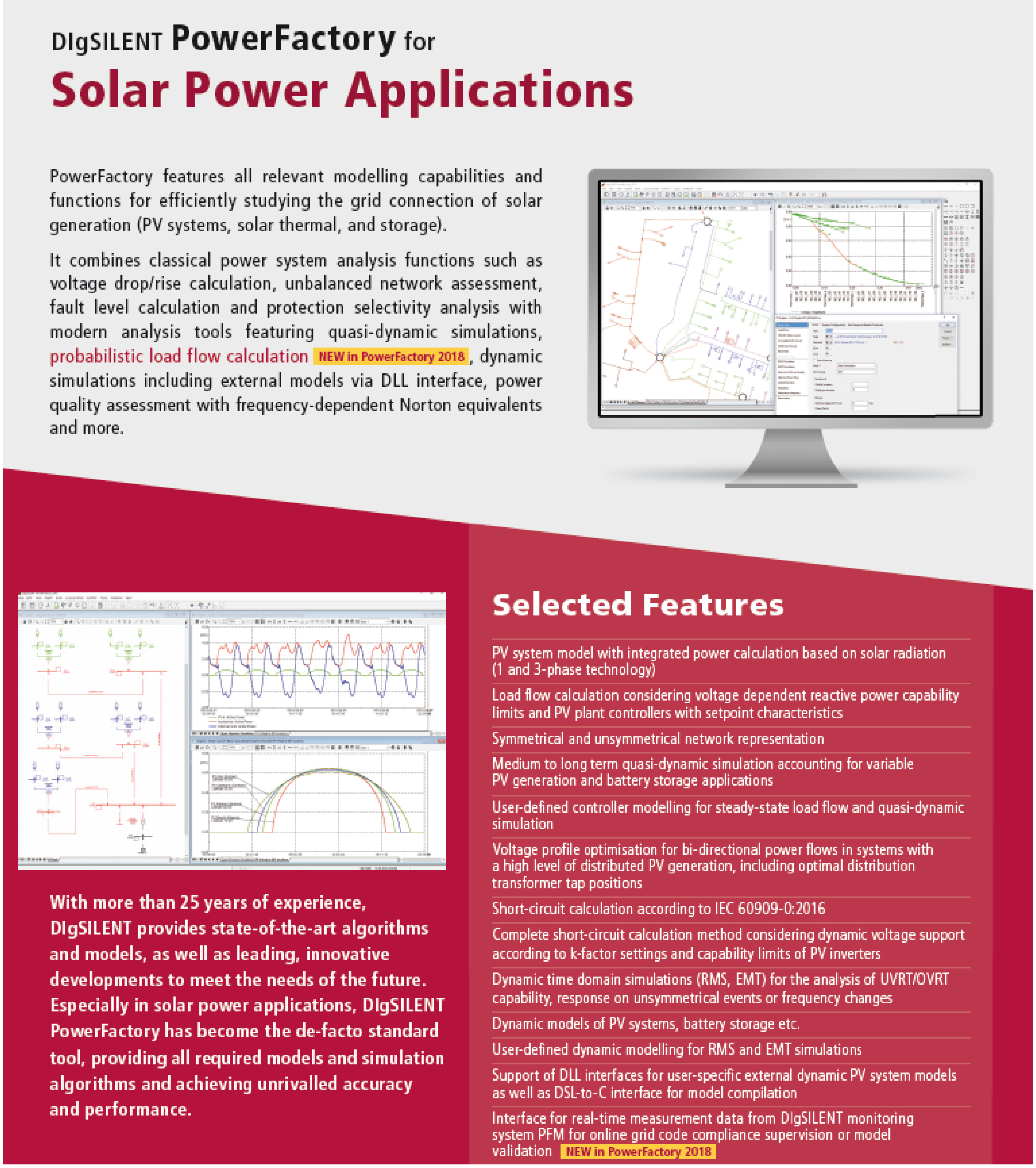
MODELLING

- Library of generic wind turbine models (generators connected via fully-rated converters, doubly-fed induction generators, induction generators with variable rotor resistance)
- Dynamic wind turbine models according to IEC 61400-27-1 and WECC
- In addition, world-class manufacturers have their specific models (validated acc. German TR4) implemented in PowerFactory. These models may be requested from the manufacturer
- Support of integrated single-phase and three-phase AC/DC grid modelling with balanced and unbalanced operating conditions
- Numerous models of power electronic devices such as voltage-sourced converters (VSC), modular multi-level converters (MMC) for HVDC systems, semiconductor valves for chopper applications, etc.
- Doubly-fed induction generator models of varying complexity, including the capability of crowbar switching
- A general "Static Generator" model representing all kinds of generators which are connected via fully-rated converters
- User-defined controller modelling for steady-state load flow and quasi-dynamic simulation
- User-defined dynamic modelling for RMS and EMT simulations
- Support of DLL interface according to IEC 61400-27-1 Annex F for user-specific external dynamic wind turbine models
- DSL-to-C interface for model compilation
- Injection of harmonics and existence of background harmonics, either phase-correct or defined by magnitudes according to IEC 61400-21 / IEC 61000-3-6: Ideal sources, frequency-dependent Norton and Thevenin equivalent sources are available

ANALYSIS FUNCTIONS

- Steady-state load flow calculations considering voltage-dependent reactive power capability limits, wind farm controllers with setpoint characteristics, automatically adjustable shunts, etc.
- Medium to long term quasi-dynamic simulation taking into account variable renewable generation
- Probabilistic load flow calculation based on Weibull distribution of wind speed and wind-power curves NEW in PowerFactory 2018
- Short-circuit calculation according to IEC 60909-0:2016
- Short-circuit calculation based on complete method with options to include dynamic voltage support according to k-factor settings of wind turbines
