PHOTOVOLTAIC SYSTEM WITH MULTILEVEL CONVERTER COUPLED TO A COMPRESSED AIR ENERGY STORAGE SYSTEM FOR GRID INTEGRATION

by

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ABSTRACT

Electricity demand is continuously increasing and nations including South Africa, are looking to exploit renewable energy sources to augment conventional electricity generation. An analysis of electricity demand and supply, the electricity infrastructure and the status of renewable electricity including the progress and plans made thereof in South Africa were carried out. A review of the challenges affecting the bulk exploitation of renewable energy (RE) resources and its future prospects are discussed to determine the sustainability of these efforts.

This research investigation focuses on a simulation model designed to harness the energy from the sun through a photovoltaic system. Based on empirical data of environmental conditions, a photovoltaic (PV) system model to generate 30 MW of electricity at Witkop substation, Polokwane (South Africa) was developed and to be fed into the grid. A maximum power point tracker (MPPT) control scheme is utilised to ensure that maximum power can be derived from the PV plant. A modular multi-level converter (MMLC) is utilised to convert the electricity generated by the PV system from direct current (DC) to alternative current (AC). The MMLC coupled to compressed air energy storage (CAES) stores the electricity generated during the day and injects it into the grid during peak periods of electricity demand.

Mathematical models of the PV system, the MMLC, the CAES and the grid integration were developed, modelled and simulated to describe the electrical behaviour and to establish the ideal operational parameters of the various systems components. Furthermore, validation of the performance of the system components in the simulation model were carried out against manufacturers' data sheets for similar studies and prototypes. The simulation model were used to combine all the system components effectively into the grid based on the electricity generation system configurations, electricity demand and the environmental conditions of the selected site.

More importantly, this investigation seeks to increase the effort of development of PV generation models in the field of renewables when compared to other alternative energy sources such as wind energy generation.

DEDICATION

My parents, the late Mr Chigangacha & Mrs Chigangacha, for the greatest gift any parent could give their girl child – the opportunity to education. Thank you for the sacrifices, the sleepless nights and above all the love I received and continue to receive each and every day of my life!

My husband, Munya, my son, Mako, and my newly born daughter, Anotidaishe, - you are the greatest family I could ever ask for! The happiness, the joy and most importantly the love we share is truly heavenly sent. I know there are times I was not there for you because I had to work on the thesis, I truly appreciate that and thank you for understanding and believing in me!

Above all, glory be to God, the Almighty!!

PREFACE

I, Precious Husvu, do hereby declare that:

1. The research reported in this thesis, except where otherwise indicated, is my original work.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
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7. I have received comprehensive guidance from my supervisor/s. Any further errors herewith are of course my own.

Signed

As the candidate's Supervisor I agree/do not agree to the submission of this thesis.

Signed:

ACKNOWLEDGEMENTS

I would like to honour and acknowledge the following people and institutes for making this study a reality:

Dr Innocent Davidson, my supervisor, you provided more than encouragement, guidance and insight. You rekindled the fire of academic excellence when all wheels were coming off. You were the inspiration throughout this study!

My family, hats off for your support and patience during the period of my study. My friends and colleagues, you did not tire when I asked the numerous questions I had. You were always encouraging and assisting as was necessary.

Eskom, for offering a study bursary, the resources and the opportunity to further my studies.

Agricultural Research Centre, for the weather data that I used as input parameters in this study.

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LIST OF ABBREVIATIONS

AC:	Alternative Current
ARC:	Agricultural Research Center
CAES:	Compressed Air Energy Storage
CHB:	Cascaded H-Bridge
CMC:	Cascaded H-Bridge Modular Converter
CSIR:	Council for Scientific and Industrial Research
CSP:	Concentrated Solar Power
DC:	Direct Current
DOE:	Department of Energy
EPRI:	Electric Power Research Institute
FC:	Flying Capacitor
GW:	Giga-Watt
GWh:	Giga-Watt-hour
HPT:	High Pressure Turbine
HX:	Heat Exchanger
IPPs:	Independent Power Producers
IRP:	Integrated Resource Plan
kW:	kilo Watt
LPT:	Low Pressure Turbine
MMLC:	Modular Multilevel Converter
MPPT:	Maximum Power Point Tracking
MW:	Mega Watt
NPC:	Neutral Point Clamped
PV:	Photovoltaic
PD:	Phase Disposition
PWM:	Pulse Width Modulation
RE IPP:	Renewable Energy Independent Power Producers
STC:	Standard Test Conditions
SWH:	Solar Water Heater

CHAPTER 1

1. INTRODUCTION

1.1. Background

Fossil fuels have traditionally been the main source of energy for industrial and economic development particularly in power generation (Rajasekar & Gupta, 2012). However, the gradual depletion in fossil fuel reserves, the ever increasing demand for energy and the need for sustainable energy supply have necessitated a paradigm shift to renewable energy globally (Rustemli & Dincer, 2011). Governments, utilities, companies, research institutions, academia, conservationists and all stakeholders are unanimous in the pursuit of more sustainable, greener and environmental friendly renewable energy sources.

Renewable energy resources such as solar, wind, fuel cells, tidal, geothermal and biomass have attracted considerable investment and research (Rajasekar & Gupta, 2012). The potential of solar energy has made it an outstanding and more attractive renewable energy resource due to its inexhaustible, unlimited and abundance nature (Rajasekar & Gupta, 2012). As a result, solar power technology has significantly increased its position amongst renewables, with the exponential growth in annual PV installations (International Energy Agency, 2007; International Energy Agency , 2006). Figure 1-1 below shows the significant increase in global cumulative installed PV capacity for the last decade (Dezso & Yahia, 2014; Masson, et al., 2013).

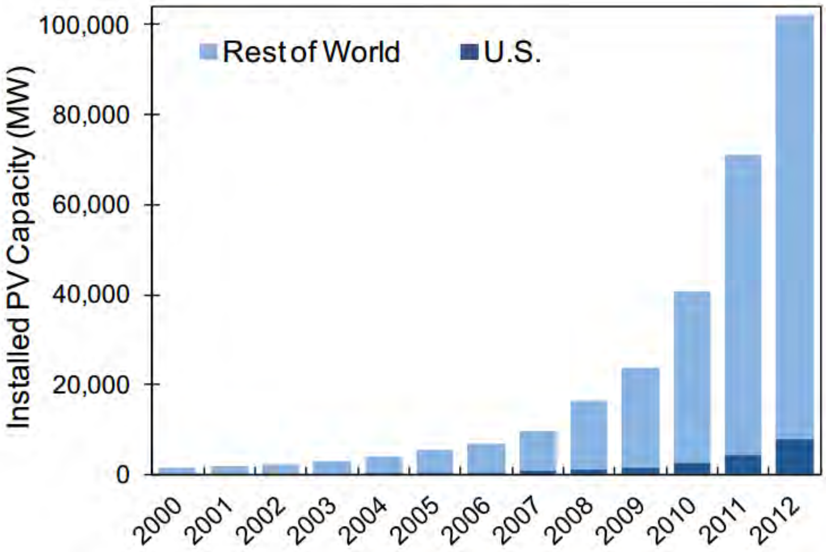

Figure 1-1: World Cumulative Installed PV Capacity

Further to this, the cost price of photovoltaic components has been on a decline making them an economically viable option of renewable energy (Buresch, 1983; Guo, et al., 2011; Dezso & Yahia, 2014) and further growth is still projected and anticipated (Yazdani, et al., 2011). Figure 1-2 below shows the trend in the decline of the PV installation price (Barbose, et al., 2013).

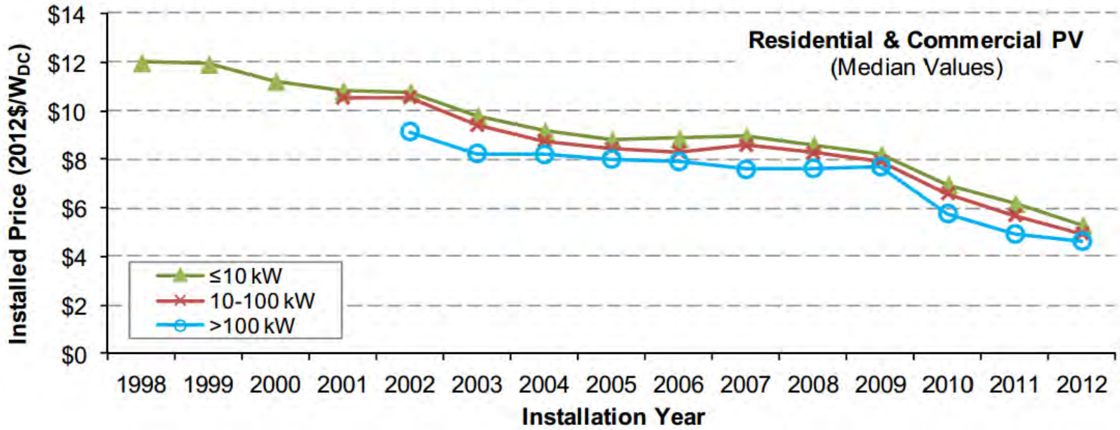

Figure 1-2: Median Installed Price for Residential & Commercial PV Systems

As a result, photovoltaic systems, in particular, have received significant attention and interest as they have enormous application capabilities ranging from small scale residential to large-scale commercial applications. These uses include but are not limited to power generation, heating, water supplying, satellite energy and air conditioning. The advent of PV technology has seen the total enhancement and utilisation of power generating systems that have benefits of developed infrastructure services, reduction of transmission lines from electricity grids, increase of regional/national energy independence, diversification of energy supply, acceleration of rural electrification in developing countries and most importantly mitigating emissions associated with fossil fuel usage (Wang & Qiu, 2009).

Similarly, South Africa is undergoing the migration to utilising the photovoltaic systems since it has sunshine all year round. In addition, it has one of the highest annual average daily solar radiation of between 4.5 and 7 kWh/m^2. Even in winter, parts of the country receive more than 6.5 kWh/m^2 per day. (Department of Energy - South Africa, 2008; Banks & Schäffler, 2006). This highlights the possible suitability of South Africa for greater use of solar energy and protracted growth in its solar equipment industry whose current annual photovoltaic (PV) panel-assembly capacity totals 5 MW (Department of Energy - South Africa, 2008). Photovoltaic systems have made inroads in South Africa with several applications already that include rural electrification, telecommunication systems, agriculture, street and traffic lights, and for powering parking ticket dispensing machines for several large and private companies.

Numerous work and research efforts has shown that PV systems can be supported by modular multi-lever converters to obtain better system stability on DC to AC conversions resulting in the high intense penetration of MMLC in power applications (Rajasekar & Gupta, 2012; Adam, et al., 2010; Alajmi, et al., 2012). This study seeks to investigate the feasibility of a PV system with a MMLC for application in South Africa.

Electricity storage technologies promise a wide range of benefits to power utilities particularly in the wake of drastic promotion of renewable energy. Some of these benefits include smoothing generated power from renewable sources and alleviating grid pressure during peak periods (The Electricity Advisory Committee, 2008; Trishna, et al., 2011). Hence, there is a growing interest in identifying large capacity and fast responding storage options to smooth power generation variations due to weather changes. Compressed air energy storage has shown great potential with numerous commissioned and operational plants the world over and more anticipated (Zunft, et al., 2006). This study also seeks to investigate usage of compressed air storage as a feasible alternative for South African PV systems.

1.2. Research Motivation

PV systems generate clean power and minimise grid pressure during peak periods to satisfy customer expectations by alleviating load shedding in South Africa. However, compared to the rest of the world, the PV systems are not as widely disseminated in South Africa despite the abundance of the solar resource. The weather, climate and environment conditions as well as the geographic locations have not been adequately explored for the installation of PV systems.

In addition, where PV systems have been installed, the solar energy from these units has not been fully utilised to harness the potential that such systems can attain. This is mainly because PV systems require special design considerations due to the dependency of the total power generated on the change of solar irradiation level. Moreover, the cell operating temperature resulting from unpredictable and sudden changes in weather conditions affects the power generated by the PV systems (Adamidis, et al., 2010). This results in the intermittent nature of the power generated by the photovoltaic system. The fact that the greatest power is generated during the day when the electricity demand is not at its peak creates the need for storage of the generated power for later use. This need for an energy storage system further extends the limitation of the photovoltaic systems as a source of alternative energy for developing nations.

Despite the above forenamed challenges, the PV systems face intense pressure to generate and deliver electricity particularly in South Africa. This motivates the inception of this study to investigate the design and simulation of a 30 MW. This investigation seeks to ensure that maximum energy output is obtained from the PV plant by utilising the MPPT control scheme. Thus, the MPPT control shall be required to operate the PV array at the optimum working point in all environmental conditions hence ensuring an efficient PV system. A modular multi-level converter shall be used to ensure that the highest possible efficiency during the DC to AC conversion process is achieved.

The challenges introduced by the fluctuation of power generated from renewable can be substantially mitigated by large-scale storage technologies. Compressed air energy storage system is one such solution and is investigated in this study. The model of this system shall create an energy storage option that together with the PV system and the

MMLC shall be operated at optimal conditions. This is expected to improve the variance between the energy demand and energy supply in South Africa since the country has high levels of solar radiation. Moreover, this study seeks to increase the effort of development of PV generation models in the field of renewables when compared to other alternative energies like wind energy generation (Papanikolaou, et al., n.d.). Significant efforts have been put on wind energy with compressed air energy storage as opposed to PV with compressed air energy storage (Trishna, et al., 2011). This therefore prompts the need to investigate the PV system with the MMLC coupled to the CAES for grid integration in the quest for effective utilisation of the power yield from PV systems in South Africa.

Since 2008, the South African electricity grid has been significantly strained during peak hours (Joffe, 2012). The CAES system investigated in this study will focus on possible alternatives to alleviate the forenamed problem. The CAES system will be investigated to meet daily peak electricity demand while increasing penetration and acceptance of renewable energy technology as a commercially viable option.

1.2.1 Aim

The aim of this project is to; "*Investigate the PV system with a modular multilevel converter coupled to the compressed air energy storage for grid integration in South Africa*".

1.2.2 Objectives

The objectives of this project are to:

- Analyse and understand the PV systems;
- Determine the optimal power control strategy;
- Analyse the various multilevel converter structures;
- Determine the possible topology for the multilevel converter;
- Determine the energy storage techniques suitable for PV with MMLC systems, by comparison of the CAES with other energy storage techniques;
- Model and run simulations of the system to predict design performance;

- Design a model of a PV system with a multilevel converter structure coupled to the compressed air energy storage for grid integration in South Africa.

1.2.3 Research Questions

The investigation will be used to answer the following specific research questions:

- *What are the performance parameters of the PV system?*
- *What are the multilevel converter structures used on the PV system?*
- *What are the various energy storage techniques used on the PV system?*
- *What are the advantages and disadvantages of Compressed Air Energy Storage over other energy storage techniques?*
- *What are the operation modes and performances of the modular multilevel converter and energy storage system?*

1.3. Scope and Boundaries

This study seeks to investigate the PV system with a modular multilevel converter structure coupled to the compressed air energy storage for grid integration. The maximising of the energy from the PV system utilisation is of paramount importance.

1.4. Limitations

This study is limited to panel crystalline silicone cells for modelling and diagnostic purposes. This means that modelling stages neglect low-level operation and dynamics of the system including the sub-modules. Thus, the electrical connection issues between sub-modules, panels and system components are not dealt with in this thesis.

1.5. Assumptions

This investigation is going to assume that the PV system incorporates a sun-tracking system, as it is imperative to enhance as much energy as is possible from the solar PV system. Numerous work has been done to confirm that the efficiency of the PV system is significantly improved by the sun-tracking system (Stjepanovic, et al., 2010; Tejwani & Solanki, 2010). Furthermore, the irradiation is based on the supplied input data and that no obstruction to the PV array is assumed. Thus, partial shading conditions will not be considered nor assumed.

In as much as circulating currents are a common occurrence in converters, an assumption to neglect their impact on the performance of the modular multilevel converter shall be made in this study (Trintis, et al., 2011).

1.6. Research Methodology

This project will make use of several research methods outlined in the following sections. The author will conduct several interviews with the academic and industrial subject matters experts who will give their valuable input into the definition and modelling of objectives and parameters for the project. The relevant data for the performance measures will be compiled from literature, previous researches, data sheets and climate history for simulation together with a careful study of the existing documentation on the PV systems. This will ensure that the problem set is carefully and accurately defined within which the objectives are formulated as input from various key stakeholders.

1.6.1 Extensive Literature Review

An exhaustive and thorough literature review shall be done on this study covering the grid connected PV system, the various PV system multilevel converter topologies and the energy storage configurations. The literature review shall focus on the where these system components have been applied, identify the positives and negatives of these applications and identify the shortfalls and gaps in the literature. The basic concepts, technical performance parameters and principles used throughout this study shall be clearly outlined.

1.6.2 Structured Approach

All the work that forms the research process shall be well structured. This includes but not limited to objectives, research questions, scope and boundaries. An investigation shall be conducted to determine and analyse how the topology can be coupled to the PV system. Various experiments shall be conducted to evaluate power control strategies and check the design performance under various configurations through the simulation model. This ensures a high quality research to ensure the outcome is validated.

1.6.3 Systematic Approach

The procedure to carry out the investigation shall follow a logical and chronologically sequence. This provides an effective way to track and monitor progress especially in the analysis of results.

1.6.4 Simulation Model Building

In order to analyse and investigate the potential of the PV system a simulation model of the system shall be developed. The simulation will allow for a critical and good evaluation of the operation modes and performance of such a system as it accepts dynamic data input in time domain. This generates precise results compared to other modelling techniques like spreadsheet calculations.

Furthermore, the effective investigation, modeling and simulation of a PV system with a modular multilevel converter coupled to the compressed air for grid integration requires a properly structured and comprehensive modeling procedure. It is because of the complex interactions between the various sections of the entire system, that modeling and simulation cannot be a simple once through linear process. In order to accommodate these interactions, the model needs to be iterative and requires careful use of engineering judgment to make appropriate assumptions that avoid excessive reiteration of the model. The Matlab/Simulink students' version simulation package shall be used in this study. The simulation results will be used as part of the recommendations and the conclusion.

1.7. Project Outline

The PV unit, the multilevel converter topologies, the energy storage techniques including the compressed air energy system are introduced. The analysis of the operation modes and performances of the multilevel converter, the energy storage and the CAES is done. The coupling of all these components is considered and finally these are then integrated onto the electricity grid. The system components for integration into the grid are modelled, simulated and their dynamic performance is evaluated. A suitable structure of the system components with the PV system is proposed.

1.8. Summary

Due to the high levels of irradiation, South Africa is a good candidate for solar PV systems, particularly Witkop solar park site, south of Polokwane. However, such PV systems will require some energy storage and integration to the grid to enhance their efficiency. The main aim of this project is to investigate the PV system with a multilevel converter structure coupled to the compressed air energy storage for grid integration. As such, an analysis of the operation modes and performance parameters of the PV system and the multilevel converter structures together with the various energy storage techniques used on the grid connected PV system, particularly the compressed air energy storage, CAES, are conducted. An integrated modelling approach with simulation models shall be applied to meet this goal.

CHAPTER 2

2. LITERATURE REVIEW

2.1. Electricity Status in South Africa

Since early in the twentieth century, electricity has been the epitome of development in South Africa. Accordingly, the electricity demand has continuous and progressively increased amid political, social, economic and environmental transformations, particularly since 1994, when the country acquired a multi-party democracy. Industry, agriculture, transport, commerce and residential sectors constitute the highest electricity demand in the economic market of South Africa (Musango, et al., 2011). The industrial sector leads the pack with consumption of over 60% of the total energy generated as depicted in Figure 2-1 below with the electricity consumption in GWh per economic sector (Department of Energy,, 2011).

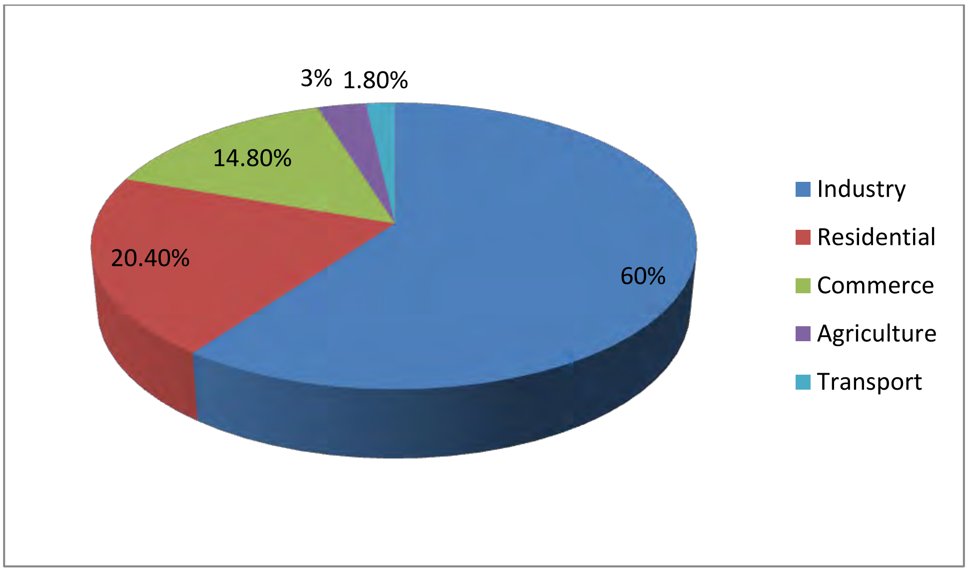

Figure 2-1: Electricity consumption per economic sector in South Africa

The South African electricity industry is not immune to both local and global challenges facing the energy sector (Joffe, 2012). The main ones among these challenges are coping with the ever-growing demand of electricity and reducing greenhouse gas emissions. Since 2008, South Africa has experienced infamous waves of load-sheds and numerous requests over the media for large industrial customers to cut their electricity consumption by 10% during peak demand times to try to relieve the strain on the electricity grid (EIA Government, 2014; Joffe, 2012). Appendix A shows a typical Eskom media statement for the request to cut down on the power usage.

The situation remains dire even though great efforts are being made to increase the base-load electricity in South Africa (Lloyd, 2012). Based on two independent forecast projections done by the System Operators and the Council for Scientific and Industrial Research, CSIR, the electricity demand was expected to outstrip electricity supply by 2012 and continue on the increase (Department of Energy, South Africa, 2010; EIA Government, 2014; Lloyd, 2012).

The South African government through the Department of Energy took a more proactive stance on electricity generation resulting in the promulgated of the Integrated Resource Plan in March 2011 (Department of Energy, South Africa, 2010; EIA Government, 2014). The Integrated Resource Plan clearly outlined strategies to determine the long-term electricity demand, set electricity targets and develop policies and tendering processes for the realisation of these targets. According to this plan, the generation capacity of electricity is expected to almost double in 20 years with a projected increase in electricity of 42 539 MW. Renewable energy was expected to contribute approximately 42% of this total capacity (Department of Energy, South Africa, 2010; EIA Government, 2014; Joffe, 2012; Bello, et al., 2013). Table 2-1 below shows the existing generation capacity together with the 20 year generation capacity projections in South Africa (Bello, et al., 2013).

Table 2-1: South Africa current and planned generation capacity

Energy source	**Existing capacity (MW)**	**20 year plan – 2011 IRP (MW)**
Coal fired	37 715	6 250
Hydro-electric	661	2 609
Pump storage	1 400	
Gas turbines	2 426	6 280
Nuclear	1910	9 600
Renewables Energy	3	17 800
Total Capacity	**44 115**	**42 539**

The most significant target set for renewable energy indicates true commitment from the government to reduce dependence on coal-fired electricity generation and reducing greenhouse gases while taking into consideration safety, health and environmental issues. However, new innovative technologies with effective and reduced carbon emissions are to be used on the newly built coal-fired plants (Department of Energy, South Africa, 2010; Joffe, 2012; Department of Energy, South Africa, 2010). Under the Integrated Resource Plan, of the total stipulated generation of 18 600 MW from renewable energy, 1 000 MW shall be generated from concentrated solar power, CSP, while 8 400 MW from wind energy and 8 400 MW from solar photovoltaic (PV) (Department of Energy, South Africa, 2010; Bello, et al., 2013; Department of Energy, South Africa, 2010). Appendix C shows the detailed 2011 IRP plan.

2.2. Electricity Stakeholders

Within the electricity sector, numerous stakeholders are collaborating to generate, transmit and distribute electricity to the different and diverse customers. High on the stakeholders' priority list are the electrification projects as well as the efficient use of electricity. The involvement of government is very imperative as policies are put in place to guide and provide a clear roadmap for the resuscitation of the electricity sector (Department of Energy,, 2011; Joffe, 2012).

2.2.1 Eskom

Eskom is South Africa's dominant electricity utility. Initially known as Escom since 1948, it was a large, powerful state-owned and a monopolistic company responsible for the generation, transmission and distribution of electricity (Koen, 2012; Eskom, 2010; Lloyd, 2012). The company built massive power stations and an integrated interconnected transmission grid to support and sustain the country's high economic growth. The parastatal company was renamed Eskom in 1987 (Koen, 2012; Edkins, et al., 2010). Eskom supplies over 90% of South Africa's electricity and exports some power to its neighbouring countries including Botswana, Namibia and Mozambique (Department of Energy, South Africa, 2008; Eskom, 2010). The company is amongst the top seven in generating capacity internationally with Koeberg power station being the only nuclear power station in Africa and Matimba power station as the biggest dry-cooled power station globally (Edkins, et al., 2010; Newbery & Eberhard, 2008).

2.2.2 Independent Power Producers

The South African government published policies and white papers that allowed and approved private-sector participation in the electricity generation industry (Department of Energy, 1998; Department of Energy,, 2003). The private sector participators are known as independent power producers, IPPs. The policies and white papers concluded that future power generation capacity would be an open market with Eskom expected to provide 70% while IPPs supplied the remaining 30% of national capacity (Joffe, 2012; Edkins, et al., 2010). This has resulted in and it is further anticipated that a plethora of myriad IPPs will jump on-board in supporting the electricity sector.

Many of these IPPs are interested in developing renewable energy and distributed electricity solutions through projects in South Africa. The projects covered by IPPs range from electricity generation to energy efficiency projects like the solar water heater. The electricity generation projects include onshore and offshore wind, solar photovoltaic, biomass, landfill gas and concentrated solar power (CSP). Table 2-2 shows the number of projects as well as the expressed generation interest in renewable energy by the IPPs (Bello, et al., 2013).

Table 2-2: Expressed generation interest in renewable energy

Technology	No of Projects	Intended Generation (MW)	DoE RE IPP Program (MW)
Wind	175	19 150	1 850
Solar PV	374	14 466	1 450
CSP	25	2 409	200
Biomass	63 (rest)	498 (rest)	12.5
Biogas			12.5
Landfill			25
Small hydro-electric			75
Total Capacity	**637**	**36 523**	**3 625**

2.2.3 Private Generators

Private generators are generally based on co-generation mostly for their own consumption and only selling electricity to the national utility, Eskom, only when in surplus. As such, private generators contribute only 3% of the national annual total generation capacity. Large and well-established manufacturing, operating companies, utilities and well-backed IPPs, currently dominate the wind generation market.

2.2.4 Municipalities

The municipalities buy 40 percent of the total electricity from Eskom that owns and controls the national integrated high-voltage transmission grid. This significant amount of electricity is distributed directly to customers by approximately 185 local municipalities mainly in the cities (Joffe, 2012). The customer base of these municipalities is just over 4 million customers. These municipalities contribute less than 1 percent of the total annual electricity generation in South Africa.

2.3. Electricity Infrastructure

The electricity infrastructure in South Africa is heavily dependent on coal. This huge dependence on coal is due to the massive coal reserves in South Africa as well as low price of coal (Joffe, 2012; Department of Minerals & Energy, 2004). Figure 2-2 below shows the consumption of energy in South Africa (Department of Minerals & Energy, 2004).

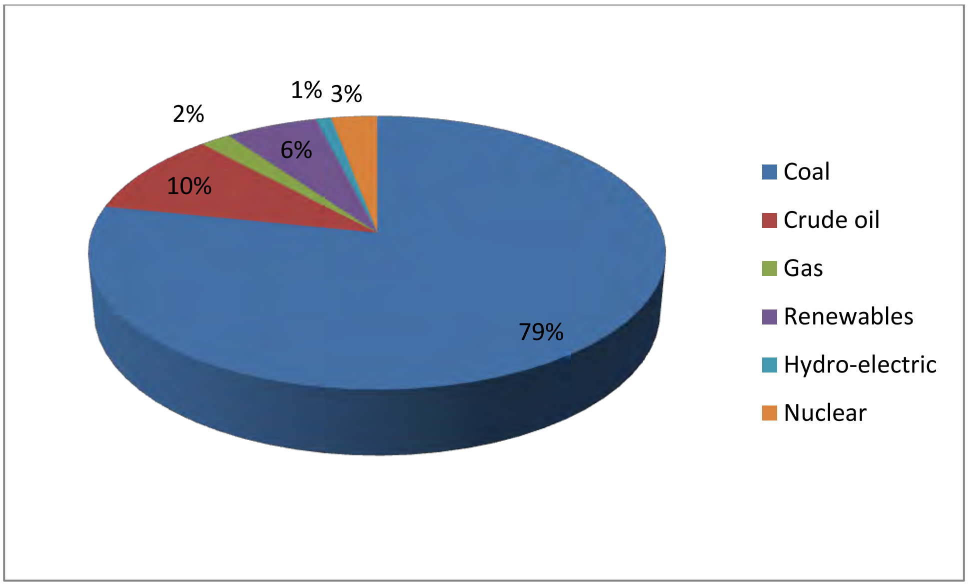

Figure 2-2: Primary Energy Consumption in South Africa

There are ten base-load power stations that are coal fired in South Africa. All these coal-based power stations account for approximately 92% of the total primary electricity supply in the country (Eskom, 2010). The eleventh base load power station is a large nuclear power station called Koeberg, located near Cape Town, and contributes to the operational electricity supply (Eskom, 2010). Overall, Koeberg nuclear station provides about 5 percent of the total electricity capacity. A further 3 percent is provided by hydro-electricity and pumped storage schemes in order to meet the national electricity peak demand (Eskom, 2010). One relatively small wind farm completes Eskom's current electricity generation portfolio (Eskom, 2010). Table 2-3 below shows a breakdown of current electricity infrastructure in South Africa.

Table 2-3: Current electricity infrastructure in South Africa

Base Load Stations		Peak Demand Stations		Renewable Energy	
Coal		**Hydro-electric**		**Wind Energy**	
Arnot	2100	Gariep	360	Klipheuwel	3.2
Duvha	3600	Vanderkloof	240		
Hendrina	2000				
Kendal	4116	**Pumped Storage**			
Kriel	3000	Drakensberg	1000		
Lethabo	3708	Palmiet	400		
Majuba	4110				
Matimba	3990	**Open cycle gas turbine**			
Matla	3600	Acacia	171		
Tutuka	3654	Port Rex	171		
Nuclear		Ankerlig	592		
Koeberg	1930	Gourikwa	444		

Several projects are planned to increase the current electricity production with Kusile and Medupi coal power station set to generate a sum of 9 588 MW, Ingula pumped storage station to produce 1 332 MW and 200 MW is expected from renewable energy with wind and CSP generating 100 MW respectively (Lloyd, 2012).

2.4. Status of Renewable Energy

Renewable energy accounts for almost 9 percent of the total energy consumption in South Africa (Joffe, 2012; Department of Environmental Affairs and Tourism, 2005) with the bulk of its generation based on the traditional unconventional technologies like fuel-wood and animal dung. This partially explains why renewable energy contributed less than 1 percent of the total electricity energy nationally (Joffe, 2012; Department of Environmental Affairs and Tourism, 2005). A paradigm shift is at hand with the South African government having put in measures to promote renewable energy from a marginal energy source into the mainstream energy source through different initiatives that include opening the electricity market sector to more players through government policies as well as investing and attracting efficient renewable technologies. These efforts have paid off and are expected to yield positively as the transition has been evident with a very rapid and constant increase in the total amount of electricity from renewable sources of the past decade. The growth in the electricity from renewable resources in South Africa is attributed to wind, solar, biomass and hydro-electricity which are the focus generation technologies as per the government specification (Joffe, 2012; Department of Environmental Affairs and Tourism, 2005). These are expanded on briefly in the following sub-sections.

2.4.1 Biomass

Biomass is a renewable energy resource derived from organic matter from both flora and fauna to produce heat, make gas and liquid fuels or generate electricity. The energy from biomass can be categorized into two distinct sources, namely wood and waste. In South Africa, wood fuel is the great source of biomass energy for cooking and space heating (Banks & Schäffler, 2006). On a large commercial scale, wood biomass resources depend on the timber industry, agricultural crops and raw materials from forestry. The waste-depend biomass resources include municipal solid waste, industrial waste and manufacturing waste.

In 2010, a 7.5 MW landfill gas to energy was inaugurated in eThekwini Municipality, Durban (Thabethe, 2010). This is the first plant of this kind in South Africa. Though the plant is not connected to the national grid, the electricity generated is utilized by the municipality, hence decreasing its demand for electricity from the national grid. In addition, the power utility in South Africa has been looking into the potential of using the biomass from municipal waste and wood-based biomass for firing or co-firing the existing coal plants (Musango, et al., 2011).

2.4.2 Hydro Electricity

Hydro-electricity has been used the world over for centuries, similarly in South Africa this technology has been widely embraced. This technique is based on the principle of the movement of water under gravitational force to drive turbines to generate electricity. Depending on the volume of water, the electricity generated from hydro plants can range from pico-stations of up to 20 kW to macro-stations of greater than 10 MW power output. Hydroelectric plants are mainly situated in rivers, dams, pipelines and canals.

In South Africa, the current installed capacity for hydro electricity generation categories is 38 MW and according to the IRP plan an estimated 247 MW was set as the baseline target. Figure 2-3 below shows a typical hydroelectric generation plant (The USGS Water Science School, 2014).

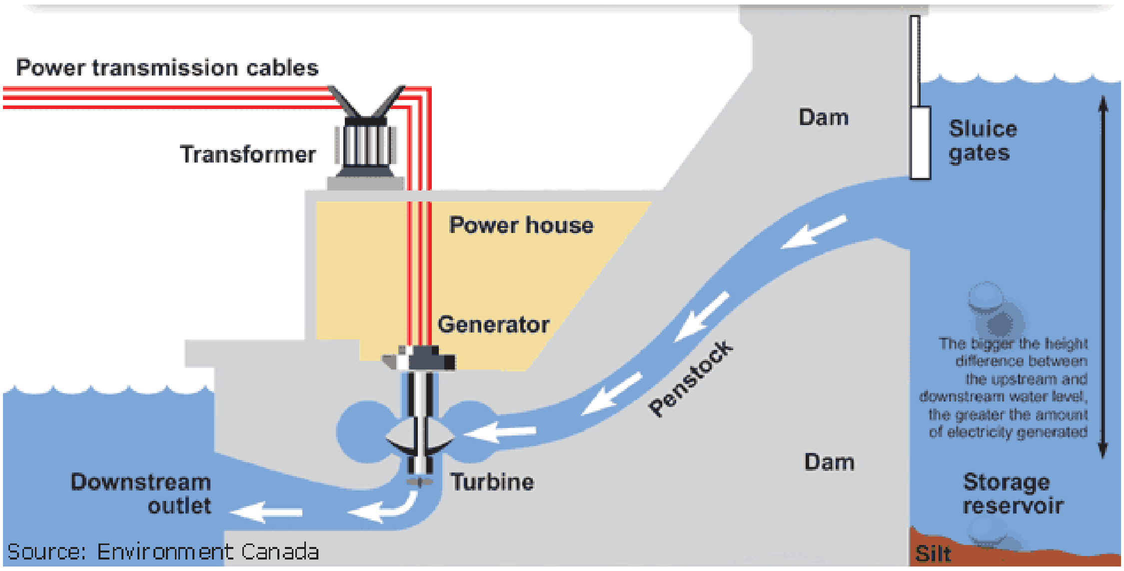

Figure 2-3: Typical Hydroelectric Generation Plant

2.4.3 Solar Energy

Solar energy is based on the technique to harness the sun's energy to either generate electricity or produce thermal energy. This includes photovoltaic panels, concentrated solar power and solar water heaters, SWH. South Africa has an enormous potential for the development of solar energy since most areas' average solar-radiation levels range between 4.5 and 6.5 kWh/m^2 in one day (Department of Energy, n.d.). The country has one of the best sunshine hours in a day with an average of 2 500 per year (Department of Energy, n.d.).

According to the Integrated Resource Plan, the PV solar technology is expected to contribute 8 400 MW, while 1 000 MW shall be from CSP (Department of Energy,, 2011) by 2030. Several different large-scale projects funded by diverse stakeholders are at stages ranging from conceptualisation and feasibility studies to commissioning across South Africa (Joffe, 2012). This includes the Solar Park in the Northern Cape Province. The proposed capacity of the solar park is 5 GW by 2020, in which the first phase is planned to develop 1 GW by 2016 (The Electricity Advisory Committee, 2008;

Thabethe, 2010). Numerous small-scale PV systems have been used for electricity generation for telecommunications, electronic media and lighting in remote areas.

2.4.4 Wind Energy

Globally, wind energy is currently the leading renewable technology in the energy industry (Banks & Schäffler, 2006), with numerous small and large wind farms that are established on- and off-shore in several countries. Wind energy uses the principles of wind turbines that are rotated by the wind and use the kinetic energy from their rotation to generate energy. This energy can either pump water or turn an electric motor. This allows the versatility of wind energy as it can be easily integrated into small and large operations.

A low of 500 MW to a high of 56 000 MW is the estimated range of the wind energy potential in South Africa (Department of Environmental Affairs and Tourism, 2005; Eskom, 2010). This potential is based on the studies done mainly across the coastal areas of South Africa. Evidently, one of the first operational and commercial wind farms in South Africa is the Darling wind farm, launched in 2008, in the peripherals of Cape Town. This site has an installed capacity of 5.2 MW and phase two of this project will entail installation of six 1.3 MW wind turbines that will result in a total installed capacity of 13 MW (Musango, et al., 2011; Eskom, 2010; Szewczuk & Prinsloo, 2010). Some wind initiatives have taken off and these are used for research and piloting reasons. Typically, the Klipheuwel project was funded by Eskom to demonstrate the characteristics and performance of different types of wind turbines (Musango, et al., 2011; Eskom, 2010; Szewczuk & Prinsloo, 2010). Furthermore, Eskom harvested electricity from these three wind turbines with the aim of investigating the viability of large-scale wind energy for electricity generation in South Africa (Musango, et al., 2011). Several projects, meant for commercial purposes, sponsored by different developers are initiated but still under feasibility studies and will reach implementation stages once all requirements, issues and concerns are concluded. These decisions would likely be based on two major factors affecting wind energy thus affordability and grid connection.

Off-grid and rural mini-grid are utilised by the larger population of South Africans can are located in extremely remote areas of the country. The off-grid system is made-up of small-scale individual projects that generate electricity for their consumption and do not feed any into the system. While the rural mini-grid encompasses stand-alone localized power generation projects aimed at bringing electricity for productive activities in remote rural communities. All these efforts thrive to bring electricity to the general population while harnessing and utilising natural resources. Figure 2-4 below shows a schematic of wind turbines.

Figure 2-4: Schematic of Wind Turbines

2.5. Challenges of Renewable Electricity

Major strides are to be taken to enable the paradigm shift towards national augmentation to sustainable energy. The following sections address the major challenges the implementation of renewable energy faces in South Africa.

2.5.1 Economic Barriers

Renewable technologies including PV systems have generally seen as very expensive and sometimes risky to invest in. The uncertainty of the capital return-on-investment often limits the financial support in the form of grants and loans for the renewable electricity technologies (Robinson, 2011). Also, compared to the conventional technologies such as coal or natural gas, the operational and maintenance cost of renewable energy technologies is still high (Robinson, 2011). This has greatly limited the penetration of the renewable energy technologies.

Over the past decade, the costs of the PV systems have subsequently been on a decline. However, very limited ground has been covered in terms of PV penetration as the cost of electricity technologies still has to be financial competent in the economic market. Furthermore, no incentives are in place for electricity generation to encourage renewable electricity production.

2.5.2 Financial Barriers

Much as the South African government invited more players in the electricity market, the purchase of electricity through the Renewable Energy Independent Power Procurement, RE IPPP, is still complex and expensive. This results in financially sound corporates and internationally funded organisation partaking in large renewable projects as these need massive capital investments and continuous monetary injection for relatively long periods before reaching profitability. The main challenge that the government is facing is to ensure that an appropriate energy mix is achieved while the platform is lucrative for both domestic and international investors.

2.5.3 Partial Opening of the Electricity Market

The move to involve more players and stop Eskom's monopoly over electricity was a welcome move. In addition, setting renewable electricity targets and regulating electricity prices alone will not be sufficient. More detailed policies are needed covering the non-discriminatory open access to key energy infrastructure such as the national electricity grid, creating an enabling market for renewable electricity and power purchase agreements (Department of Energy,, 2011; Robinson, 2011). Moreover, the legal and regulatory requirements, approval processes and issue of licences are tedious and not consistent within the government departments.

2.5.4 Energy Storage Problems

The major setback of renewable energy is that it is intermittent as it is time dependent and susceptible to weather changes. This makes it difficult to rely on renewable energy to meet electricity need particularly during peak hours. The idea of electricity storage will help curb this challenge by storing the energy from renewable systems during generation and only releasing it when the load demand is high (Robinson, 2011). However, not enough financial and resource efforts had been invested towards energy storage. Coupled to storage solutions, smarter grids and distributed generation can be explored to embrace the full potential of renewable energy.

2.5.5 Research, Development and Demonstration

Renewable energy technologies, like any new technology have to be researched and developed before large-scale rollouts. However, the pace of the research, development and demonstration of renewable electricity technologies in South Africa has been slow at both small and large-scale levels (Department of Energy,, 2011; Wlokas, et al., 2012). Key stakeholders including government need to build long-term foundations for technological and industrial development to research as well as development and demonstration of renewable energy technologies to enable the quick harnessing of the abundant natural renewable resources (Edkins, et al., 2009). This can be achieved through collaborating with existing research and development institutions that can make available technological support centres to facilitate the promotion and ongoing development of renewable energy technologies.

Moreover, the development and implementation of appropriate standards, guidelines and codes of practice for the appropriate use of renewable energy technologies is to be promoted to ensure standardisation and conformance in the industry. Enough support, investment and resources should be allocated to ensure that the local manufacture of renewable energy technology is enhanced while optimising the implementation of these technologies.

2.6. Summary

The transition from a monopolistic stated owned coal based electricity generation to a diverse energy mix with more diverse players is very apparent in South Africa. This has resulted from the government of South Africa putting measures in place towards sustainable electricity generation. Significant changes are to unfold as plans of more renewable energy projects gather momentum, as is the case already.

It is with this background that the need for this study stems to develop a PV system with a modular multi-level converter coupled to the CAES system, as a viable and efficient tool for PV integration into the grid. The investigation will entail developing a model for this system, simulate it for optimal performance, perform model tests to validate the results and run model simulation with empirical weather data from the Witkop site. The results from this study will assist in giving an informed insight into the feasibility of the PV system as an alternative renewable energy option.

CHAPTER 3

3. SYSTEM COMPONENTS AND DESIGN

Photovoltaic systems are analyzed with particular emphasis on the need to identify the system components of grid connected PVs. The scrutiny of multilevel converter topologies and energy storages is made to determine their functionalities and ultimately establish the relevant system components to enable the design of the system. The goal for these actions is to identify how these components perform individually and when integrated in solar system. This is then intended to expose the shortfalls of such systems and thereby lead to the design of the subject of study.

3.1. Solar Electricity Generation Technologies

Solar power is the conversion of sunlight directly or indirectly into electricity (European Solar Thermal Industry Association, 2005; Rajasekar & Gupta, 2012; Villalva, 2009). The technologies of sunlight conversion into solar power generation technologies are categorised into two distinct groups, the solar thermal power generation and the photovoltaic generation (Szymanski, et al., 2011). In solar thermal power generation, the solar energy is used to heat the water of a conventional heat engine to produce steam, which can then drive a turbine-generator (Szymanski, et al., 2011). In photovoltaic generation, solar energy is in the form of electromagnetic radiation bundles of energy (photons) and when these strike electrons in some material, the bonds are broken and the free electrons could result in a current flow in the external circuit (Szymanski, et al., 2011). Different types of the above-named technologies are discussed in details in the following sections.

3.1.1. Concentrating Dish (Stirling Engines)

This system is based on parabolic dish shaped concentrator, similar to a satellite dish arrangement that focuses light rays onto a receiver at the central point of the dish. The temperatures at the receiver can be as high as 750 ºC (European Solar Thermal Industry Association, 2005) providing sufficient heat to a thermal fluid, which in turn runs a steam or Stirling engine. Both the schematic diagram and the real picture of a concentrating dish are shown in Figure 3-1 below (European Solar Thermal Industry

Association, 2005; US, 03/09/2013; Centre for Renewable and Sustainable Energy Studies, 2013).

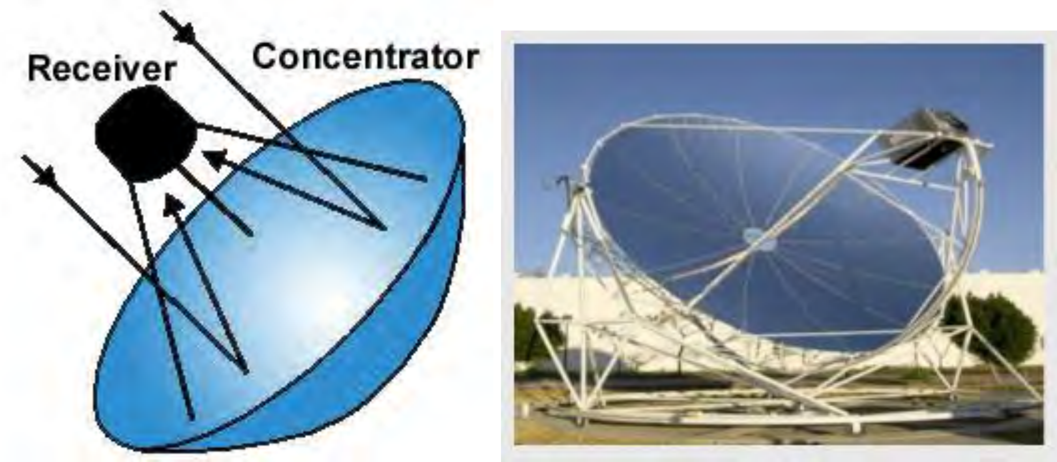

Figure 3-1: Schematic Diagram and Picture of the Concentrating Dish

3.1.2. Central Receiver

The solar power tower plant generates electric power based on the principle of concentrated solar radiation being focused on a tower mounted centrally located receiver (Szymanski, et al., 2011). The solar power tower system uses several thousand mirrors, called heliostats that constantly track the sun, to focus the incident sunlight onto the central receiver. The central receiver is a high-technology heat exchanger, usually molten salt, located atop the tower.