- Dynamic time-domain simulations with adaptive step-size algorithm allowing fast, efficient, robust simulations – for example for fault-ride-through (FRT) simulations
- Small Signal Stability Analysis (eigenvalue analysis; Arnoldi-Lanczos and QR-method) of power system models including wind turbines, park controllers, HVDC systems, etc.
- Electromagnetic transients (EMT) simulation for analysis of transformer inrush, fast actions of power electronic converters, etc.
- Interface for real-time measurement data from DIgSILENT monitoring system PFM for online grid code compliance supervision or model validation NEW in PowerFactory 2018
- Power quality assessment for harmonics and flicker propagation according to IEC 61000-3-6, IEC 61400-21, as well as impedance frequency sweeps
- Flickermeter according to IEC 61000-4-15 for analyzing measured or simulated curves
- Generation adequacy assessment on basis of Monte Carlo Analysis for determination of generation reliability indexes for capacity credit studies, considering wind power characteristics and stochastic wind models

Figure A.1: Extract of technical document for wind power applications (DigSilent, 2018b)



DIgSILENT **PowerFactory** for

Solar Power Applications

PowerFactory features all relevant modelling capabilities and functions for efficiently studying the grid connection of solar generation (PV systems, solar thermal, and storage).

It combines classical power system analysis functions such as voltage drop/rise calculation, unbalanced network assessment, fault level calculation and protection selectivity analysis with modern analysis tools featuring quasi-dynamic simulations, probabilistic load flow calculation NEW in PowerFactory 2018, dynamic simulations including external models via DLL interface, power quality assessment with frequency-dependent Norton equivalents and more.

With more than 25 years of experience, DIgSILENT provides state-of-the-art algorithms and models, as well as leading, innovative developments to meet the needs of the future. Especially in solar power applications, DIgSILENT PowerFactory has become the de-facto standard tool, providing all required models and simulation algorithms and achieving unrivalled accuracy and performance.

Selected Features

- PV system model with integrated power calculation based on solar radiation (1 and 3-phase technology)
- Load flow calculation considering voltage dependent reactive power capability limits and PV plant controllers with setpoint characteristics
- Symmetrical and unsymmetrical network representation
- Medium to long term quasi-dynamic simulation accounting for variable PV generation and battery storage applications
- User-defined controller modelling for steady-state load flow and quasi-dynamic simulation
- Voltage profile optimisation for bi-directional power flows in systems with a high level of distributed PV generation, including optimal distribution transformer tap positions
- Short-circuit calculation according to IEC 60909-0:2016
- Complete short-circuit calculation method considering dynamic voltage support according to k-factor settings and capability limits of PV inverters
- Dynamic time domain simulations (RMS, EMT) for the analysis of UVRT/OVRT capability, response on unsymmetrical events or frequency changes
- Dynamic models of PV systems, battery storage etc.
- User-defined dynamic modelling for RMS and EMT simulations
- Support of DLL interfaces for user-specific external dynamic PV system models as well as DSL-to-C interface for model compilation
- Interface for real-time measurement data from DIgSILENT monitoring system PFM for online grid code compliance supervision or model validation NEW in PowerFactory 2018

Figure A.2: Extract of technical document for solar power applications (DigSilent, 2018c)

APPENDIX B:

Key policies in South Africa's renewable integration
(World Wildlife Fund, 2017).

In South Africa, the **Integrated Resource Plan** (IRP) is termed the 'living plan" for the energy system nationally. The following are the other key policies and legislation which influence the energy system.

The **National Development Plan** (NDP) outlines the 2030 vision for South Africa's energy sector and envisages a sector that will promote, inter alia, 'economic growth and development through adequate investment in energy infrastructure and the provision of quality energy services.

The **Green Economy Accord** is an agreement between government, business and labour sectors which focuses on the need to stimulate the green economy and the critical need to create employment through renewable energy.

The **Integrated Energy Plan** (IEP) (2016), is more energy specific in that it provides a roadmap for the future energy landscape in South Africa and guides future energy infrastructure investments and policy development.

The **National Energy Act 34 of 2008**, is energy-specific legislation which provides for energy planning (including appropriate upkeep and access to energy infrastructure), increased generation and consumption of renewable energies. The legislation empowers the Minister of Energy to determine, approve and procure new electricity generation capacity. A licence for generation capacity is subject to ministerial approval.

Summary of regulations influencing Germany's renewable electricity system (German-Swedish Chamber of Commerce, 2018)

In Germany, the most general law with regards to energy is the **Energy Sector-Act** (*Energiewirtschaftsgesetz*, EnWG). The following are the more specific laws which are supposed to set the course for phase two of the energy transition.
The **Underground Cable-Act** (Erdkabelgesetz), which gives priority to underground cables instead of electricity pylons for newly planned transmission paths. This, however, prolongs the construction time.

The **Power Market-**Act (*Strommarktgesetz*) which aims to increase renewable energy share and competition. Furthermore, it provides regulations for a capacity reserve as a safety net for the new power markets being created.