The molten-salt in the solar power tower is pumped from a “cold” storage tank liquid salt at 290 °C through the receiver where it is heated to 565 °C from which it flows to a “hot” tank for storage. During peak hours when the power demand peaks, the power tower plant acknowledges by pumping hot salt to a steam generating system that produces superheated steam for the turbine hence generating electricity. Once the molten salt heats the steam, its temperature drops. The cold salt is then returned to the cold tank where it is stored and eventually reheated in the receiver. Figure 3-2 and Figure 3-3 show the typical layout of the concentrated solar power tower system (Centre for Renewable and Sustainable Energy Studies, 2013).

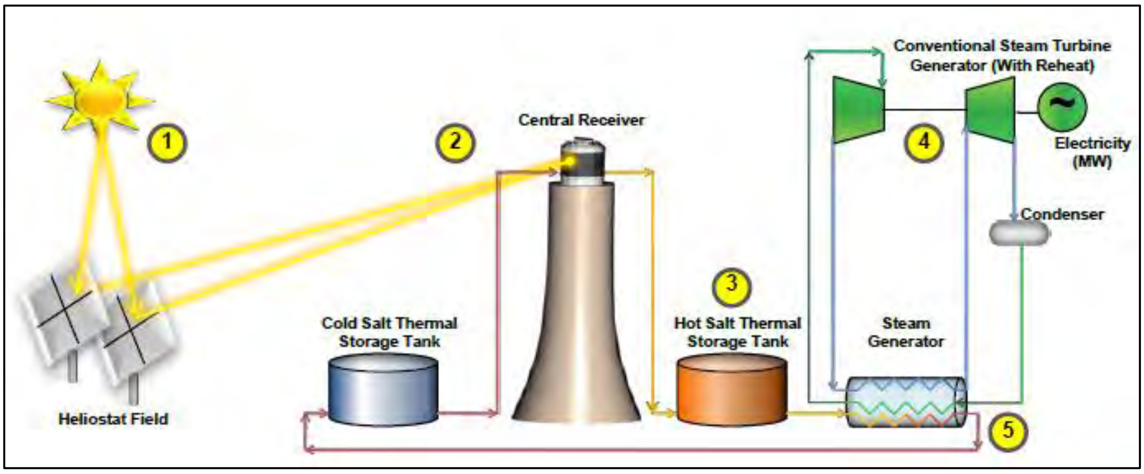

Figure 3-2: Schematic Layout of the Solar Central Receiver System
(Centre for Renewable and Sustainable Energy Studies, 2013).

Figure 3-3: Solar Central Receiver System
(Centre for Renewable and Sustainable Energy Studies, 2013).

3.1.3. Parabolic Trough

The parabolic trough solar power plant operates based on a parabolic mirrored trough, which focuses direct solar radiation onto a glass vacuum tube containing a fluid (oil, molten salt or pressurized steam). The fluid, also called the absorber, collector or receiver, is positioned at the focal point of the parabolic mirrors and runs the entire length of the trough. The trough solar system has a modular structure and comprises many parallel rows of solar collectors aligned on a north-south horizontal axis tracking the sun from east to west during the day to ensure that the sun is continuously focused on the collector that generates heat.

The fluid in the glass vacuum tubes is heated as it circulates through the collector to a series of heat exchangers in the power block where the fluid is used to generate high-pressure superheated steam. The superheated steam is then fed to a conventional steam turbine to generate electricity. Figure 3-4 and Figure 3-5 show a process flow diagram for the trough technology (Centre for Renewable and Sustainable Energy Studies, 2013).

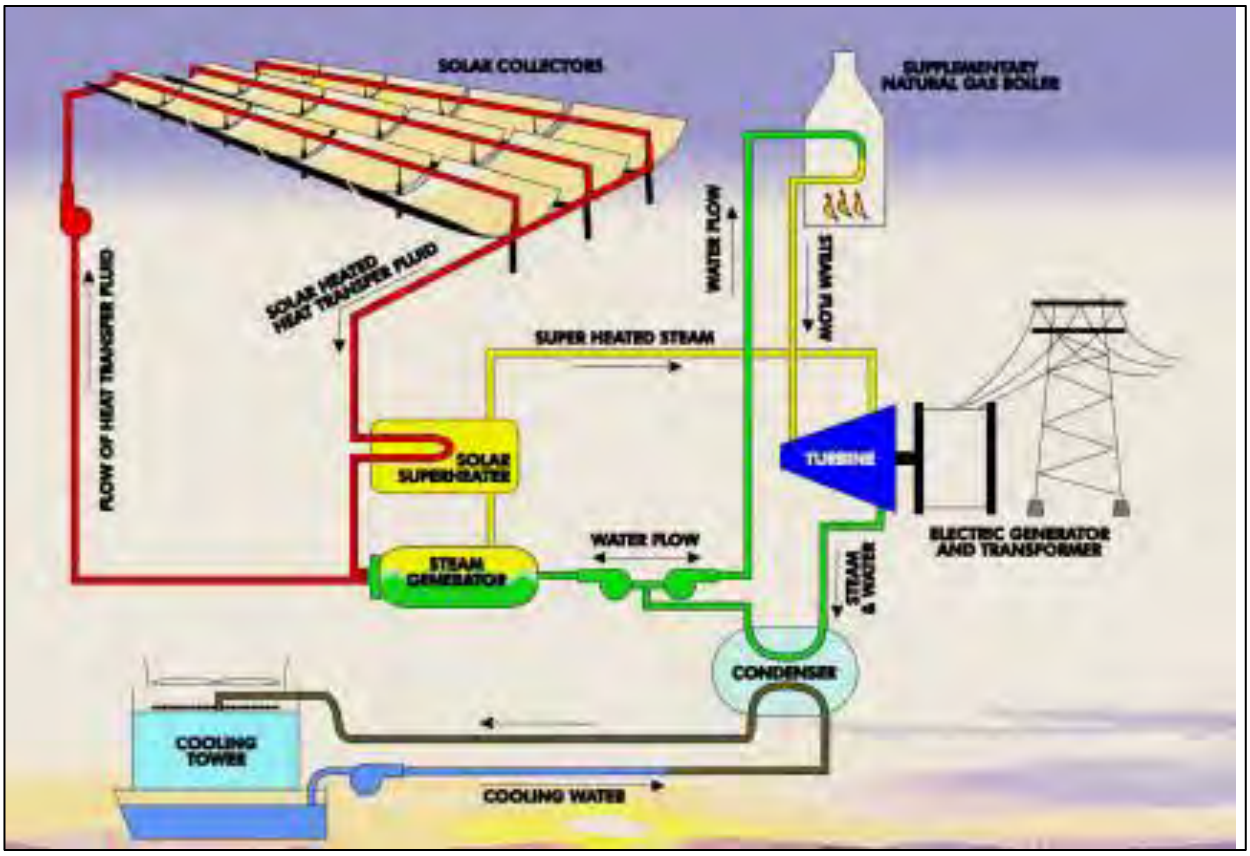

Figure 3-4: Schematic Diagram of the Parabolic Trough System

Figure 3-5: Parabolic Trough System

3.1.4. Linear Fresnel Reflectors

Linear Fresnel reflectors are similar to parabolic trough collectors, but use long rows of nearly flat, rotating mirrors to concentrate light at fixed receivers elevated above the plane of the mirrors. The rotating mirrors are configured to rotate along a single-axis tracking system and hence each mirror is individually optimised to ensure that sunlight is always concentrated on the fixed receiver. Different receivers either use a thermal transfer fluid or directly generate steam to power turbines. Figure 3-6 and Figure 3-7 show a process flow diagram for the trough technology (Feldhoff, 2012).

Figure 3-6: Schematic of Linear Fresnel Reflectors Electricity Generation System

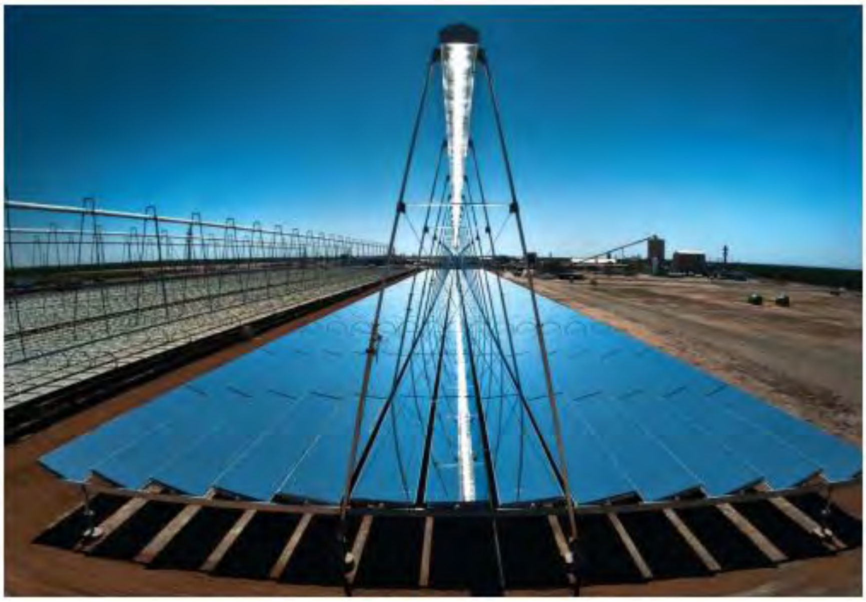

Figure 3-7: Linear Fresnel Reflectors Electricity Generation System

The concentrating dish and the central receiver are known as the point focus technologies while the parabolic trough, and Linear Fresnel Reflectors are the line focus technologies. All the forenamed solar thermal generation technologies come, however, with huge setbacks. The most electricity is generated in the presence of direct light and these systems require energy storage facilities for their full optimisation while in operation. Any light ray obstruction by clouds, fumes or dust in the atmosphere will seriously compromise the performance of these systems. Furthermore, this makes solar thermal power be limited to site locations with high direct solar radiation. In addition, the setup costs of such systems are very high and these systems require regular maintenance. The other most significant drawback of the solar thermal power systems is the environmental impact since the land required for the collector field is about 10 acres per megawatt. The rest of the other drawbacks of the solar thermal power systems are highlighted below:

- Downtime due to machinery (turbine, pumps) failure, break down and maintenance;
- Erosion and wear of tubes and pipes due to flowing salts, water and steam;
- Possibility of fluid leakages in the system;
- Need for fluid top-ups.

3.1.5. Photovoltaic Electricity

Photovoltaic power generation system is an electricity generating system that directly converts solar radiation into electricity through the use of semi-conductive material (XiaoYun, et al., 2011). Crystalline-silicon and thin-film types are the two primary PV technologies available for commercial photovoltaic electricity generation (U.S. Government Printing Office, 1982; National Solar Power Reasearch Institute, Inc., 1998). Crystalline-silicon technology is based on individual PV cells that are cut from large single crystals while in thin film technologies, the PV material is deposited on glass or thin metal that mechanically supports the cell or module. Single-crystal silicon is the most frequently used, best-understood material for solar cells and has resulted in extensive applications (U.S. Government Printing Office, 1982; National Solar Power Reasearch Institute, Inc., 1998). Thin-film based modules are produced in sheets that are sized for specified electrical outputs (U.S. Government Printing Office, 1982; National Solar Power Reasearch Institute, Inc., 1998). See Table 3-1 for common material types and their production efficiencies.

Table 3-1: PV Module Technologies and Efficiencies

PV Technology		Cell Conversion Efficiency	Module Conversion Efficiency
Crystalline	Monocrystalline Silicon (Si)	25.0%	14% - 16%
	Multicrystalline Si	20.4%	14% - 16%
	Gallium Arsenide (GaAs)	26% - 30%	N/A
Thin Film	Amorphous Si (a-Si)	13.4%	6% - 9%
	Cadmium Telluride (CdTe)	19.6%	9% - 12%
	CIS / CIGS	20.4%	8% - 14%

3.2. Photovoltaic Systems

PV systems comprise of photovoltaic cells that are made up of semiconductor materials, which absorb photons of light thereby releasing electrons from the atoms of the material (XiaoYun, et al., 2011). These electrons are then captured to generate an electric current. Different permutations of series and parallel combinations of the photovoltaic cells result in different current and voltage outputs of the photovoltaic systems. Photovoltaic systems have numerous installation configurations and applications available on the market today.

3.2.1. PV Technology

The amount of sun light illuminating the photovoltaic cell will be converted into electrical current in the process of excitation of electrons (Szymanski, et al., 2011). The electrical current generated depends on the intensity of irradiation, the temperature and the size of the cell. The higher the irradiation intensity, the more the current generated and the converse is true for low irradiation intensity. Figure 3-8 shows the typical Current-Voltage graph together with the key characteristic features of the photovoltaic cell.

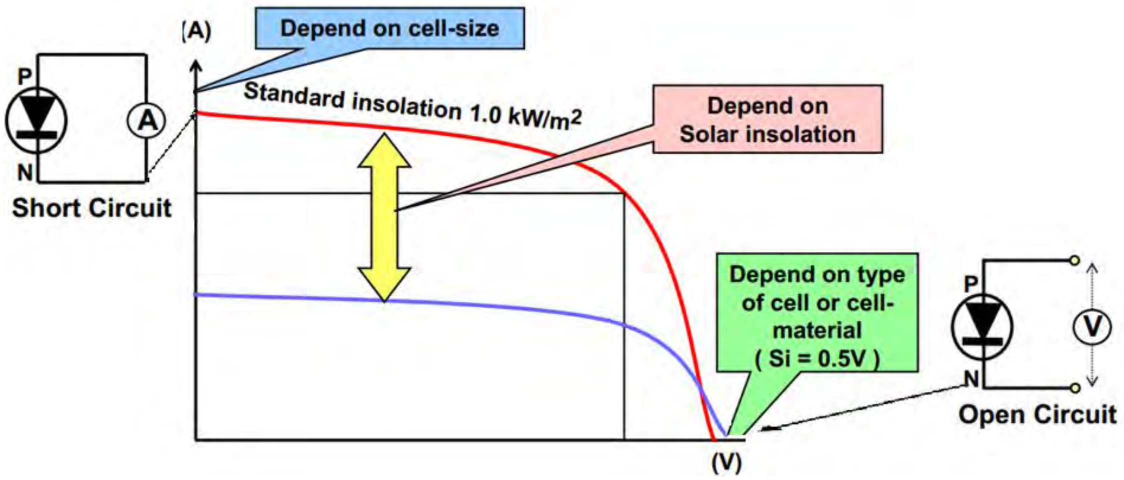

Figure 3-8: Typical Photovoltaic Current-Voltage Graph

The current generated by the photovoltaic cells in very small, therefore a number of these cells are electrically connected to each other and mounted in a support structure or frame called a photovoltaic module. Photovoltaic modules are designed to supply increased electricity power. Multiple modules can be wired together to form an array. In general, the larger the area of a module or array, the more electricity that will be produced. Photovoltaic modules and arrays produce direct-current (DC) electricity. They can be connected in both series and parallel electrical arrangements to produce the required voltage and current combination. Figure 3-9 below shows the components of a PV Solar Panel.

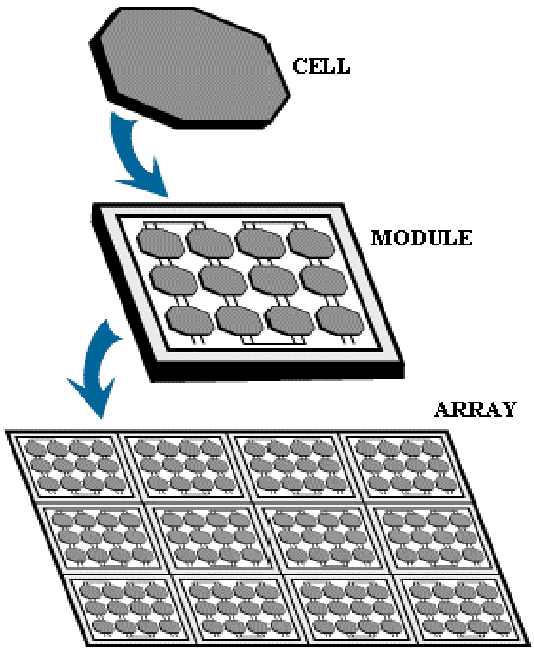

Figure 3-9: The Components of a PV Solar Panel

PV systems are emerging as a major power source due to their numerous environmental and economic benefits and proven reliability. They are among the most important renewable energies in the world with high installed capacities and annual growth rate. These systems play a significant role in our modern daily lives, with applications ranging from powering simple calculators and wristwatches to the more complicated systems like road and traffic signals, satellites, water pumps, and machines (U.S. Government Printing Office, 1982). Photovoltaic technology development has necessitated their incorporation in off-grid, grid connected and hybrid systems. The extent of these systems right now is just the tip of the iceberg when compared to their future possibilities.

3.2.2. PV Systems: Energy Outputs and Performance

The energy output and performance of photovoltaic systems installed at any location depends to a great extent on the environmental conditions they are exposed to and the photovoltaic technology used. Finding the equilibrium between the two is very crucial for systems to operate at the optimal. The technology used is very critical as it provides the ability to quantify the overall effect of system losses. Both the environmental and technological effects are called the de-rate factors. The typical system and component de-rate factors together with their brief description are given in Table 3-2 below:

Table 3-2: Factors Affecting the Performance of PV Systems

Factor Type	Factor	Brief description
Technological Factors	PV Module mismatch	Module mismatch is a result of slight manufacturing inconsistencies where modules of the same size are not identical. Current/voltage characteristics vary slightly from module to module. This results in a module which operates at the output level of the lowest performing module in the string.
	Inverter	Losses due to power inversion from DC to AC.
	DC Wiring	Accounts for resistive loss between the modules and the inverter.

Factor Type	Factor	Brief description
	AC Wiring	Accounts for the resistive loss between the inverter and meter.
	System Availability	Takes into account system maintenance and utility outages, both of which result in down time
	Optical reflection	This includes the losses due to reflection of sunlight from PV panel top surface and the refractive index of the panels
	Downtime failures	This indicates the times the electrical equipment, particularly the inverter, is not available or not working as required.
Environmental Factors	Location, Soiling and Pollution	These are mainly the geographical effects of the area on the PV system and include dust, wildlife droppings, leaves, mist. These effects may be minimal or severe depending on location.
	Shading	These are any obstruction of the panels due to structures or other nearby objects.

3.2.3. Stand Alone Off – Grid PV Systems

These are known as stand-alone PV systems as they are not connected to the electrical grid. The off-grid systems are used to supply local loads that are usually in the power range of several kilowatts (Szymanski, et al., 2011). Remote rural electrification is an ideal application for off-grid solar electric systems. However, off-grid systems have penetrated the urban space with applications in security camera devices, streetlights, electric signs and weather observation systems (Nakayama, et al., 2008). For improved efficiency and reliability, these systems usually utilise batteries for storing energy during the day and releasing energy during the night. Figure 3-10 below shows a typical diagram of a stand-alone off-grid PV system (Ruiher Electric Co.Ltd, 2006).

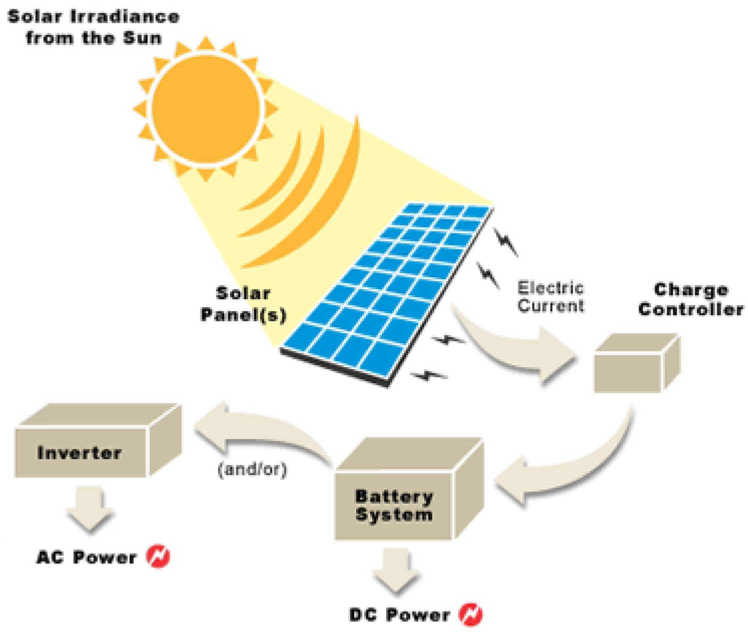

Figure 3-10: Off- Grid PV Systems

3.2.4. Grid Connected PV Systems

Grid-connected PV systems are connected to the electrical grid by means of a proper electronic power conditioning system based on a power electronic inverter (Szymanski, et al., 2011; Carbone, 2009; XiaoYun, et al., 2011). The power electronic inverter converts the DC power produced by the PV cells into alternating current. The development and advancement of the modern control techniques in converters gives the ability to maximize the energy production, improve power quality and improve electromagnetic compatibility. It also minimizes electrical losses on the plant as well as assist in meeting safety and protection requirements for application in the interface between the PV system and the grid (Carbone, 2009; XiaoYun, et al., 2011). Grid-connected photovoltaic system can either be with energy or without energy storage. There has been a significant increase in the number of PV systems interconnected to the electric grid over the recent past (Carbone, 2009). The diagram of a typical grid connected solar system in shown in Figure 3-11 below.

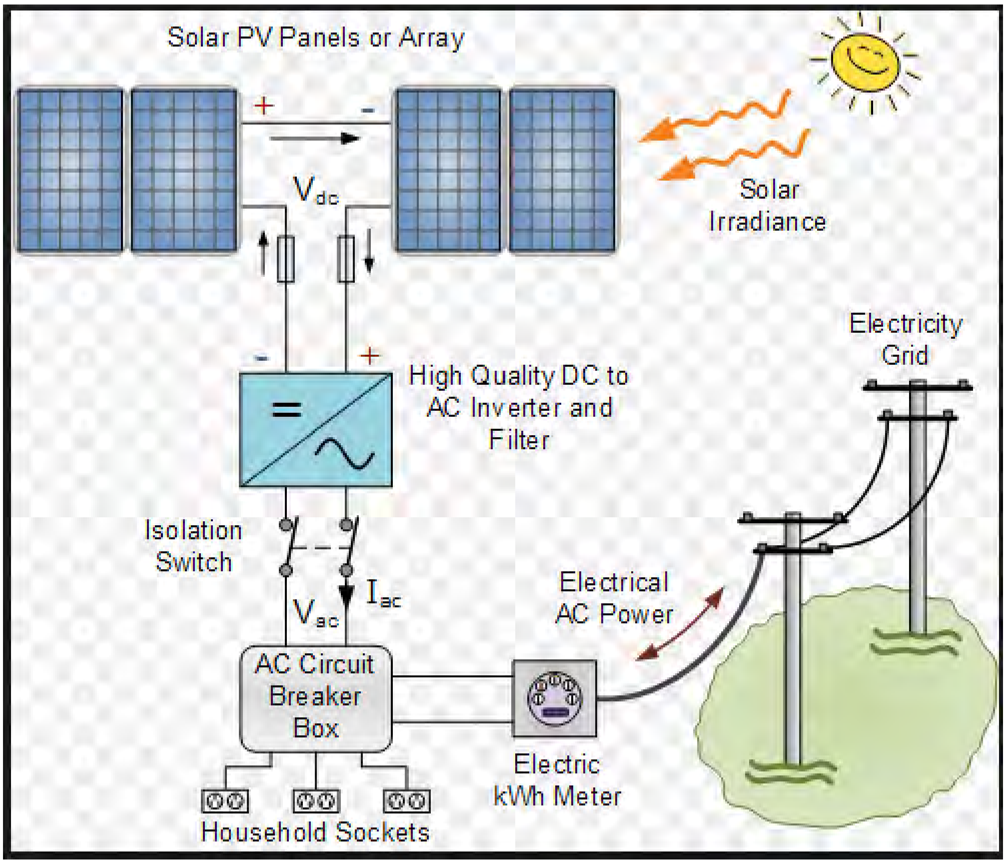

Figure 3-11: Grid Connected PV Systems
(Alternative Energy Tutorials, 2014).

3.3. Multi-Level Converters

Several multilevel converters have been analysed and their application investigated by both academia and industrial personnel (Konstantinou, et al., 2011; Lesnicar & Marquardt, 2003; Marquardt & Lesnicar, 2004 ; Alajmi, et al., 2012; Shehu, et al., 2014). As a result, four converter topologies have become popular and successfully made their way into the industry as they are considered a mature and proven technology for low and medium voltage applications (A. Lesnicar, 2003; Alajmi, et al., 2012; Shehu, et al., 2014; Marquardt & Lesnicar, 2004 ; Konstantinou, et al., 2011). These are the Cascaded H-Bridge (CHB), Diode-clamped type (Neutral Point Clamped, NPC), Capacitor-clamped (Flying Capacitor, FC), and the Modular Multilevel converter. These are mature semiconductor technology due to a number of special features such as high voltage capability, low voltage distortion on the line side, low harmonic distortion of the AC currents, low switching losses, less blocking voltage of the switching device (Alajmi, et al., 2012; A. Lesnicar, 2003; Du, et al., 2006; Konstantinou, et al., 2011).

3.3.1. Cascaded H-Bridge Multilevel Converters, CMC

A cascaded multilevel inverter is a power electronic device based on two-level bridges built to synthesize a desired AC voltage from independent DC sources (Shehu, et al., 2014; Du, et al., 2006). These DC sources may be the PV cells, batteries or fuel cells. The AC terminal voltages of different-level converters are connected in series such that the synthesized voltage waveform is the sum of the individual converter outputs. The number of output-phase voltage levels is defined by m = 2N+1, where N is the number of DC sources (Shehu, et al., 2014; Du, et al., 2009). The diagram of a typical cascaded H-bridge multilevel converter is shown in Figure 3-12 below.

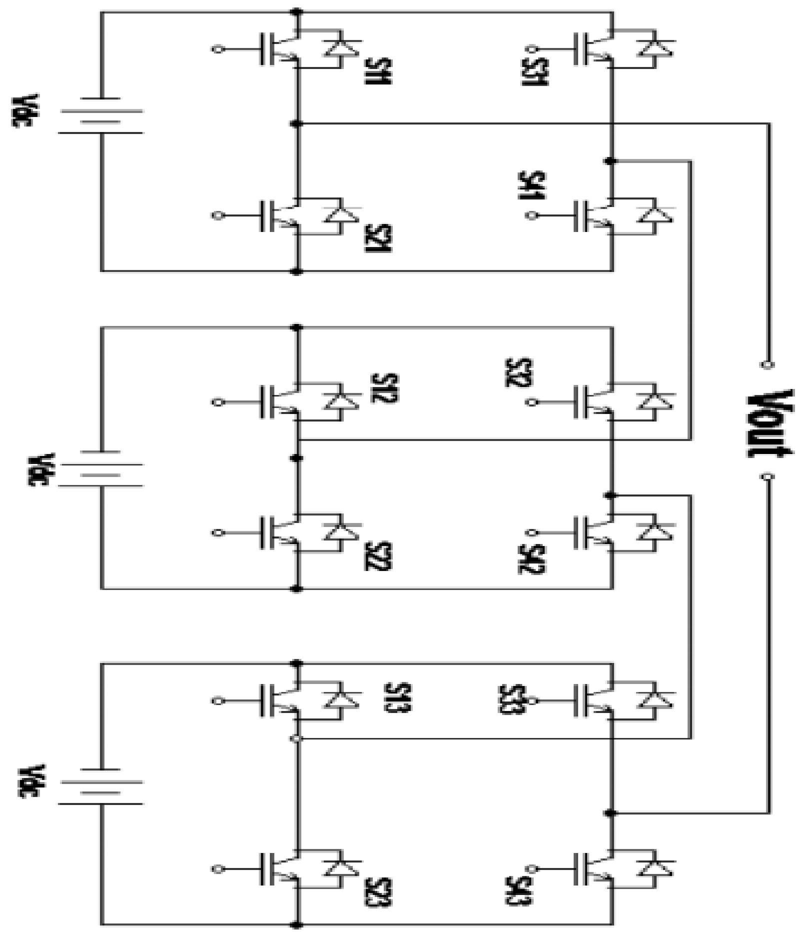

Figure 3-12: Conventional structure of a Cascaded H-bridge Multilevel Converter (Shehu, et al., 2014; Du, et al., 2006).

Some of the advantages and disadvantages of the cascaded H-bridge multilevel converters are given below (Shehu, et al., 2014; Du, et al., 2006):

Advantages:

- Compared to other multilevel topologies, the CMC requires the least number of components to achieve the same number of voltage levels;
- Device voltage sharing is automatic because of the independent DC supplies, thus the regulated output voltage can be obtained even if one or more energy sources are removed;
- A modular circuit layout is possible because each level has the same structure and there are no extra clamping diodes or voltage balancing capacitors;
- This topology allows for redundancy;
- The topology is easily extendable to connect more sources without increasing the control complexity and circuit layout. This is good for manufacture and maintenance.

Disadvantages:

- Each H-bridge needs an isolated DC supply compared to the other solutions which need only one supply;
- In the case where a transformer is used, circulating currents between phases during unbalanced network conditions are produced and it may cause asymmetrical phase voltages.

3.3.2. Diode Clamped Multilevel Converters

The diode-clamped inverter was also called the neutral-point clamped (NPC) inverter when it was first used in a three-level inverter in which the mid-voltage level was defined as the neutral point (Busquets-Monge, et al., 2009). Diode-clamped converters are especially interesting because of their simplicity and ability to obtain multiple voltage levels through a series connection of identical capacitors (Busquets-Monge, et al., 2009; Rashidi-Rad, et al., 2012). The application of the Diode Clamped converter thrived in the 1980s due to the device effectively doubling voltage level without requiring precise voltage matching (Busquets-Monge, et al., 2009; Rashidi-Rad, et al., 2012) and that allows for the reduction of the reactive components, such as the inductors used for a grid-connected converter (Busquets-Monge, et al., 2009; V.Vinothkumar & C.Muniraj, 2013). However, some authors do not recommend the use of diode clamped converters with more than three levels (Rashidi-Rad, et al., 2012).

They based their conclusion on the fact that the high voltage stress on three clamping diodes increases and the number of clamping diodes for each level also increases quadratically. The diagram of a typical diode clamped multi-level converter is shown in Figure 3-13 below.

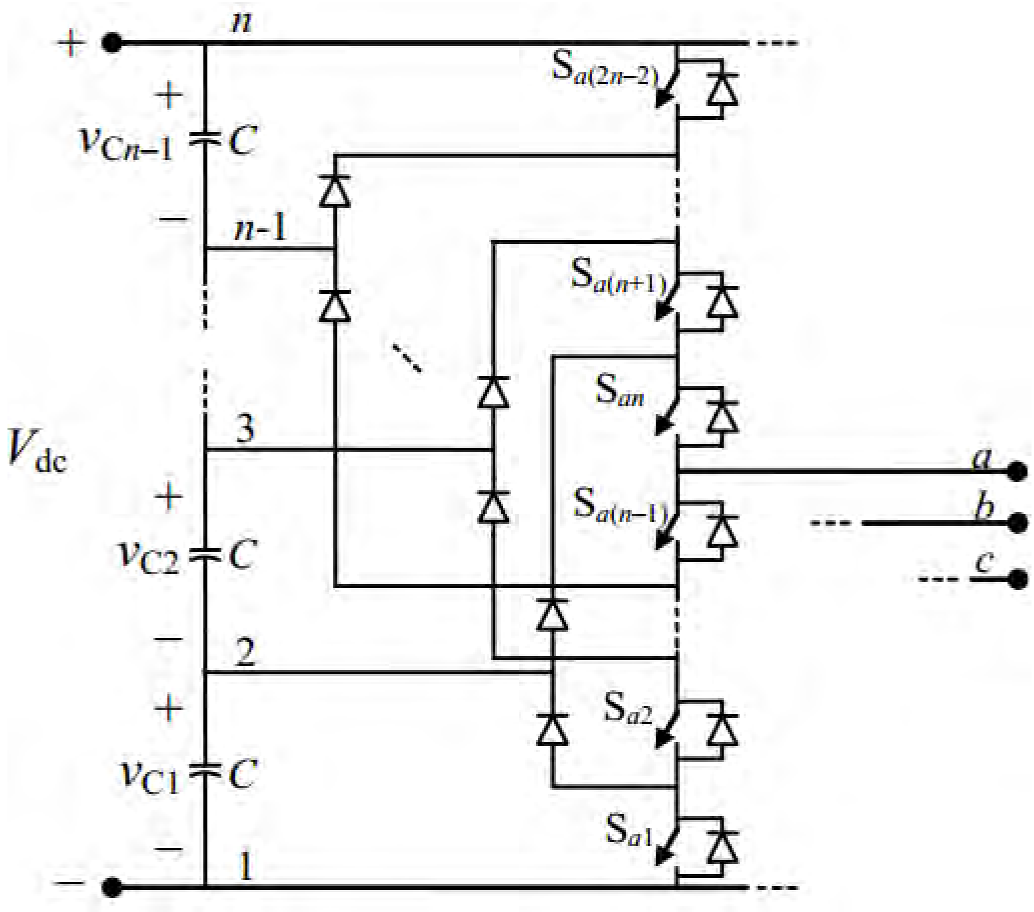

Figure 3-13: Typical Diode Clamped Multilevel Converter
(Busquets-Monge, et al., 2009)

Some of the advantages and disadvantages are highlighted below (V.Vinothkumar & C.Muniraj, 2013; Rashidi-Rad, et al., 2012; Busquets-Monge, et al., 2009):

Advantages:

- All of the phases share a common dc bus, which minimizes the capacitance requirements of the converter;
- Efficiency is high because all devices are switched at the fundamental frequency;

- When the number of levels is high enough, harmonic content will be low enough to avoid the need for filters;
- Reactive power flow can be controlled;
- The capacitors can be pre-charged as a group.

Disadvantages:

- Real power flow is difficult for a single inverter because the intermediate dc levels will tend to overcharge or discharge without precise monitoring and control;
- The number of clamping diodes required is quadratically related to the number of levels, which can be cumbersome for units with a high number of levels.

3.3.3. Capacitor – Clamped Multilevel Converter

In 1992 Meynard and Foch introduced a flying-capacitor-based converter with a structure similar to that of the diode-clamped inverter (Meynard & Foch, 1992; Meynard, et al., 1997). The main difference between these converters is that the flying capacitor used capacitors in place of the clamping diodes. Furthermore, the capacitor-clamped converter allows for more flexibility in waveform synthesis and balancing voltage across the clamped capacitor (Meynard, et al., 1997; Zhang, et al., 2002). The converter has a ladder structure of dc side capacitors and each phase-leg has an identical structure (Zhang, et al., 2002), where the voltage on each capacitor differs from that of the next capacitor. The number of possible voltage levels is related to the number of power switching devices connected in series in each inverter limb (Zhang, et al., 2002). The voltage increment between two adjacent capacitor legs gives the size of the voltage steps in the output waveform. The diagram of a three level flying capacitor is shown in Figure 3-14 below.

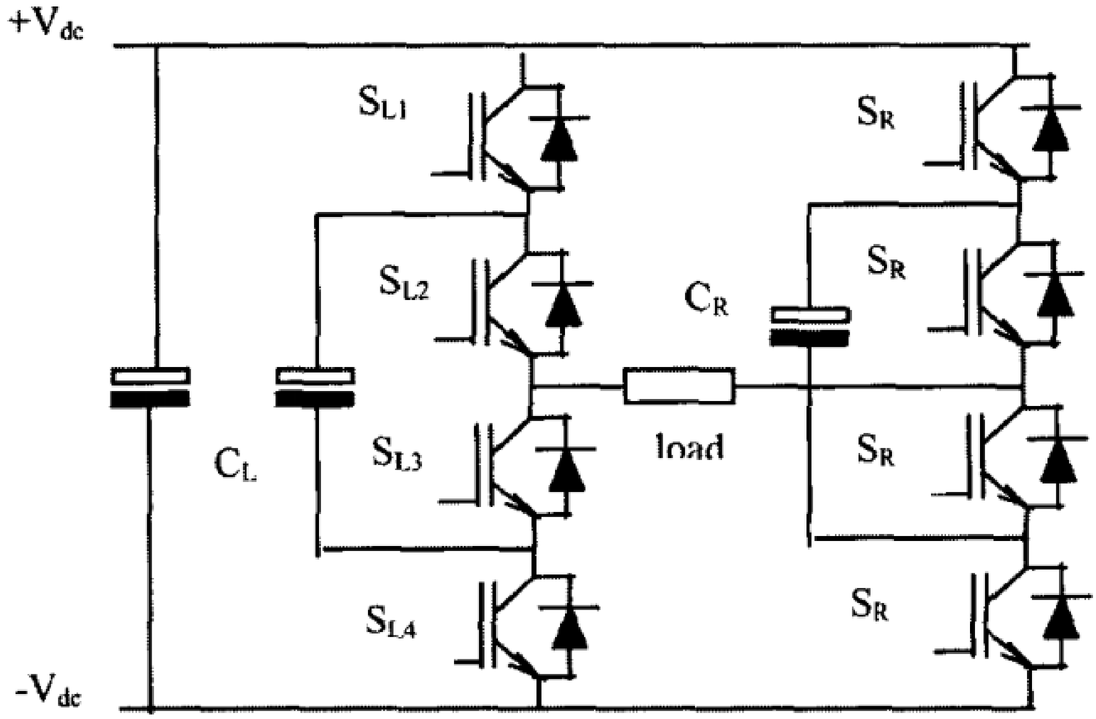

Figure 3-14: Typical Capacitor Clamped Multilevel Converter
(Zhang, et al., 2002).

Some of the advantages and disadvantages are highlighted below (Meynard & Foch, 1992; Meynard, et al., 1997; Zhang, et al., 2002):

Advantages

- Large number of levels allows the capacitors extra energy during long discharge transient;
- Flexible switch redundancy for balancing different voltage levels;
- Lower total harmonic distortion when the number of levels is high;
- Real and reactive power flow can be controlled.

Disadvantages

- Large number of capacitors are bulky and generally more expensive than the clamping diodes used in the diode clamped multilevel inverter;
- Complex control is required to maintain the capacitors voltage balance;
- Poor switching utilization and efficiency for real power transmission.

3.3.4. Modular Multilevel Converters

The multilevel converter technology is based on the synthesis of the AC voltage from several different voltage levels on the DC bus by use of the cascaded interconnection of half-bridge switching sub-modules (Konstantinou, et al., 2011). The increase in the number of voltage levels on the DC side results in more steps on the synthesised output waveform, thus producing a staircase wave that approaches the sinusoidal wave with minimum harmonic distortion (Rajasekar & Gupta, 2012). Multilevel converters have high availability as they make use of approved devices and incorporate redundant operation capability in the event of component failures (Marquardt & Lesnicar, 2004). Modular multilevel converters are suitable for medium and high voltage applications as well as several industrial applications (Konstantinou, et al., 2011), particularly in PV systems, as they have significant characteristics and hence maximise the performance of PV systems.

The basic structure and its operational description of the modular multilevel converter are best summarized in 3 levels given below (Rajasekar & Gupta, 2012; Konstantinou, et al., 2011):

- Sub-modules (the lower level);
- Arm (second level of the converter, half of the leg-phase);
- Leg (can be considered one phase).

The sub-module comprises of two controlled semiconductors switches, two reversing diodes and a DC energy storage capacitor (Soong & Lehn, 2014). A sub-module is considered to be bypassed if the lower switch is closed and the upper switch is open. If the lower switch is open and the upper switch is closed, the sub-module is considered to be inserted (Konstantinou, et al., 2011; Alajmi, et al., 2012). Several series-connected sub-modules in a half bridge configuration with one arm inductor, with the inductance *L,* make up the converter arm. The phase leg of the converter consists of one upper and one lower arm connected in series between the dc-terminals. The function of the inductor is to limit the arm current by taking up the voltage difference produced when a module is switched on and off (Soong & Lehn, 2014). The resistance of the inductor and sub-modules in one arm is denoted *R*. The resistance *R* and inductance *L* are referred to as the arm impedance. The number of levels in the output phase-leg depends mainly on the number of sub-modules in each leg as well as the converter leg modulation (Rajasekar & Gupta, 2012). Figure 3-15 below shows the basic structure of a modular multilevel converter.

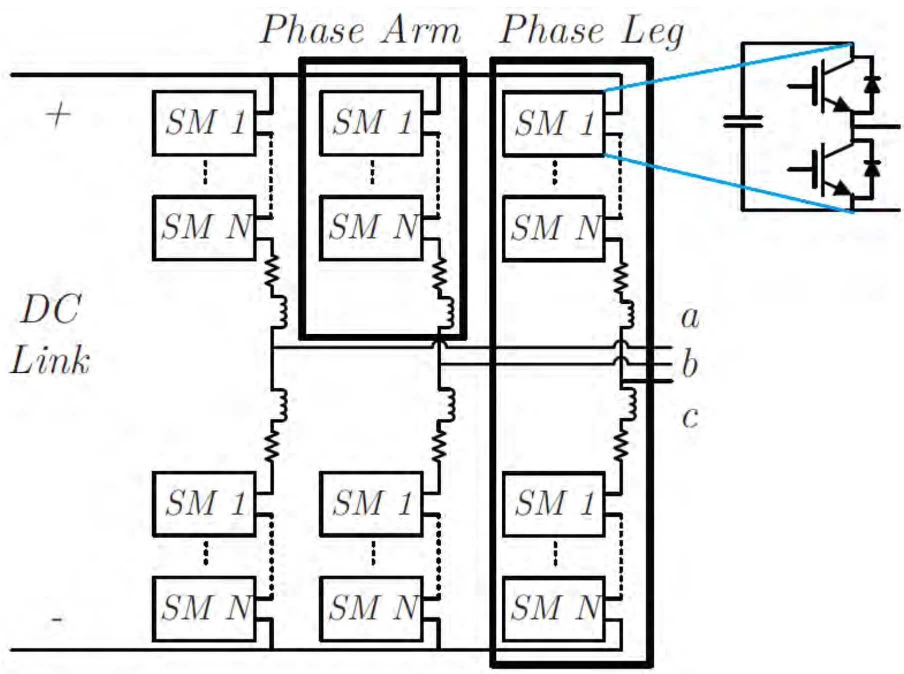

Figure 3-15: Modular Multilevel Converter Structure
(Soong & Lehn, 2014).

The most attractive features of modular multilevel converters are as follows (Marquardt & Lesnicar, 2004 ; Soong & Lehn, 2014; Alajmi, et al., 2012):

- Modular structure allows to extend higher number of levels easily;
- Multilevel waveform permits expandability to any number of voltage steps and generates low total harmonic distortion on the output voltage thereby eliminates filtering requirements;
- High availability as modular multilevel converters use approved devices and redundancy functionality;
- Failure management as the devices have fail safe operation;
- Capacitor voltage balancing is attainable independently of the load;
- Able to function independent of operating conditions;
- For medium voltage application, it allows to avoid interfacing transformer.

3.4. Electricity Energy Storage

The energy which comes from the PV power plants is generally intermittent in nature. This is purely because it depends on the weather conditions and the time of the day. Considering this together with the myriad of challenges facing electricity utilities has caused the need to focus at electricity storage as technically and economically viable solutions.

Many energy utilities have already embraced electricity storage with batteries still remaining as the storage norm for emergency operations (Electric Power Research Institute; U.S Department of Energy. EPRI - DOE , 2003). However, many storage options have been considered as an essential requirement to the performance improvement of renewable energy.

In PV systems, the energy is stored when there is excess energy generated, mostly during the day, when irradiation is highest. The stored energy can be distributed back into the grid when there is a high electricity demand (Daneshi, et al., 2010; Sun, et al., 2010 ; Electric Power Research Institute; U.S Department of Energy. EPRI - DOE , 2003). With the help of modern power electronics and control, storage technologies like the compression or expansion of gas, super-capacitors, batteries, flywheel and chemical storage systems are considered as means to improve quality of electricity supply, reliability, availability and particularly the PV system performance and efficiency (Daneshi, et al., 2010; Sun, et al., 2010 ; Electric Power Research Institute; U.S Department of Energy. EPRI - DOE , 2003). Further significant benefits of energy storage systems include a reduced strain on transmission and distribution networks and improved operating reserves due to the reduced need for peak generation (Daneshi, et al., 2010).

3.4.1. Batteries

The electrochemical reactions in the battery generate current. Depending on the PV system configuration and electricity demand, current flows from the batteries to the load when required. The use of batteries has rendered them ideal for applications in both stand-alone power networks and in grid connected systems. Some of the typical battery types used are Lead-acid batteries, Ni- Cd Batteries, Li-ion batteries and Nas Batteries (Daneshi, et al., 2010; Sun, et al., 2010).

The operation and performance of PV systems with battery storage is affected by the following parameters but not limited to;

- Physical characteristics, e.g. weight, dimensions, terminals, etc.;
- Planned installation life and expected cell life;
- Frequency and depth of discharge;
- Environmental conditions like ambient temperature variations, corrosive atmosphere, pollution, etc.;
- Charging characteristics;
- Maintenance requirements;
- Ventilation requirements;
- Seismic requirements i.e. shock and vibration;
- Cell orientation requirements;
- Battery maintenance requirements.

A reliable and efficient battery should be able to charged and discharged indefinitely as well as have high efficiency, high energy density, low-self discharge and be of low cost.

3.4.2. Flywheel

Flywheels have for many centuries been used for energy storage and their transformation in shapes and sizes have since rendered them a competitive edge from other energy storage applications. This transformation continued into the modern times with recent flywheel improvements in material, magnetic bearings and power electronics. These improvements give flywheels the ability to handle high power levels which is a desirable quality in applications where a large peak power is required for a short while. The flywheel-based energy storage systems are relatively environmentally friendly technology solutions that neither use hazardous materials for production, nor create them during operation.

The basic flywheel storage device components are the high-density rotating mass (rotor) spinning at a very high velocity and an integrated motor-generator. The motor-generator machine transfers energy, in the kinetic energy form, in and out of the flywheel. The amount of kinetic energy stored as rotational energy depends on the inertia and speed of the rotating mass. For efficient performance, the flywheel is placed inside a vacuum containment to eliminate friction-loss from the air and suspended by bearings for a stabile operation (Daneshi, et al., 2010). Figure 3-16 below shows the main components of a flywheel.