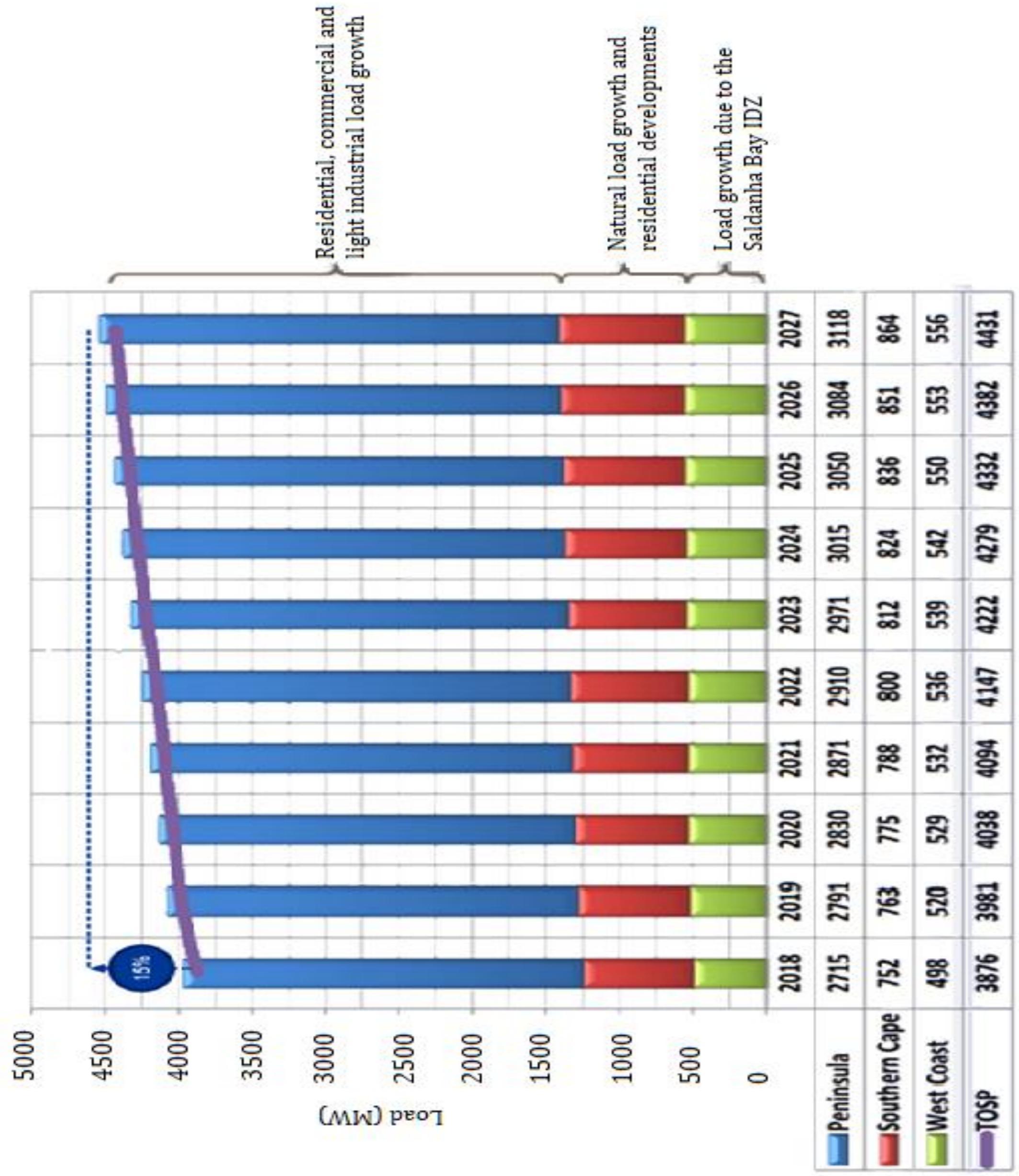
The **Digitising the energy Transition-Act** (*Gesetz zur Digitalisierung der Energiewende*) promotes smart grids, smart meters and smart homes in Germany. The most significant impact of this act is the rollout of smart meters with a pre-defined pricing model.

The **Renewable Energy Sources-Act** (*Erneuerbare Energien Gesetz*, EEG) which promotes renewable energy in a competitive and market oriented manner. This also reduces the constant price increases for the end-user. However, power plants with a capacity of less than 750 kW are not included in the tendering regulation.

APPENDIX C:

C. SIMULATION DATA

C.1. System Model Definition



	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
🟦 Peninsula	2715	2791	2830	2871	2910	2971	3015	3050	3084	3118
🟥 Southern Cape	752	763	775	788	800	812	824	836	851	864
🟩 West Coast	498	520	529	532	536	539	542	550	553	556
TOSP	3876	3981	4038	4094	4147	4222	4279	4332	4382	4431

Figure C.1: Western Cape load forecast (Eskom, 2017

Table C.1: Demand and generation data used for simulation model (Department of Energy, 2016b)