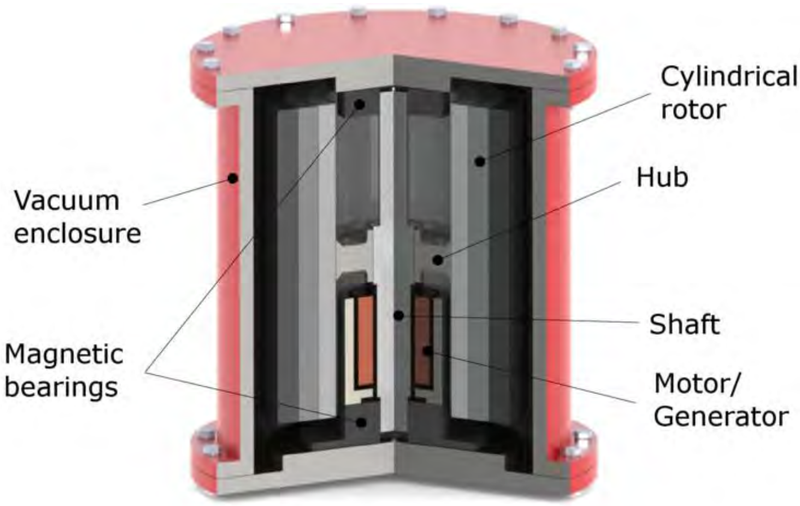

Figure 3-16: The main components of a typical flywheel.
(Wikimedia Commons, 2012)

3.4.3. Pumped Hydro Power

Pumped storage hydroelectricity is a method of storing and producing electricity to supply high peak demands by moving water between reservoirs at different elevations. When demand requires electricity in peak load periods the flow is discharged through a turbine which generates hydroelectricity. At times of low electrical demand, excess electrical capacity is used to pump water into the higher reservoir (Daneshi, et al., 2010). The evaporation losses from the exposed water surface and mechanical efficiency losses during conversion compromise the performance of these systems. However, the pumped hydropower system is economical as it injects significant power into the grid to balance out the electricity demand. The diagram of the pumped hydro storage facility owned and operated by the Tennessee Valley Authority (TVA) is given in Figure 3-17 below (Tennessee Valley Authority, 2009).

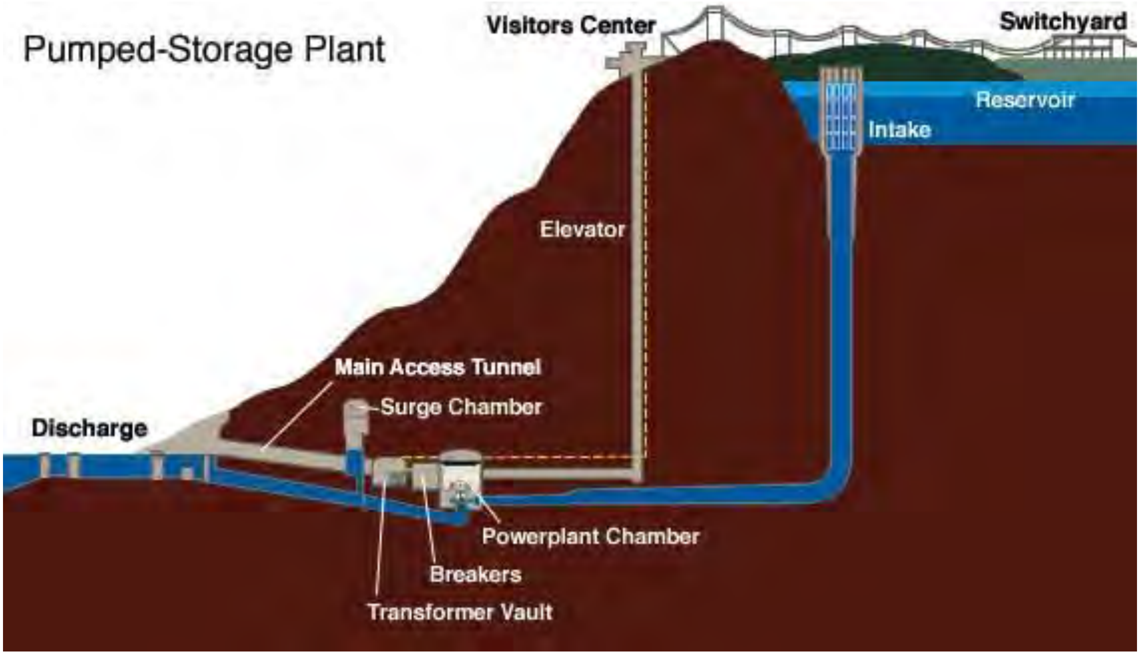

Figure 3-17: Pumped Hydro Storage Plant installed at Raccoon Mountain (Tennessee Valley Authority, 2009)

3.4.4. Super-Capacitors

The principle of physically separating the negative and positive charges traditionally used in capacitors is incorporated by super-capacitors to store energy. The super capacitors can charge and discharge a large amount of power in a very short time though they are not suited to storage of significant amounts of long term energy storage as they have a high self-discharge rate of 10% per day (Daneshi, et al., 2010; Electric Power Research Institute; U.S Department of Energy. EPRI - DOE , 2003). However, they are increasingly being used in combination with batteries to provide both rapid charging and long term capability, particularly relevant for automotive applications. Figure 3-18 below shows super-capacitors (Oregon State University, 2014).

Figure 3-18: Super-Capacitors

(Oregon State University, 2014)

3.4.5. Compressed Air Energy Storage

The progressive and gradual technological advancements of the compressed air energy storage systems have resulted in the latest Adiabatic CAES system. The Adiabatic CAES system is based on the principle of utilising the heat generated during the compression stage through the heat storage plant (Hasan, et al., 2012). Unlike conventional CAES systems, the Adiabatic CAES eliminates the burning of natural gases since the compression heat is used in the expansion process hence increasing system efficiency (Hasan, et al., 2012; Electric Power Research Institute; U.S Department of Energy. EPRI - DOE , 2003). The technological differences between these systems saw the modern system having higher efficiency, lower investment costs and not using natural gas, hence emission free system, when compared to the previous generations (Electric Power Research Institute; U.S Department of Energy. EPRI - DOE , 2003).

The operation of the CAES system comprises three main stages; the compression stage, expansion stage and the turbine stage (Electric Power Research Institute; U.S Department of Energy. EPRI - DOE , 2003; Zunft, et al., 2006). The compression stage is operated during off-peak periods when there is excess power on the grid. In this stage, the electric motor in the CAES plant is used to drive a compressor train comprising several compressors and heat exchangers. After the atmospheric air is compressed by the first compressor it goes to a heat exchanger that extracts heat for the compressed air (Zunft, et al., 2006). The atmospheric air goes through the entire train of compressors and heat exchangers before finally going in the cavern storage. The extracted heat from atmospheric air is stored in the heat storage tank for later utilisation (Zunft, et al., 2006).

The expansion stage happens at times of peak demand where the compressed atmospheric air is drawn from the cavern. This stage is formed by an expansion train formed by a high air pressure turbine followed by a low air pressure turbine, together with the necessary heat exchangers to reheat the extracted air from the cavern. The atmospheric air temperature will increase every time its discharges from the tank, while further heating of the atmospheric air is provided by the heat transfer fluid in the heat storage cavern (Zunft, et al., 2006; Hasan, et al., 2012). Finally, in the turbine stage, the heated air drives the turbine which is an electrical generator and supplies electricity to the grid (Zunft, et al., 2006; Hasan, et al., 2012). Thus, the photovoltaic system is able to supply electricity even in the absence of solar irradiation. The basic layout of the Adiabatic CAES power plant is shown in Figure 3-19 below.

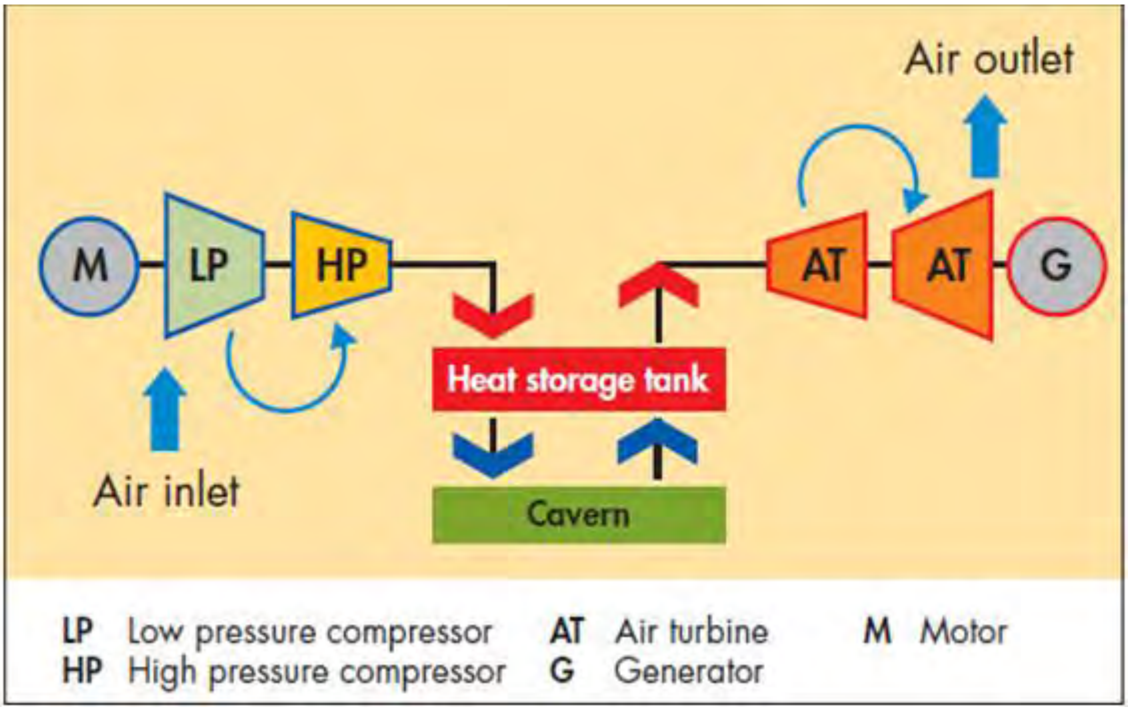

Figure 3-19: Layout of the Adiabatic Compressed Air Energy Storage Power Plant (BINE Information Service Energy Expertise, 2007)

The CAES system has high power density capabilities and a long lifespan period due to the fact that its losses are very small. The advantages and disadvantages of the CAES system are given below (Daneshi, et al., 2010).

Advantages

- Higher efficiency than a conventional natural gas plant;
- Stable heat rate at low capacity;
- High output in hot weather, since the air flowing into a CAES turbine is at a constant heat and pressure;
- No emissions;
- Can withstand frequent starts and stops;
- Can easily switch between compressing or expanding processes or even run both at simultaneously;
- Can respond quickly to market demand, thus they have shorter ramp rates.

Disadvantages

- Requires large airtight reservoir, which may be site specific;
- Temperature sensitive.

3.4.6. Comparison of the Electricity Energy Storages

The application and criteria of the energy storage technology used at any site is based on several performance characteristics like the energy efficiencies, life cycle period, sustainable development and the impact of technology on environment (Daneshi, et al., 2010; Electric Power Research Institute; U.S Department of Energy. EPRI - DOE , 2003; Sun, et al., 2010 ; Cavallo, 2007). Table 3-3 below shows a comparison of some energy storage technologies.

Table 3-3: Comparison of Energy Storage Technologies

(Daneshi, et al., 2010; Electric Power Research Institute; U.S Department of Energy. EPRI - DOE , 2003; Sun, et al., 2010)

Technology	**Efficiency**	**Facility size range**	**Application**	**Advantages**	**Disadvantages**
Battery	80 - 95%	100 W - 20 MW	Automobile; Variability reduction; Uninterruptible power supply (UPS); Power quality.	High power & energy capacity; High power & energy density; Long life time.	Production cost; Safety concerns; Relatively expensive; Production challenges.
Flywheel	90 - 95%	kW scale	Power quality; Transportation defense.	High power capacity; Short access time; Low maintenance effort; Small environmental impact; Quick recharge.	Low energy density; Low energy capacity; Large standby losses; Potentially dangerous failure mode.
Pumped Hydro Storage	70 - 85%	Up to 2.1 GW	Spinning / standing reserve energy; Arbitrage.	High power & energy capacity, medium access time, long life, lower energy generation cost.	Special site Requirements, adverse impact on environment; Expensive to site built; Long construction time.
Super Capacitor	90 - 95%	10 - 20 kW	Power quality; Emergency bridging power; Consumer electronics; Transportation defense.	High efficiency; Long life cycle; Quick recharge.	Low energy density; Few power system applications; Expensive; Sloped voltage curve require power electronics.
CAES	70 - 80%	25 - 350 MW	Spinning / standing reserve energy; Arbitrage; Frequency regulation.	Very high energy & power capacity; Long life time.	Geographical limited.

3.5. Simulation Packages

A simulation model is the imitation of the operation of a real world process or system over time. Simulation models capture time-varying dynamic phenomena and have the ability to evaluate performance variables in as much detail as desired (Harrell & Tumay, 1995). Developing a good simulation model can be divided into several distinctive steps that have to be followed from the identification of a need to providing the recommendations based on the output of the model. Although these steps are sequential, they are iterative and several steps have to be repeated until a suitable model is produced. Several assumptions that define the model need to be explicitly defined and agreed upon by the simulation analyst and all the other parties involved in the investigation, like plant and process engineers. Simulation modelling typical follows several distinct steps as highlighted in Figure 3-20 below (Musselman, 1994; Azadivar, 1992; Carson & Maria, 1997).

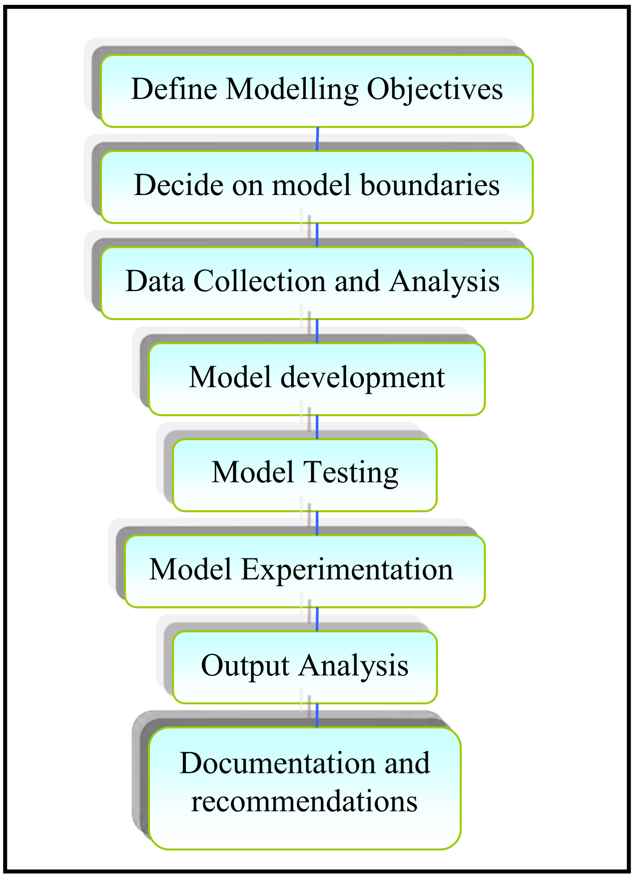

Figure 3-20: The Process of Simulation Modeling

Below are detailed explanations of the above simulation model process. However, the explanations now give a more customized version of the particular research in question focusing on the PV system with MMLC coupled to CAES for grid integration.

a. Define Modeling Objectives for a Grid-connected PV System

This relates to determining the required outcome of the modeling and which information the model should provide. It involves identification of decisions and uncontrollable variables, specification of constraints on the decision variables, definition of performance parameters and system configurations.

b. Decide on Model Boundaries

This decides which processes or systems should be incorporated into the model based on the importance of certain processes and the suitability of particular processes to be captured in the simulation model.

c. System Data Collection and Analysis

This involves determination of the system input parameters, system configuration, and the logical flow of information within the model through consultations with system experts, observations of the existing systems and study of existing documentation of the systems.

d. Matlab/Simulink Model Development

This is done using a simulation software package through an iterative process and in this case Matlab/Simulink package is used. Here a simple model is initially developed before being expanded and refined until an acceptable model is obtained.

e. Model Testing and Validation

In this phase, the model should be thoroughly tested using as many verification and validation techniques as feasible. Once no significant problems are noted, then the model can be used for experimentation as a valid representation of the original process.

f. Model Experimentation

Production runs are made with the input of the various performance parameters under investigation. Formal experimental design seems to be appropriate where there is a number of alternative ways to perform the same process, one of which is applied to each experimental organization unit performing the process, and measurable observations are made for each unit.

g. Output Analysis

Output results should be analyzed using appropriate techniques, usually statistical techniques related to the estimation of the values of the simulation output variables.

h. Documentation and Recommendations

There are two types of documentation: program and progress. Program documentation is necessary as it assists the modeler and other analyst, according to Musselman, (1994) to re-model and change parameters of the model at will in an effort to determine the relationships between input and output measures of performance, or input parameters that 'optimize' some output measure of performance. Recommendations can then be made relating to the objectives of the whole study.

Several types of simulation tools are available in literature which offer support for modular building of models, data exchange and integration with other simulators and engineering applications (Sklenar, 2013; Raghuwanshi, et al., 2012). These tools are classified into discrete, continuous and robotic simulation tools.

3.5.1. DigSilent

DIgSILENT is a computer aided engineering tool for the design, control and analysis of industrial, utility and commercial electrical power systems with the main applications in planning and operation optimization. DIgSILENT Version 7 was the world's first power system analysis software with an integrated graphical on-line interface. That interactive one-line diagram included drawing functions, editing capabilities and all relevant static and dynamic calculation features. However, this package will not be utilised in this study, as access to this package was not possible within the period of study.

3.5.2. PSCAD/EMTDC

PSCAD/EMTDC is an industry standard simulation tool for studying the transient behaviour of electrical networks. PSCAD/EMTDC is most suitable for simulating the time domain instantaneous responses, also popularly known as electromagnetic transients of both AC and DC electrical systems. The PSCAD Graphical Interface greatly enhances the power and efficiency of the simulation as it allows the user to schematically construct a circuit, run a simulation, analyse the results, and manage the data in a completely integrated graphical environment.

Simplicity of use is one of the outstanding features of PSCAD/EMTDC as users create a process by merely dragging and dropping icons, which represent elements typically found in electrical systems, from the central library onto the screen or from images such as photographs, video clips or CAD layouts. The basic elements have numerous buttons and tabs for which parameters can be set or control code can be added. It has many great modelling capabilities and highly complex algorithms and methods are transparent to the user, leaving one free to concentrate efforts on the analysis of results rather than on mathematical modelling. For the purpose of system assembling, the user can either employ the large base of built-in components available in PSCAD/EMTDC or to its own user-defined models.

3.5.3. Matlab™

MATLAB stands for Matrix Laboratory and is a programming environment for algorithm development, data analysis, visualization and numerical computation. Matlab™ is based on the mathematical model of the process to be simulated. It incorporates a variety of control system design techniques that have been implemented successfully to control a wide range of electrical systems including robots hence enhancing their performance and throughput. Using the built-in math and graphics functions and easy-to-use tools, engineers can analyse and visualize data on the fly. The structured language and programming tools let users save the results of interactive explorations and develop own algorithms and applications. The Matlab/Simulink modelling and simulation packages will be used in this dissertation because of its ability to accept numerous dynamic data. Additionally, the candidate has access to this simulation package (The MathWorks Inc., 2011; The MathWorks, Inc., 2012).

3.6. Summary

The manner in which various components of a system are integrated and connected can have a major implication on the performance of the system. The key to solar power system performance and reliability is the proper integration of components into a complete system.

CHAPTER 4

4. SIMULATION MODELLING

The design of the PV system must be robust, as it tries to integrate and simplify the complexities brought about by constantly changing weather conditions, solar irradiation levels, cell-operating characteristics and fluctuating load demand. The following are the major system design considerations and configurations used in modelling the grid connected PV system in the MATLAB/Simulink environment.

4.1. PV System Modelling

A Simulink model for the PV system was designed to highlight the behaviour of the system under different operating conditions with varying input parameters. The model comprises of several sub-systems of numerous modules connected in series/parallel notation with each other. The model considers the environmental temperature and the radiation as the main input variables, while it predicts the output parameters of voltage, output current and power of the PV panel. The construction of this model is detailed in the sections following.

4.1.1. Photovoltaic Cell Model

Though there are several PV models, the single diode (single exponential) and the double diode (double exponential) are the well-known and widely used models (Yazdani, et al., 2011). Both of these are based on the Shockley diode equation. The single diode model offers a good trade-off between simplicity and accuracy (Yazdani, et al., 2011; Rustemli & Dincer, 2011; Ding, et al., 2012; Ishaque, et al., 2011). This is also referred to as a four-parameter model and it comprises a current source in parallel with a diode, the series resistance and the parallel resistance. Overall, this model accounts for the losses due to the module’s internal series resistance and the contacts and interconnections between cells and modules. Figure 4-1 shows the equivalent circuit of a single diode PV cell (Rustemli & Dincer, 2011).

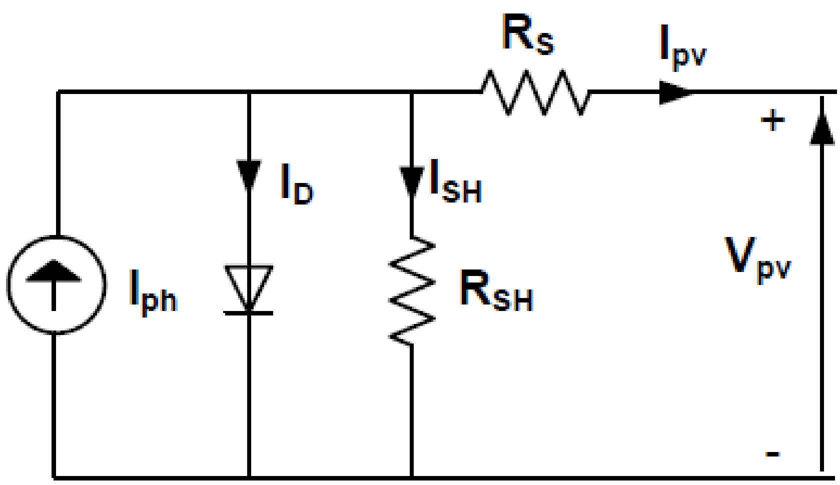

Figure 4-1: Equivalent Circuit of a Single Diode PV Cell
(Guo, et al., 2011; Rustemli & Dincer, 2011; Ishaque, et al., 2011)

The photocurrent, I_{PH}, depends on the panel temperature and the solar radiation on the panel. For a particular temperature and irradiation level, this model has different current, voltage and power output parameters. According to Kirchhoff's current law (KCL) the terminal output current, I_{PV}, produced by the real PV cell is given by (Guo, et al., 2011; Rustemli & Dincer, 2011; Ding, et al., 2012):

$$I_{PV} = I_{PH} - I_D - I_{sh} \qquad (4\text{-}1)$$

$$I_{PV} = I_{PH} - I_o\left[e^{\frac{(V_{PV}+I_{PH}*R_S)}{V_T}} - 1\right] - \frac{V_{PV} + I_{PH}*R_S}{R_{sh}} \qquad (4\text{-}2)$$

Where,

I_{PV}	Terminal current of the real PV cell
V_{PV}	Terminal voltage of the real PV cell
I_{PH}	Photocurrent
I_o	Diode saturation current
R_s	Series resistance
R_{sh}	Shunt resistance
V_T	Thermal voltage

Figure 4-2 shows the simulation structure of the photovoltaic cell modelled in Matlab/Simulink based on equations 4-1 and 4-.2. This model uses the electrical parameters of the PV cell such as the PV voltage (V_{PV}), solar irradiance (I) and environmental temperature (T) as the inputs to yield the PV current (I_{PH}).

4.1.2. The PV Module

The electricity from the photovoltaic module is characterized by the open-circuit voltage (V_{oc}), short circuit current (I_{sc}), maximum power voltage (V_{mp}) and maximum power current (I_{mp}). The open-circuit voltage of a module is the voltage across the module when no current is being supplied while the short circuit current flows when the module is not connected to any load. When the module is short-circuited, the current is at maximum and the voltage across the module is zero. When the PV module circuit is open, with the leads not making a circuit, the voltage is at its maximum and the current is zero. The maximum power voltage and maximum power current are the module voltage and current levels for which the module delivers the maximum possible power for a given irradiance and temperature level (Guo, et al., 2011; Rustemli & Dincer, 2011; Chen & Zhu, 2012).

The standard test conditions, STC, show the list of the electrical characteristics of PV modules under the internationally agreed conditions since these electrical properties vary with irradiance and temperature. The Standard Test Conditions are a module temperature of 25 °C, an Air Mass of 1.5 and under an irradiance level of 1 000 W/ m^2 (Papanikolaou, et al., n.d.; Rustemli & Dincer, 2011; Chen & Zhu, 2012). These conditions are conducive to testing in a manufacturing environment but tend to overestimate actual performance, as the cell temperature is rarely at a temperature of 25 °C and an irradiance of 1 000 W/m^2 at the same time. Furthermore, the nominal efficiency of the module is also calculated under these conditions. This information is then complied and offered as module Manufacturer's Data.

The SunPower E20/333 solar panel PV module with an all-back-contact solar cell was considered in this design (SunPower Corporation, 2011), Appendix F. This choice was based on the module having the highest efficiency, up to 20.4%, and the highest performance in the world (Solarplaza, 2012). Appendix G shows a list of the most efficient PV modules. The high voltage output of each module gives it an edge over other modules as the overall system voltage may be met with the minimal possible number of modules. The SunPower E20/333 PV module parameters are given in the Table 4-1 below.

Table 4-1: SunPower E20/333 PV Module Parameters

SunPower E20/33 PV Module Parameters		
Nominal Power	P_{nom}	333 W
Maximum Power Voltage	V_{mpp}	54.7 V
Maximum Power Current	I_{mpp}	6.09 A
Open Circuit Voltage	V_{oc}	65.3 V
Short Circuit Current	I_{sc}	6.46 A
Maximum System Voltage	IEC	1000 V
Temperature coefficient for	Power (P_{max})	-0.38 %/ºC
Temperature coefficient for	Voltage (V_{oc})	-176.6 mV/ ºC
Temperature coefficient for	Current (I_{sc})	3.5 mA/ ºC
All technical data measured at Standard Test Conditions (STC): Irradiance = 1000 W/m^2, Air Mass = 1.5 and Cell Temperature = 25 ºC		

The typical relationship between module current and module voltage for different levels of sunlight (irradiance) incident for the SunPower PV module are shown in Figure 4-2: 2 below.

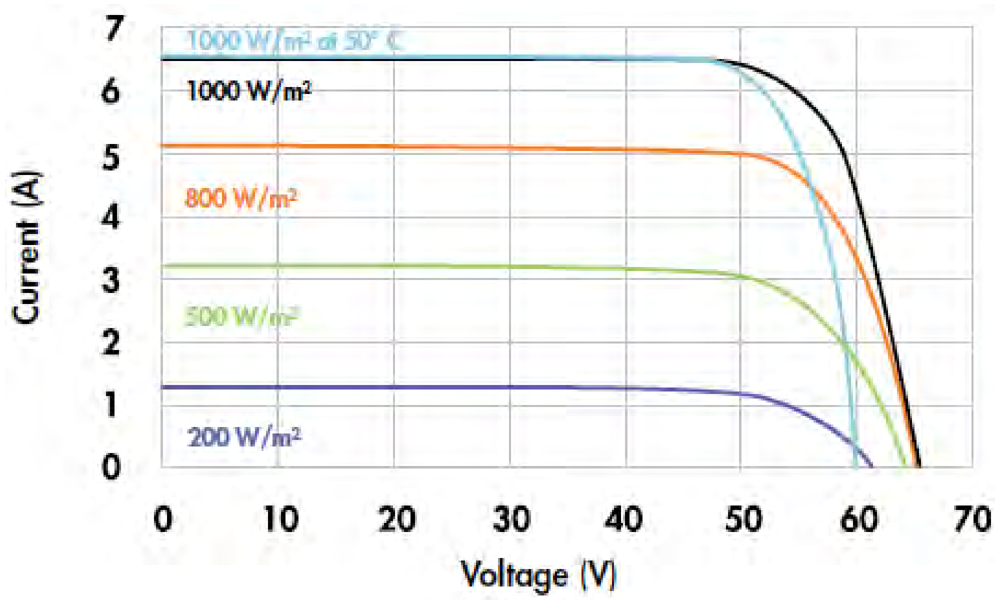

Figure 4-2: SunPower PV Module Current-Voltage Curve

(SunPower Corporation, 2011)

4.1.3. The 30 Megawatt Plant

The magnitude of the solar plant for this investigation was set at 30 MW, following the trends in the country with the recently installed PV systems of 28 MW and 30 MW at Soutpan and Witkop solar parks respectively. The total energy generated by the solar parks is dependent on various combinations of the PV modules. The 30 MW plant for this simulation is made up of several thousands of modules that are in series and parallel interconnections as shown in Table 4-2 below. The sum of modules connected in parallel determines the current produced while the sum of modules in series determines the output voltage of the solar plant. Hence, the number of series-connected modules needed to produce the desired voltage must be calculated. Similarly, the calculation has to be made for the number of parallel-connected modules to produce the desired current. The main assumption considered in the design of the 30 MW plant is that the modules used are identical in physical and chemical properties, thus the same I – V and P – V characteristics. To determine the number and the combinations of the modules to be connected in series and in parallel, the equations given below were used in the determination of the module currents and voltages (Vergura, 2012).

$$V_{sub} = N_{sm} * V_{mpp} \quad (4\text{-}3)$$

$$I_{sub} = N_{ps} * I_{mpp} \quad (4\text{-}4)$$

$$P_{sub} = V_{sub} * I_{sub} \quad (4\text{-}5)$$

Where,

N_{sm}	Number of series-connected strings
N_{ps}	Number of parallel-connected strings
V_{mpp}	Maximum value of voltage
I_{mpp}	Maximum value of current
I_{sub}, V_{sub}, P_{sub},	Values of sub-array current, voltage and power

The 30 MW plant comprises of four independent 7.5 MW sub-plants. Each sub-plant has a 7.5 MW inverter, 11 combiner boxes, 14 arrays, 15 sub – arrays parallel-connected strings, each one of them having 10 PV modules connected in series. This combination gives a total 23 100 modules per 7.5 MW plant and 92 400 modules for the entire 30 MW plant.

Table 4-2: 30 MW Plant Component Breakdown

#	Item / Designation	Number of Units
1	PV System Power (MW)	30
2	No. of Inverters	4
3	Inverter size (MW)	7.5
4	No. of Combiner boxes	17
5	No. of Arrays	14
6	No. of sub-arrays per parallel-connected string	10
7	No. of series-connected modules per string	10
8	Total modules per inverter	23 100
9	Total modules in PV plant	92 400

4.2. Site Selection

The selection of the site location is of paramount importance to the overall system performance since the key system input parameters depend on the environmental characteristics of the location. The most important parameters are the solar irradiation or insolation and the temperature measured in watts per square meter (W/m^2) and degrees Celsius respectively. Other climatic and environmental factors such as precipitation, wind and land topography will limit and constrain a PV plant but these factors are all secondary when compared with the availability of insolation. Furthermore, the energy output of a photovoltaic system is directly proportional to the irradiation input.

In summer, when the sun is nearly directly overhead, its irradiance at the surface of the Earth, at sea level, is approximately 1 000 W/m^2. This irradiance is referred to as “full” or “peak sun” and it is the standard irradiance for testing and rating PV modules. In South Africa, it is possible to receive close to peak sun nearly every sunny day at noon when the PV modules are mounted perpendicular to the sun’s rays. The mean annual and monthly solar energy received per horizontal square metre (MJ/m^2) has been calculated for South Africa. Solar duration and solar radiation data, collected over a 40 year period at 130 sites by the Agricultural Research Centre of South Africa was available for use. Figure 4-3 shows the annual solar radiation for South Africa.

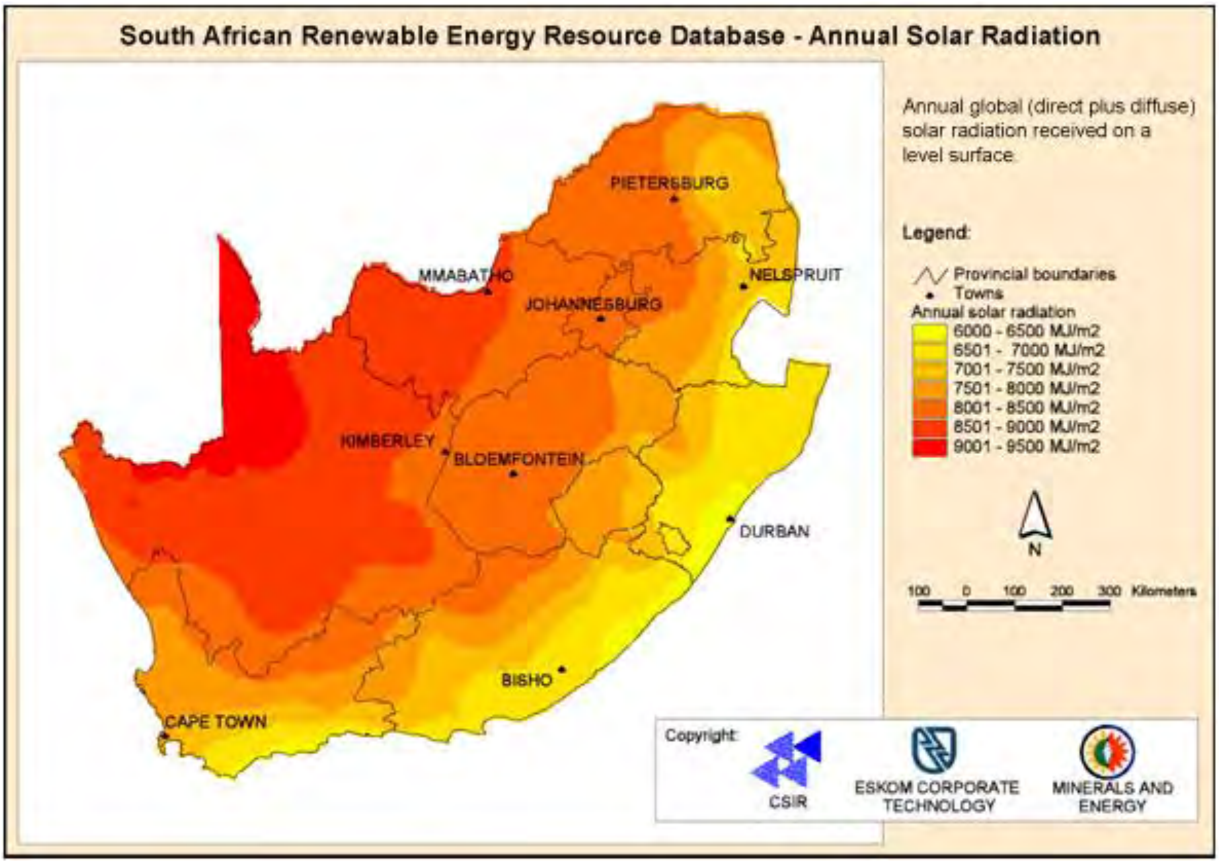

Figure 4-4: Annual Solar Irradiation of South Africa

(Flur, 2009)

From the feasibility studies carried out, this project is proposed to be cited at the Mokopane area as the site area of choice since this area receives appropriate irradiation. This location is further justified by the establishment of the IPP/Eskom solar park in South Africa. Moreover, this area also has a relatively well-developed electricity transmission infrastructure. These two complimentary factors imply that the plant will be able to deliver predictable and reliable power generation with minimal transmission loss issues.

4.3. Modular Multilevel Converter Modelling

The modular multilevel converter modelling is based on the converter being able to deliver maximum power to the CAES system and to the grid. Hence, the principal objective of converter is to effectively convert the available solar power throughout the life of the system.

4.3.1. Converter Modelling and Parameter Specifications

The basic structure of the modular multilevel converter is a sub-module comprising a half bridge configuration of two active switches, inverse diodes and a capacitor, *C,* for DC energy storage (Alajmi, et al., 2012). Each arm consists of n series-connected sub-modules and one arm inductor with the inductance, *L*, to form the Arm. The main function of the inductor is to limit the current flowing in each arm while the inductor takes up the voltage difference produced when a module is switched on and off (Rajasekar & Gupta, 2012). The resistance of the inductor and sub-modules in one arm is denoted *R*. The resistance *R* and inductance *L* are referred to as the arm impedance. Each sub-module toggles between two states, ON and OFF. The phase leg of the converter consists of one upper and one lower arm connected in series between the dc-terminals (Alajmi, et al., 2012). The DC side is modelled by two DC voltage sources ($V_{DC}/2$), while the AC side is modelled by an AC voltage source (V_{out}), a resistor (R_{out}) and an inductor (L_{out}). Figure 4-5: 4 shows the model circuit of the 7-level converter.

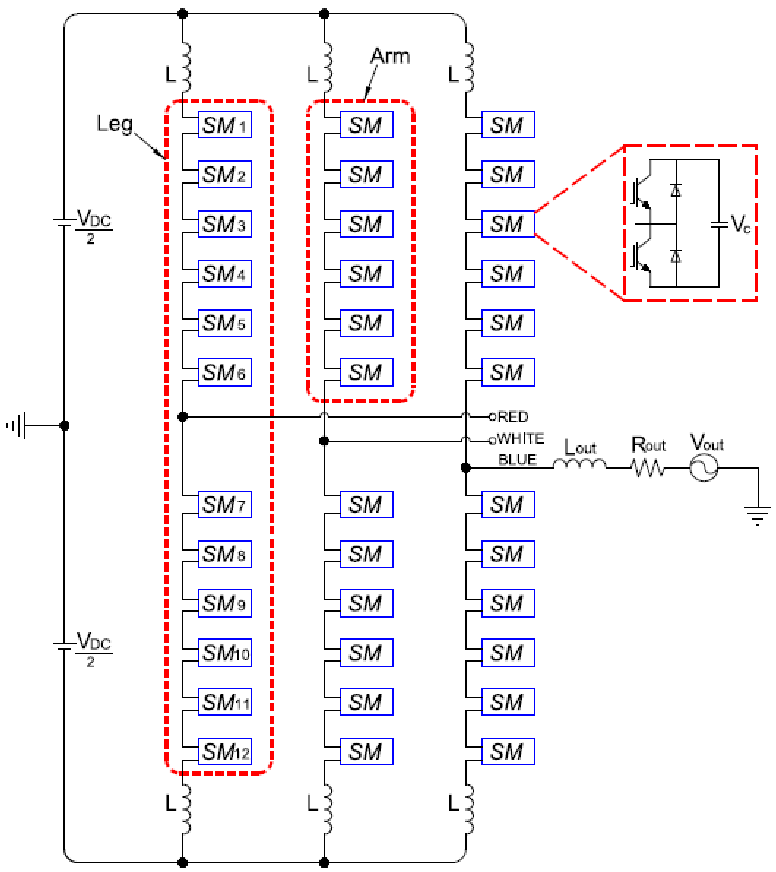

Figure 4-5: Block Diagram of a 7 Level Three Phase MMLC

The number of voltage levels in the output of the converter can be increased if at any switching instant, a sub-module is turned on or off in only one of the arms of the phase-leg (either the upper or the lower). In this case, 2N+1 levels in the output can be acquired from the converter for a topology with 2N sub-modules per phase-leg. By increasing the number of voltage levels, the quality of the output voltage is improved and the voltage waveform becomes closer to sinusoidal waveform. The number of levels in the output phase-leg depends straightly on the number of sub-modules in each leg as well as the converter leg modulation. So the more sub-modules there are, the better is the output signal, thus the closer the output signal is to a sinusoidal wave. The equation for the number of voltage levels for the converter is given below (Rajasekar & Gupta, 2012):

$$\text{Number of voltage levels} = N/2 + 1 \tag{4-6}$$

Where,

N Number of sub-modules per phase

The 7-level converter is modelled and simulated in this study, as in Figure 4-5: 5 above. Thus, each arm has 6 sub-modules, while each leg will have 12 sub-modules and the total number of sub-modules in the converter is 36.

4.3.2. Phase Disposition PWM: The Modulation Strategy

The modulation of the converter means that two switching states take place within the phase-leg of the converter at any instant on the converter. The duration of the switching states determine the total power delivered to a load without losses with more total power delivered for longer periods when the pulse is closed compared to the opened periods. The PWM technique is used to adjust the number of voltage levels as well as the total power generated by the converter by comparing the reference waveform to the carrier waveforms. The intersections between the reference voltage waveform and the carrier waveform give the opening and closing times of the switches.

Multiple voltage levels in the converter are achieved in this dissertation by utilizing the phase disposition PWM (PD PWM). The PD PWM is typically based on the comparison of a sinusoidal reference signal with multiple carrier signals in phase cutting across a defined voltage range. Thus, the multiple carrier signals are in phase, have the same frequency, f_c and have the same peak to peak amplitude V. However, the main difference between them is the offset voltage between them. Each carrier signal determines the voltage level that the converter should switch to. Figure 4-6: 5 shows the PD PWM used in this study.

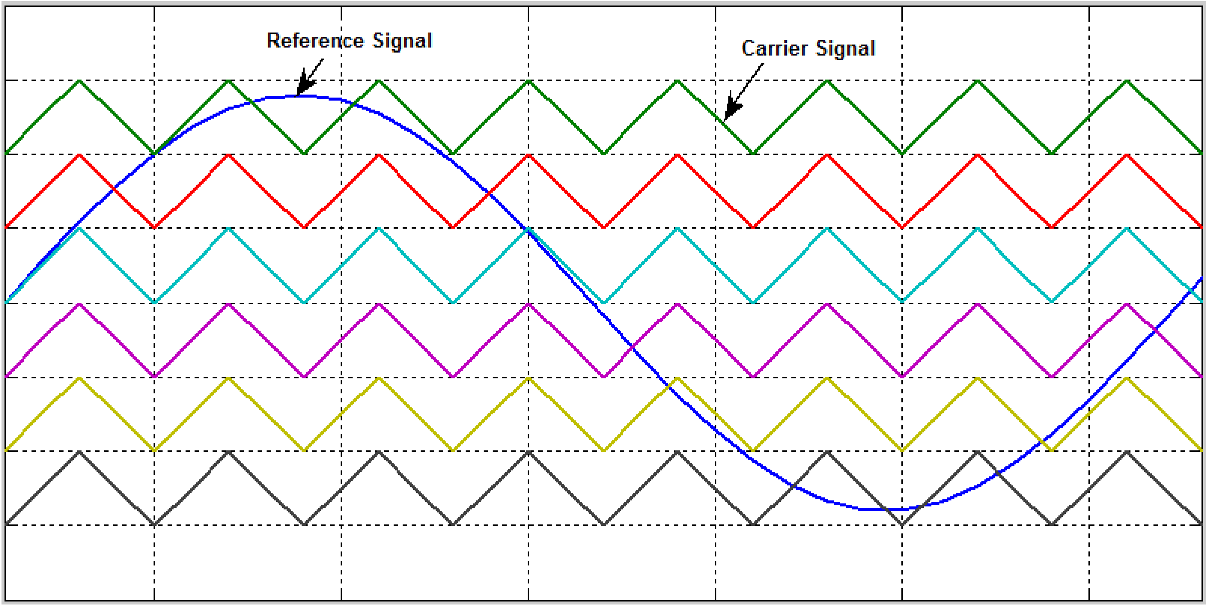

Figure 4-6: PD PWM Carrier and Reference Signals

4.4. CAES Modelling

The CAES system is coupled to the converter of the PV system to ensure optimal utilization of the power generated by the individual PV panels. This section describes the CAES model construction and running. The CAES model was based on the four main stages that are the Compression Stage, the Thermal Energy Storage, the Cavern and the Expansion Stage. The model was built in the Matlab/Simulink environment. Figure 4-7: 6 below shows the schematic layout of the Adiabatic CAES power plant model.

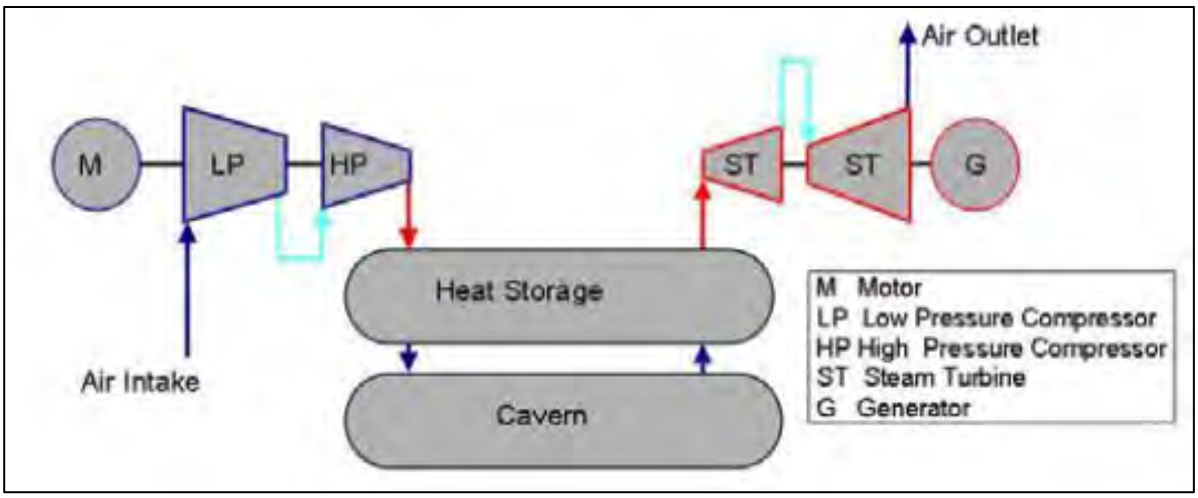

Figure 4-7: Adiabatic Compressed Air Energy Storage Power Plant Layout (Zunft, et al., 2006)

The modelling of the CAES system in this study is based on several assumptions highlighted below. However, the main assumptions to this study are that the CAES system will be discharged every day to its operational minimum during peak periods to cater for the spiked daily peak demand for electricity. The other main assumption is that electricity trend in the electricity demand and supply has not been included nor considered in this study. Other modeling assumptions employed are as follows;

- Simulation with atmospheric dry air;
- The air is considered as an ideal gas;
- Heat transfer between medium and tubing is negligible;
- Energy losses that occur during the idling state are small and negligible for the purposes of the simulation;
- Pressure losses are involved in the tubing or heat exchangers are negligible;
- No leaking takes place in the tubes transporting the Heat Transfer Fluid (HTF);
- No air mass losses throughout the system.

4.4.1. The Compression Stage Model

The compression stage comprises four compressors and four heat exchangers in the model building and simulation run. The atmospheric air is compressed by the first compressor, generates heat as it is compressed, then it goes to the heat exchanger where the heat is transferred to the heat transfer fluid inside the heat exchanger (Hasan, et al., 2012). The air temperature will increase every time it is discharged from the compressor, so heat transfer is used to reduce this temperature by transferring some of the heat. The transferred from the compressed air is used to heat up the heat transfer fluid, HTF, inside a heat exchanger. The compressors and the heat exchangers are normally connected in series to allow the air to flow from one compressor and heat exchanger to the next as the process repeat right through to the last compressor. Figure 4-8: below is the layout of the compression stage showing the compressor train and the heat exchangers.