Time	66 kV Load (MW)	132 kV Load (MW)	400 kV Load (MW)	66kV PV (MW)	132 kV PV (MW)	Wind (MW)
00:00	259.19	618.39	3096.72	0.00	0.00	133.67
01:00	259.19	618.39	3096.72	0.00	0.00	116.94
02:00	259.19	618.39	3096.72	0.00	0.00	277.00
03:00	259.19	618.39	3096.72	0.00	0.00	195.39
04:00	255.25	610.49	3048.03	0.00	0.00	316.73
05:00	269.54	539.08	3224.32	0.00	0.00	373.49
06:00	285.88	571.75	3425.79	0.64	8.93	403.90
07:00	295.95	591.90	3550.03	1.93	26.78	492.86
08:00	297.99	595.98	3575.22	5.50	72.48	341.31
09:00	300.03	600.07	3600.40	6.57	87.35	244.31
10:00	305.14	510.28	3663.36	7.07	98.18	303.84
11:00	300.03	500.07	3600.40	7.93	110.08	320.70
12:00	297.99	595.98	3575.22	8.57	119.00	400.88
13:00	294.93	489.86	3537.44	9.00	124.95	330.43
14:00	293.91	487.81	3524.85	9.00	124.95	420.92
15:00	295.95	491.90	3550.03	5.36	114.38	354.51
16:00	295.07	590.14	3539.19	5.28	112.50	359.70
17:00	296.97	493.94	3562.63	4.00	104.65	620.92
18:00	332.70	545.41	3903.35	3.71	98.80	690.88
19:00	318.55	537.09	3828.74	3.07	88.88	545.56
20:00	303.10	606.19	3638.18	1.43	29.95	470.88
21:00	289.82	579.65	3474.48	0.00	0.00	394.19
22:00	257.29	514.58	3273.21	0.00	0.00	294.19
23:00	253.20	506.41	3222.84	0.00	0.00	193.98