The compression ratios at each compression stage are set to 3.9, 3.1, 2.4 and 2.2, given a total compression ratio of 70 bars. The initial pressure is considered to be equal to the atmospheric pressure, 1 bar. This means that the compression stage will be stopped if pressure inside the tank reaches 70 bars, thus at this point the air mass flow rate to the compressor into the cavern will be zero. During the compression a constant air mass flow of 140 kg/s is assumed. The compressors and the heat exchangers where considered to have efficiencies of 85% and 75% respectively. The compressor outlet temperature is given by (Hasan, et al., 2012):

$$T_{out,c} = T_{in,c} * \beta^{\frac{(k-1)}{k}} \quad (4\text{-}7)$$

Where,

$T_{out,c}$	Compressor outlet temperature
$T_{in,c}$	Compressor inlet temperature
β	Compressor ratio
k	Polytrophic index

4.4.2. The Thermal Energy Storage Stage Model

The air generates heat during the compression process. This heat is very critical to the thermal energy storage system of the CAES system and involves two distinct thermal cycles. Firstly, the heat is extracted from the air through the heat transfer fluid, HTF, and stored in the heat storage facility. In the compression stage, the electrical energy from the renewable source is converted into mechanical energy. When the compressed air finally reaches the cavern its temperature is significantly reduced to the optimal operating temperatures of the cavern, since the cavern storage is not designed to store energy at high temperatures (Hasan, et al., 2012).

The second cycle of the thermal energy storage involves the expansion stage where air is heated as it flows from the cavern into the turbine. The efficiency of the heat exchanger, ε_{hx}, is assumed to be 70% for this dissertation. The air temperature that comes out from each heat exchanger, $T_{hx,out}$, during the compression stage is given by the expression (Hasan, et al., 2012):

$$T_{hx,out} = T_{hx,in} + \varepsilon_{hx}(T_{hx,htf} - T_{hx,in}) \quad (4\text{-}8)$$

Where,

$T_{hx,out}$	Outlet heat exchanger air temperature
$T_{hx,in}$	Heat exchanger inlet temperature
ε_{hx}	Efficiency of the heat exchanger
$T_{hx,htf}$	Temperature of the heat transfer fluid

The operation of the thermal energy storage unit was modelled based on the above expression in equation 4-8. The heat exchangers are connected in parallel to increase the overall model efficiency.

4.4.3. The Cavern Model

Once the atmospheric air has gone through all the compression and heat storage stages, the air is stored in the cavern for later usage. There are two conceptual different reservoir types possible for the underground storage system, the constant volume reservoir and the constant pressure reservoir (Hasan, et al., 2012). The constant volume reservoir can either be a salt cavern or an abandoned mine. While the constant pressure reservoir is usually the hard rock cavern with water compensation or the aquifer storage. The salt dome reservoir is a proven technology with applications at Huntorf, Germany (290 MW) and McIntosh, USA (110 MW) (Hasan, et al., 2012; Daneshi, et al., Nov 29 - Dec 1, 2010; Sun, et al., 2010). The cavern considered in this model is the salt dome reservoir underground cavern. The cavern stores the cooled air from the heat exchanger for the periods from charging to discharging through the idle period. The pressure of the air in the cavern is the same as the output of the compressor train. Figure 4-8: 7 below shows the reservoir alternatives for CAES.

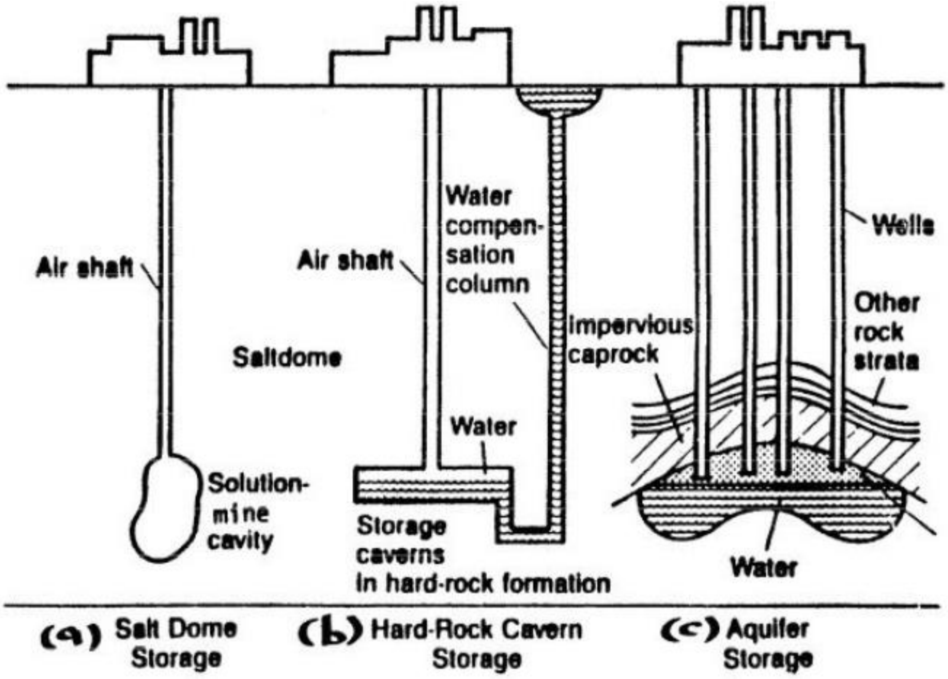

Figure 4-8: Reservoir Alternatives for CAES Systems
(Vadasz, 2009)

4.4.4. The Expansion Stage

The compressed air in the cavern has low temperature and low pressure. The expansion stage ensures that the compressed air is re-heated as it passes through the heat storage unit. Similar to the Huntorf design, the model utilised two turbines, the high-pressure turbine (HPT) and low-pressure turbine (LPT), and two heat exchangers in the expansion stage (Hasan, et al., 2012; Daneshi, et al., 2010). Compressed air from cavern passes through the heat exchangers to increase its temperature before entering high-pressure turbine. Once the compressed air leaves the high-pressure turbine, its pressure and temperature drop, thus the air will passes through the heat exchanger once again to increase its temperature before entering low-pressure turbine. Since heat exchangers are used to increase the air temperature of the turbine, so the output temperature of heat exchangers is higher compared to output temperature of turbine. The two pressure turbines are considered to have 80% efficiencies with the high-pressure turbine operating at 2.5 ratio while the low-pressure turbine operates at 17.2 ratio.

The Simulink mathematical model of CAES for the outlet temperature of the heat exchanger, the turbine outlet pressure as well as the turbine outlet temperature where based on the following equations (Hasan, et al., 2012).

$$T_{hx,out} = T_{hx,in} + \varepsilon_{hx}(T_{hx,htf} - T_{hx,in}) \quad (4\text{-}9)$$

$$p_{t,out} = p_{t,in} * \beta^{-1} \quad (4\text{-}10)$$

$$T_{t,out} = T_{t,in} * \beta^{\left(\frac{1-m}{m}\right)} \quad (4\text{-}11)$$

Where,

$T_{hx,out}$	Outlet heat exchanger air temperature
$T_{hx,in}$	Heat exchanger inlet temperature
ε_{hx}	Efficiency of the heat exchanger
$T_{hx,htf}$	Temperature of the heat transfer fluid
$p_{t,out}$	Turbine output power
$p_{t,in}$	Turbine input power
β	Compression ratio of each turbine
$T_{t,out}$	Turbine output temperature
$T_{t,in}$	Turbine input temperature
m	Air mass flow

Once in the air turbine, the mechanical energy of the hot pressurised air is used to drive a generator. For maximum efficiency, early studies have shown that the turbine should be able to adapt to a range of pressures and mass flow from the cavern (Hasan, et al., 2012). The compression and expansion pressure directly depends on airflow rate and system efficiency.

4.5. Summary

This chapter starts-off by addressing a brief description of the mathematical modelling of PV cells and modules in Matlab Simulink. The model parameters are discussed in order to model the effects of atmospheric temperature and irradiation on PV cells. Furthermore, a PV array model, as a tool for testing MPPT algorithms' efficiencies is developed and implemented.

CHAPTER 5

5. RESULTS ANALYSIS AND DISCUSSION

Various simulations were conducted to determine the daily, monthly and yearly energy generated by the comprehensive photovoltaic modelling system. Total array power output was expressed in kilowatt-hours integrated over daily and monthly intervals. Additionally, monthly and daily level results were reviewed for the Witkop substation site. To confirm these simulation results, the initial simulation was to validate the characteristics curves of the simulated SunPower E20/333 PV module. This was done by comparison of the SunPower E20/333 PV module manufacturer given characteristic curves with the characteristic curves produced by the simulation model. The results of the simulations together with the variations of the input parameters are shown in the following sections.

5.1. The PV Circuit

The foundation of the simulations was to determine the performance characteristics of the PV module. This was a very important experiment because it is obvious that we must know about the characteristics of the panel with which we will be working with as well as the fact that this was the basis on which all other simulations in this thesis were based on.

The results of the PV circuit are based on the equation given below (Guo, et al., 2011; Rustemli & Dincer, 2011; Ding, et al., 2012).

$$\mathrm{I_{PV}} = \mathrm{I_{PH}} - \mathrm{I_o}\left[e^{\frac{(V_{PV}+I_{PH}*R_S)}{V_T}} - 1\right] - \frac{V_{PV} + I_{PH}*R_S}{R_{sh}} \qquad (5\text{-}1)$$

5.1.1. The PV Module Characteristic Curves

There are two main characteristics that are considered for the PV module, namely the current voltage curve (I – V curve) and the power voltage curve (P – V curve). Simulations for the SunPower E20/333 PV Module were carried out to determine these curves at standard conditions of temperature 25 ºC and irradiation 1 000 W/m^2. The characteristic curves of current - voltage and power – voltage of the SunPower E20/333 PV module are shown in Figure 5-1: 1 and Figure 5-2: 2 respectively below. It can be noted that the maximum current output is 6.09 A and the maximum voltage is 54.7 V.

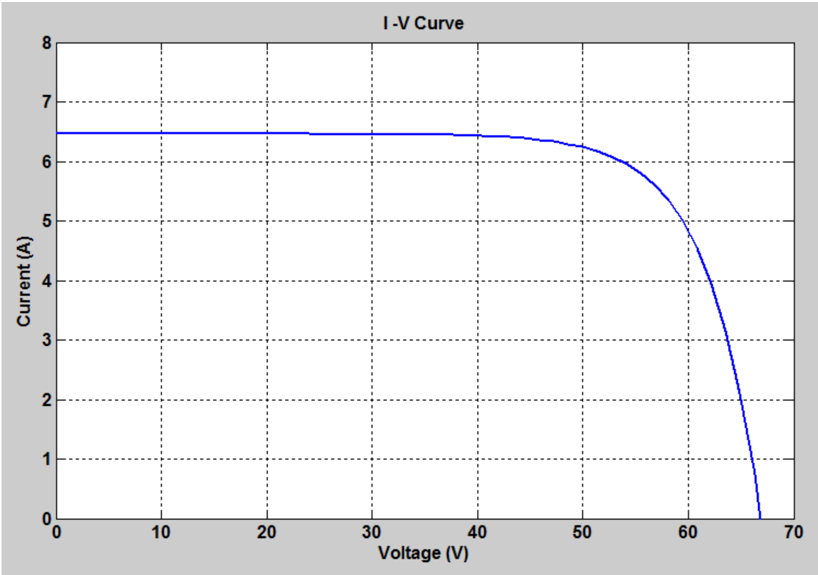

Figure 5-1: I-V Curve at temperature 25 ºC and irradiation 1 000 W/m^2.

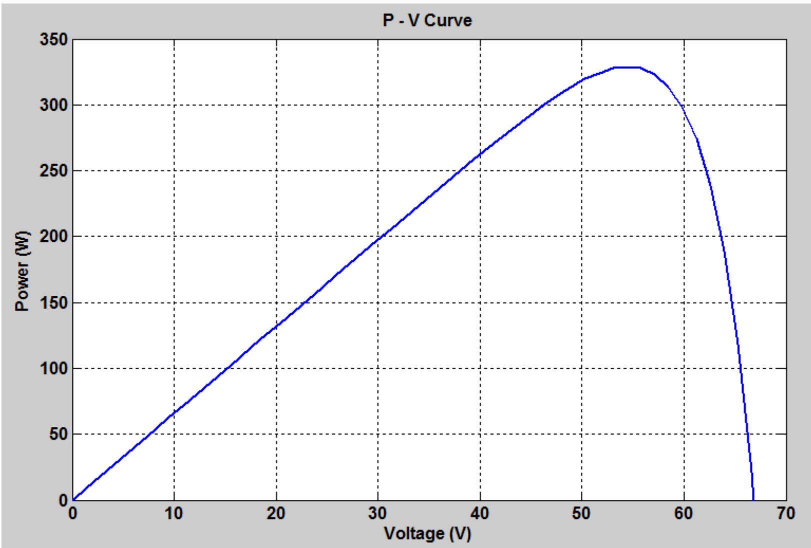

Figure 5-2: P-V Curve at temperature 25 ºC and irradiation 1000 W/m^2.

5.1.2. Simulation of the PV with varying irradiation

The irradiation levels were varied at 100, 200, 400, 600, 800, 1 000, 1 200 W/m^2 while temperature was kept constant at 25 ºC. The outcome of this action is depicted in Figure 5-3:3. The current-voltage (I-V) curve shows that the current increases significantly with an increase in the irradiance level. The result in Figure 5-4:4 is the power-voltage curve which shows that the maximum power of the PV increases when the irradiance level increases.

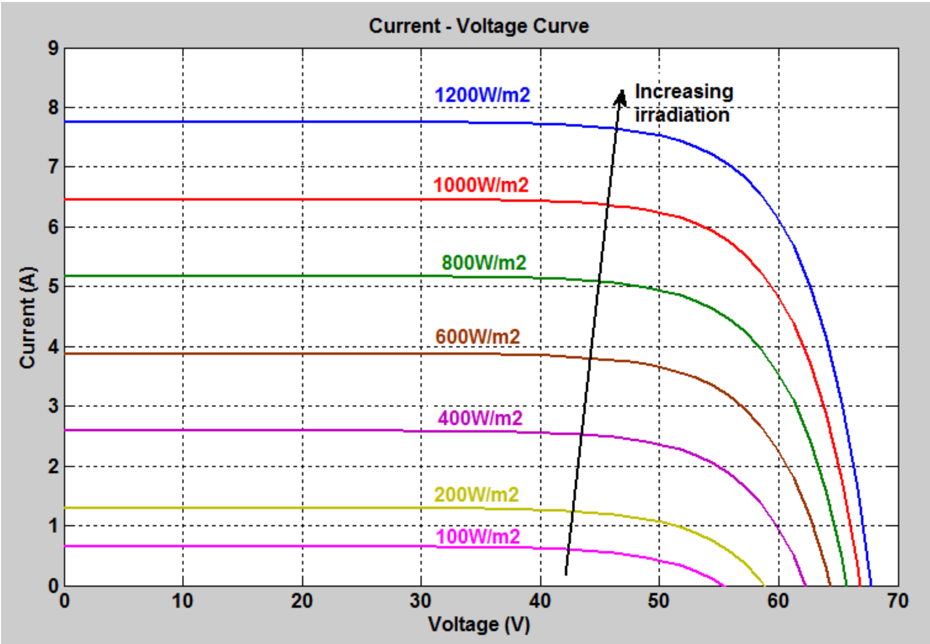

Figure 5-3: I-V curves at varying irradiation levels.

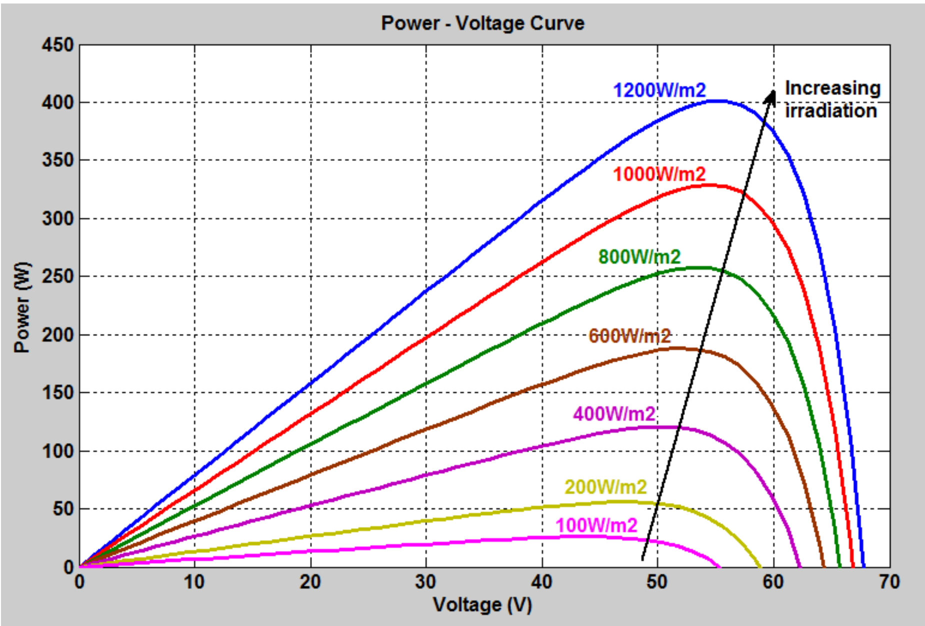

Figure 5-4: P-V curves at varying irradiation levels.

5.1.3. Validation of PV Module Characteristics

According to the SunPower E20/333 PV module manufacturers' datasheet, the relationship of current and voltage at varying irradiation levels is shown in Figure 5-5: 5 below:

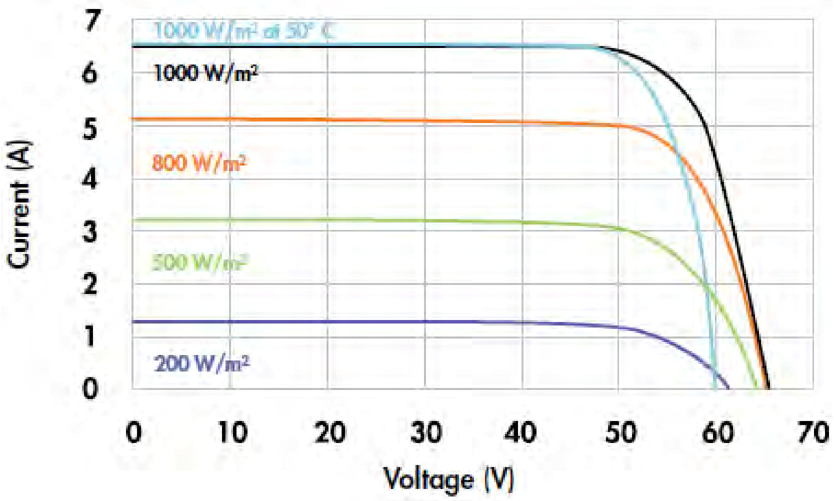

Figure 5-5: Manufacturer's Datasheet of the I-V curves at varying irradiation levels.

Comparison of the characteristic curves and the manufacturers' graph was made to determine any similarities and differences. Analysis of the simulated I-V curve shows that the PV module produces a maximum current (short-circuit current) of 6.4 A while the maximum voltage (open-circuit voltage) is 65.3 V. Furthermore, analysis of the simulated P-V curve reveals that the maximum power generated by the PV module is 333 W.

The deduction, after comparison of the simulation characteristics and those from the manufacturer's datasheet, is that the simulation model developed suffices the need to be utilized in the thesis as it is a true reflection of actual SunPower E20/333 PV module.

5.1.4. PV Plant Output Current, Voltage and Power

This section highlights the key simulations of the designed 30 MW PV plant that this thesis was set to generate. The photovoltaic output current, voltage and power given in this section are the predictable outputs of the PV plant based on the verified simulations of the PV modules in the earlier sections. The PV modules are connected in the varying combinations of series and parallel configurations as indicated in Table 5-1 below.

These output parameters were obtained for simulations conducted under standard test conditions of solar radiation of 1000 W/m^2 and temperature of 25 ºC.

Table 5-1: Parameters of the designed and simulated PV plant

#	Item / Designation	Number of Units
1	PV System Power (MW)	30
2	No. of Inverters	4
3	Inverter size (MW)	7.5
4	No. of Combiner boxes	17
5	No. of Arrays	14
6	No. of sub-arrays per parallel-connected string	10
7	No. of series-connected modules per string	10
8	Total modules per inverter	23 100
9	Total modules in PV plant	92 400

The simulation is run and Figure 5-6: 6 depicts that the PV plant current sets off at 64.6 A, which is the short-circuit current and eventually settles at a maximum value of 60.9 A.

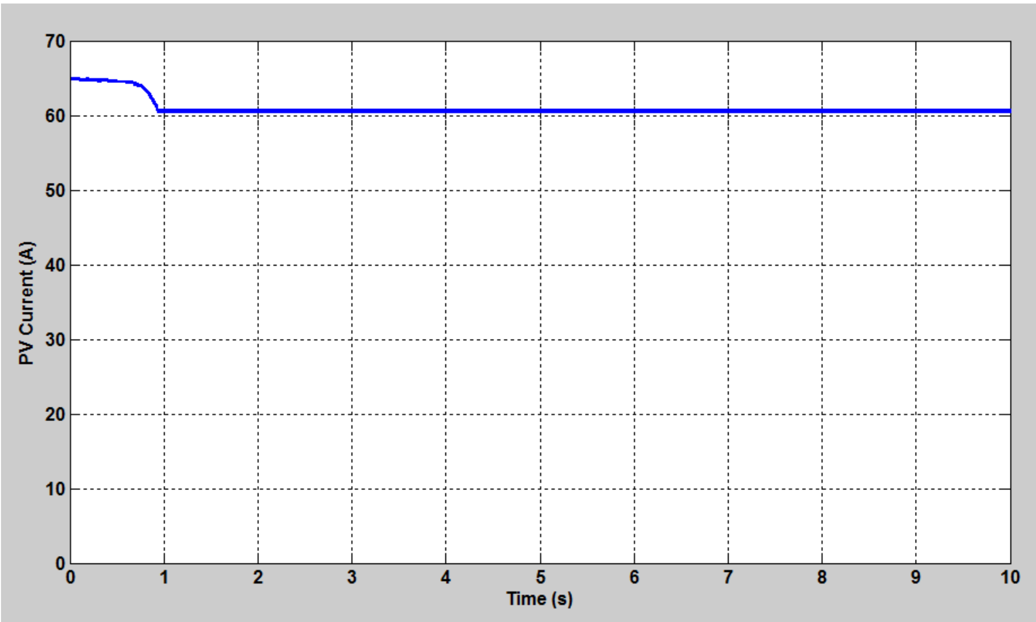

Figure 5-6: Photovoltaic output current

Figure 5-7: 7 below shows the output voltage of all the four inverters in the PV plant. As expected the output voltage of the PV plant reaches a maximum of 520 kV, according to the calculations. Furthermore, the output voltage rises gradually from zero to the maximum voltage.

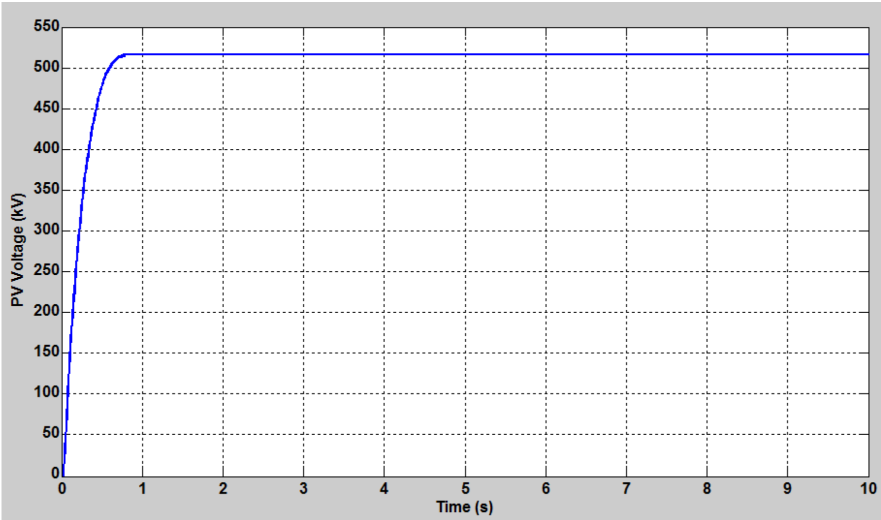

Figure 5-7: Photovoltaic output voltage.