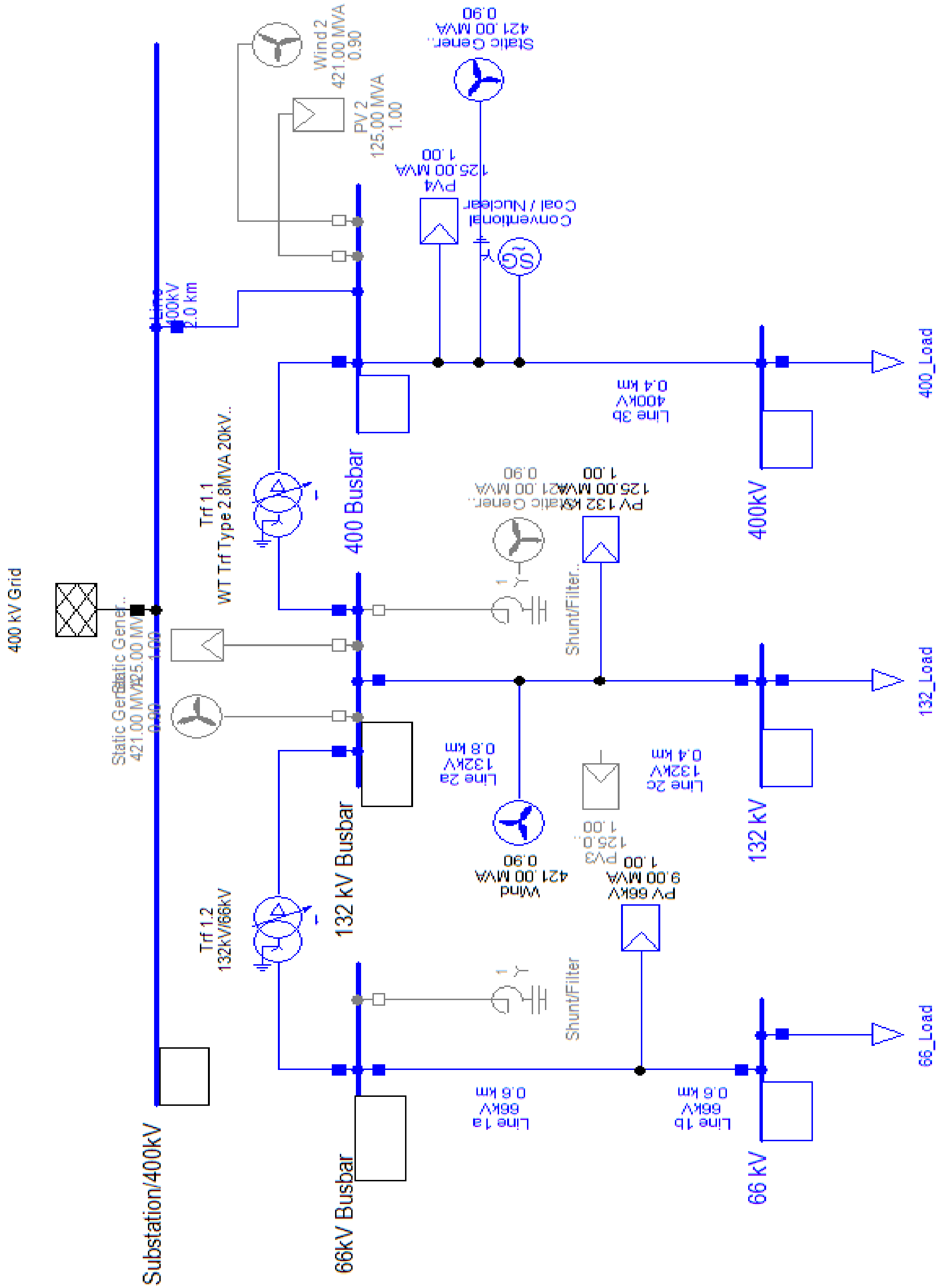


Figure C.2: Voltage increase with renewable energy penetration

C.2. Simulation Results

Table C.2: Simulation results to determine the ideal point of connection

Time	load66	load132	load400	PV 66kV (MW)	PV 132 kV (MW)	Wind (MW)	Scenario 1	Scenario 2	Scenario 3
0:00	259.19	618.39	3096.72	0.00	0.00	133.67	24,5	43,2	42,3
1:00	259.19	618.39	3096.72	0.00	0.00	116.94	30,7	45,4	45,3
2:00	259.19	618.39	3096.72	0.00	0.00	277.00	3,9	28,0	28,0
3:00	259.19	618.39	3096.72	0.00	0.00	195.39	7,9	26,1	25,9
4:00	255.25	610.49	3048.03	0.00	0.00	316.73	36,8	11,0	11,9
5:00	269.54	539.08	3224.32	0.00	0.00	373.49	23,6	19,3	19,3
6:00	285.88	571.75	3425.79	0.64	8.93	403.90	17,4	41,8	41,9
7:00	295.95	591.90	3550.03	1.93	26.78	492.86	17,8	43,3	43,4
8:00	297.99	595.98	3575.22	5.50	72.48	341.31	22,3	45,7	45,8
9:00	300.03	600.07	3600.40	6.57	87.35	244.31	18,4	44,0	44,0
10:00	305.14	510.28	3663.36	7.07	98.18	303.84	20,2	23,4	24,3
11:00	300.03	500.07	3600.40	7.93	110.08	320.70	29,8	19,8	19,8
12:00	297.99	595.98	3575.22	8.57	119.00	400.88	50,7	9,0	9,0
13:00	294.93	489.86	3537.44	9.00	124.95	330.43	36,5	15,8	15,8
14:00	293.91	487.81	3524.85	9.00	124.95	420.92	56,6	5,1	5,1
15:00	295.95	491.90	3550.03	5.36	114.38	354.51	39,5	14,4	14,3
16:00	295.07	590.14	3539.19	5.28	112.50	359.70	37,4	15,3	15,4
17:00	296.97	493.94	3562.63	4.00	104.65	620.92	49,9	9,3	9,4
18:00	332.70	545.41	3903.35	3.71	98.80	690.88	34,7	21,2	21,2
19:00	318.55	537.09	3828.74	3.07	88.88	545.56	38,4	17,6	17,7
20:00	303.10	606.19	3638.18	1.43	29.95	470.88	25,5	24,0	24,2
21:00	289.82	579.65	3474.48	0.00	0.00	394.19	23,6	21,7	21,7
22:00	257.29	514.58	3273.21	0.00	0.00	294.19	31,1	14,1	14,1
23:00	253.20	506.41	3222.84	0.00	0.00	193.98	9,1	24,7	13,1

Table C.3: Simulation results to determine loading on 132 kV line

	No controller			With shunt controller		
	Loading on 132kV Line			Loading on 132kV Line		
Time	Line 2a (%)	Line 2b (%)	Line 2c (%)	Line 2a (%)	Line 2b (%)	Line 2c (%)
0:00	42,3	68,8	59,9	40,9	66,6	58,1
1:00	45,3	68,8	60	43,9	66,6	58,1
2:00	28	68,7	59,9	27,1	66,5	58
3:00	25,9	68,6	59,8	25	66,5	58
4:00	11,9	67,6	58,8	10,6	65,3	57
5:00	19,3	71,4	62,3	18,7	69,2	60,3
6:00	41,9	74,9	66,3	40,4	72,5	64,2
7:00	43,4	75,2	68,7	41,8	72,7	66,5
8:00	45,8	71,1	69,2	44,3	68,8	67
9:00	44	69,6	69,6	42,6	67,4	67,4
10:00	24,3	68	70,6	23,5	65,9	68,4
11:00	19,8	65,1	69,4	19,1	63	67,2
12:00	9	63,3	68,9	8,8	61,3	66,7
13:00	15,8	61,7	68,2	15,2	59,7	66
14:00	5,1	61,4	67,9	4,9	59,4	65,8
15:00	14,3	63,2	68,3	14	61,4	66,3
16:00	15,4	63,8	68,2	14,8	61,7	66,1
17:00	9,4	66,2	68,7	9	64,1	66,5
18:00	21,2	77,4	77,2	20,5	74,9	74,7
19:00	17,7	74,2	73,8	17,1	71,9	67,6
20:00	24,2	80,8	73,9	19,7	73,3	67,1
21:00	21,7	76,9	67,1	21	74,6	65
22:00	14,1	68,1	59,4	13,6	66	57,5
23:00	13,1	66,9	58,4	23,8	64,9	56,6

Table C.4: Simulation results to determine voltage deviation on 132 kV line

	No controller				With shunt controller			
	Bus 66kV	Voltage 132kV			Bus 66kV	Voltage 132kV		
Time	Δ Voltage %	Without controller (%)	Voltage PV 132kV (%)	Voltage wind (%)	Δ Voltage %	With reactive power Control (%)	Voltage PV + controller 132kV (%)	Voltage wind + controller (%)
0:00	-4,91	94,14	97,06		1,15	100,26	100,23	100,53
1:00	-4,93	94,13	97,03	97,34	1,14	100,25	100,2	100,5
2:00	-4,84	94,21	97,2	97,51	1,22	100,34	100,37	100,67
3:00	-4,83	94,22	97,22	97,53	1,23	100,36	100,39	100,89
4:00	-4,75	94,32	97,38	97,68	1,32	100,45	100,55	100,95
5:00	-4,86	94,16	97,22	97,54	1,21	100,28	100,39	100,7
6:00	-5,06	93,86	96,9	97,23	1	100,02	100,07	100,4
7:00	-5,12	93,8	96,83	97,17	0,94	99,92	100	100,33
8:00	-5,14	93,7	96,82	97,14	0,92	99,9	99,9	100,3
9:00	-5,14	93,77	96,83	97,14	0,91	99,9	100	100,31
10:00	-5,07	93,83	97,01	97,31	0,99	99,96	100,18	100,47
11:00	-5,02	93,91	97,09	97,38	1,04	100,04	100,26	100,54
12:00	-4,96	93,96	97,21	97,49	1,1	100,11	100,37	100,65
13:00	-4,97	93,96	97,17	97,45	1,09	100,11	100,34	100,61
14:00	-4,92	94,03	97,27	97,56	1,14	100,16	100,71	100,44
15:00	-4,98	93,96	97,17	96,45	1,08	100,08	100,33	100,61
16:00	-4,97	93,95	97,16	97,45	1,09	100,01	100,33	100,61
17:00	-5,23	93,95	97,19	97,49	1,01	100,09	100,36	100,65
18:00	-5,13	93,55	98,84	97,19	0,83	99,69	100,01	100,35
19:00	-5,16	93,7	96,96	97,3	0,93	99,84	100,13	100,45
20:00	-4,98	93,67	96,87	97,23	0,99	101,22	101,42	101,75
21:00	-4,77	93,95	97,06	97,41	1,08	100,08	100,23	100,57
22:00	-4,75	94,29	97,34	97,65	1,32	100,42	100,51	100,81
23:00	-4,74	94,33	97,38	97,68	1,27	100,41	100,44	100,73