Figure 5-8: 8 below represents the output power of the PV plant. The nominal power estimation of the panel is used to quantify the overall power generated by the photovoltaic panel using the validated characteristic curves and environmental data acquired. The PV plant reaches a maximum power of 31.7 MW.

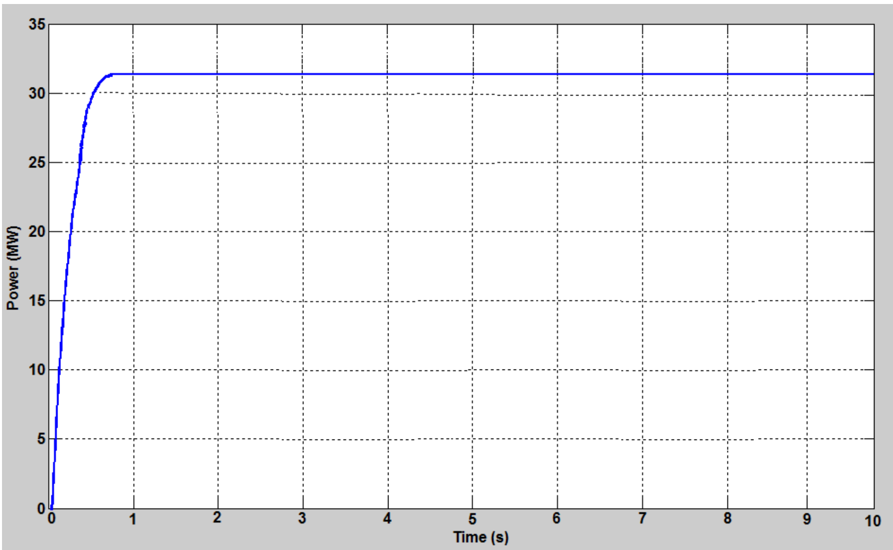

Figure 5-8: PV output power

5.1.5. Daily Electricity Generated based on Weather Parameters

The daily electricity generated by the photovoltaic plant was based on the daily weather temperature and irradiation parameters provided by the Agricultural Research Council, ARC, of South Africa. The author requested and received weather data of the particular area dated back as far as the past 5 years, until November 2013 since the information was requested in 2013. This laid a very vast platform for data analysis as trends and patterns could be noticed with much greater ease. The system was simulated for November 23, 2013. The analysis of the weather data indicated that this day has the most irradiation with the maximum at 1067 W/m^2 and the temperature peaking at a maximum of 28.6 ºC. The weather data was sampled at hourly intervals for this simulation.

The hourly temperature and irradiation data for November 23, 2013 are given in Figure 5-9: below and it can be observed that the temperature gradually increases and is in the range of ±4 ºC of 25 ºC during day time. This is the optimal temperature for the operation of the photovoltaic modules. Furthermore, Figure 5-9: 9 shows that the irradiation graph has a more curved shaped depicting that the irradiation received was high for the day hence more electricity generated by the 30 MW PV plant.

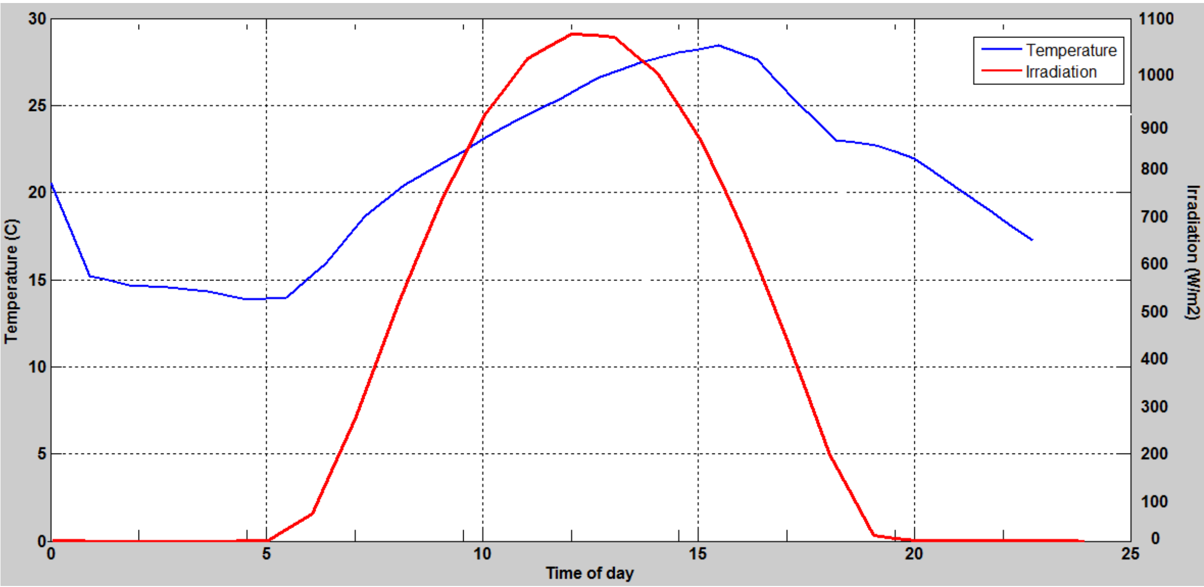

Figure 5-9: Temperature and irradiation data for November 23, 2013.

The corresponding hourly temperature and irradiation values were entered into the simulation model for the PV power plant that was configured as a 30 MW plant. The simulated photovoltaic plant power output is shown in Figure 5-10: 0 below. This shows the PV plant starts generating power every hour from the time of sunrise at around 6 o'clock in the morning to sunset around seven o'clock in the evening with the peak power of 22.4 MW around noon.

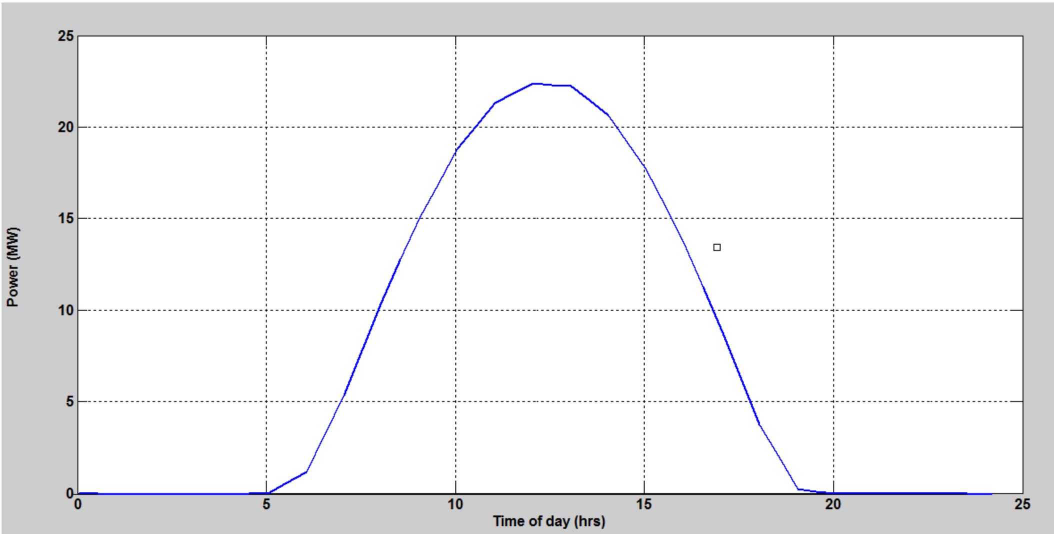

Figure 5-10: Hourly simulated PV power during daylight.

5.2. The MPPT Validation

The solar cell generates maximum power at a point known as the maximum power point where the product of current and voltage is maximum on the current-voltage characteristic curve. This point is unique for every hourly temperature and irradiation input value. A simulation model was run to establish the effect of the MPPT on the power generated by the PV plant. Therefore, simulation results for the same input temperature and irradiation values when the MPPT was not implemented were compared with the condition when the MPPT was in place. The comparison of these results is shown in Figure 5-11: 1 below, where it can be seen that at every time step the power generated without the MPPT on is much less than the power with the MPPT in place. This test validates that the MPPT is able to boost the power output of the solar array with a peak of the power generated improving from 22.4 MW to 29.5 MW respectively.

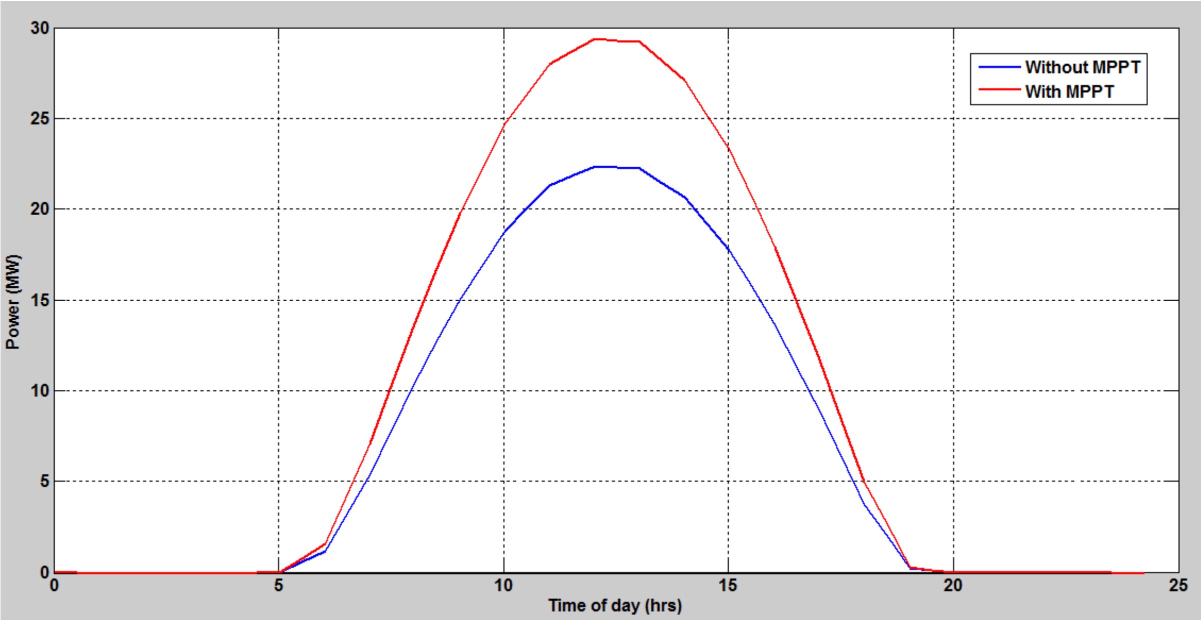

Figure 5-11: Effect of MPPT on the power generated by the PV plant

5.3. Electricity Generated from PV Plant for May and October 2013

The 30 MW PV plant was also simulated for the months of May and October which according to the data analysis had the lowest and highest irradiation levels respectively. Firstly, the daily maximum temperatures for the two months were simulated and the results are given in Figure 5-12: 2 below.

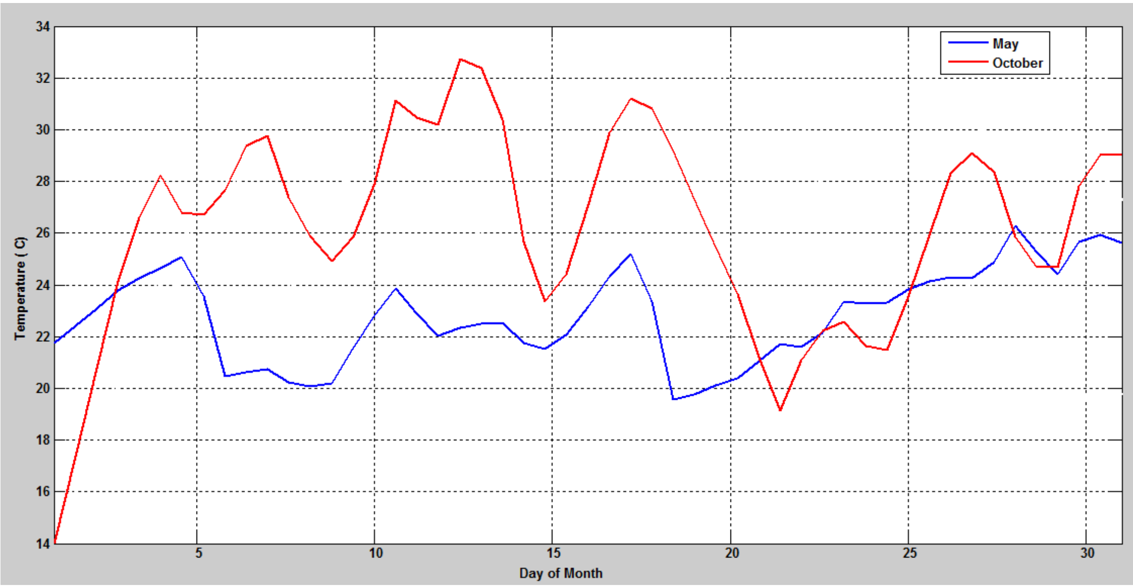

Figure 5-12: May and October Daily Temperatures

The daily irradiation data for May and October 2013 are given in Figure 5-13: 3 below and it can be observed that the irradiation levels for October where generally higher that these of May. However, October had cold and overcast days from 20th to 22nd October. This resulted in significantly low irradiation levels being recorded during that period.

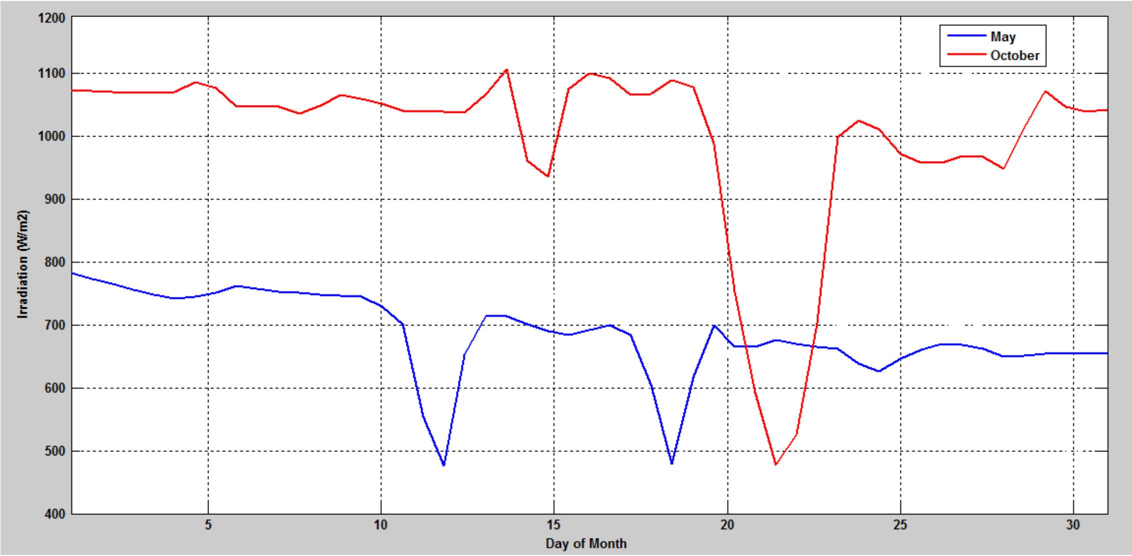

Figure 5-13: May and October Daily Irradiation Levels

The daily temperatures and irradiation data was input into the simulation model and the corresponding PV generated power was obtained as shown in Figure 5-14: 4 below. This shows the PV plant generates power very close to the rated power during the month of October when the irradiation is around the region of 1 000 W/m^2. As expected, the power generated takes a dip during the days when the weather is overcast with the generated power reaching a minimum on October 21.

The power generated in May was very low since the irradiation and temperature levels were generally lower. The simulation results show that the power generated in the month of May was low though it generated above 50% of the system rated power output. Furthermore, the power generated in the month of October was significantly more than that generated in May, except for the three days when the weather was cold and overcast in the month on October.

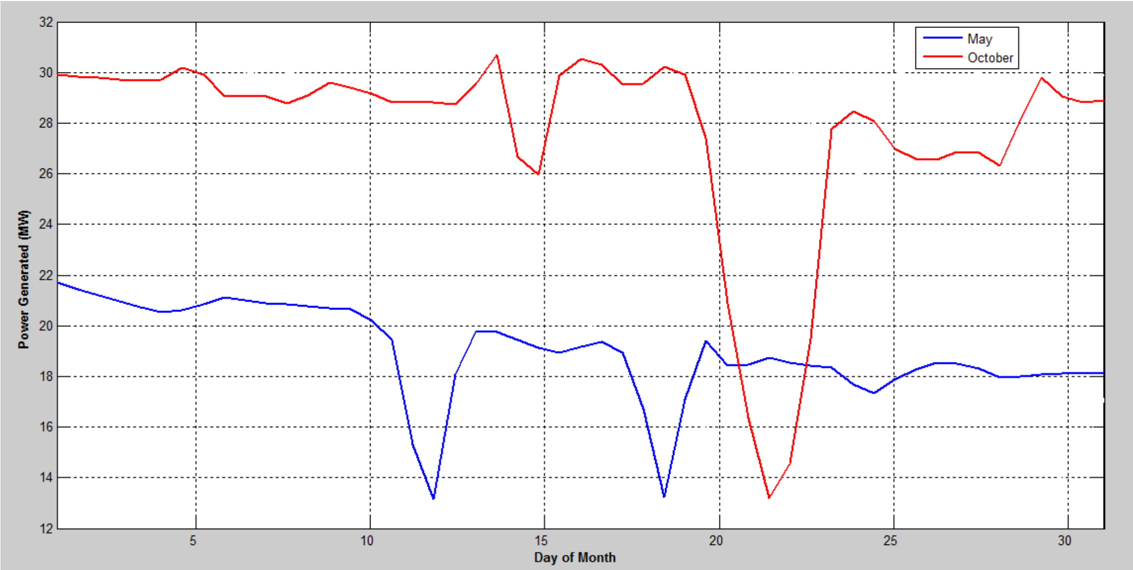

Figure 5-14: May and October Daily Electricity Generated

5.4. The MMLC Circuit Simulation Results

5.4.1. Converter Modulation - PD PWM Modulation

Numerous modulation strategies can be utilized to operate the functioning of multilevel converters based on the pulse width modulation, PWM. This has led some authors to conduct studies to compare the different PWM strategies with the objectives that include showing the spectral analysis produced by the modulation processes (Govindaraju & Baskaran, 2009; Holmes & McGrath, 1999). These studies reveal that phase disposition, PD, PWM is harmonically superior across the bulk of the modulation region because it is the only technique which places harmonic energy into a common mode carrier harmonic which cancels in the line-to-line voltage. Therefore, the PD PWM strategy was utilized in the simulations in this thesis.

In this research a PD PWM scheme with 6 carrier signals is considered. The carrier based PD PWM scheme calculates when a switching should occur based on the comparison of the control or reference voltage with the six triangular carrier signals. The results of this operation scheme are switching signals for a seven-level modular multi-level converter. Figure 5-15: 5 below shows 6 carrier signals with an amplitude of 1 and the control voltage of amplitude 2.8.

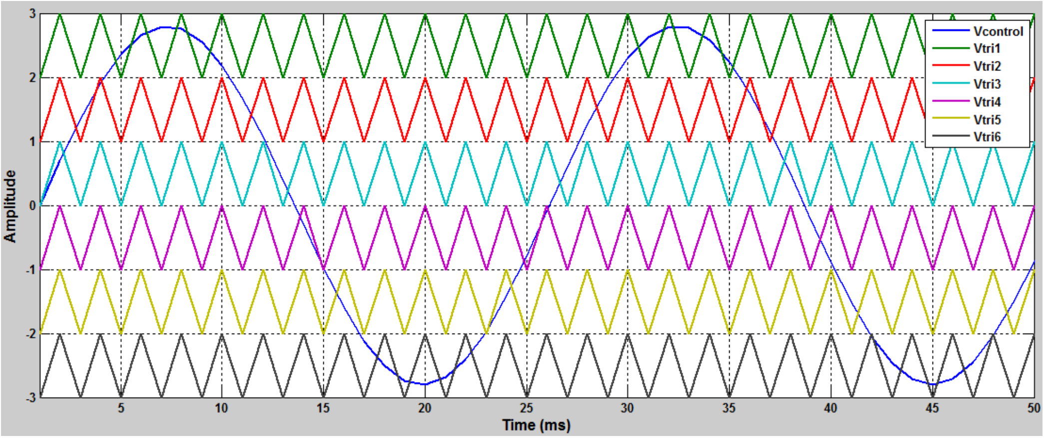

Figure 5-15: PD PWM comparator scheme for six sub-modules

5.4.2. Converter Model Verification

Georgios S. Konstantinou *et al* (2011) presented a study to verify the expectations from simulation studies of modular multilevel converters. This study features the modular characteristics that allow its expandability by focusing on the two different modulation levels of the converter among other key objectives. The two different modulation levels that were used in this study are the seven and eleven modulation levels. The study, according to Georgios S. Konstantinou *et al* (2011), was based on the simulation parameters given in Table 5-2 below, thus a converter with six sub-modules per arm is considered (12 in the phase-leg and a total of 36 sub-modules for the three-phase topology).

Table 5-2: Simulation parameters based on the Georgios S. K et al study

Simulation Parameters	
DC Voltage	3 kV
R_{load}	15 Ω
L_{load}	15 mH
Sub-module Capacitance	3.5 mF
Arm Inductance	3.6 mH
Sub-module Voltage	500 V
Number of Sub-modules per arm	6
Number of Output Levels	7

According to this study, this results in a total of seven distinct levels in the output phase voltage waveform as shown in Figure 5-16: below. While Figure 5-17: 7 shows the three phase load currents of the converter.

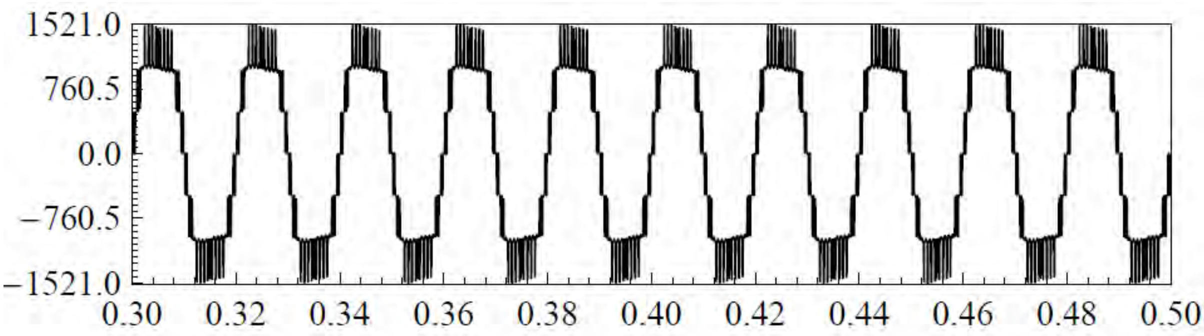

Figure 5-16: Output phase voltage for the 7-level waveform

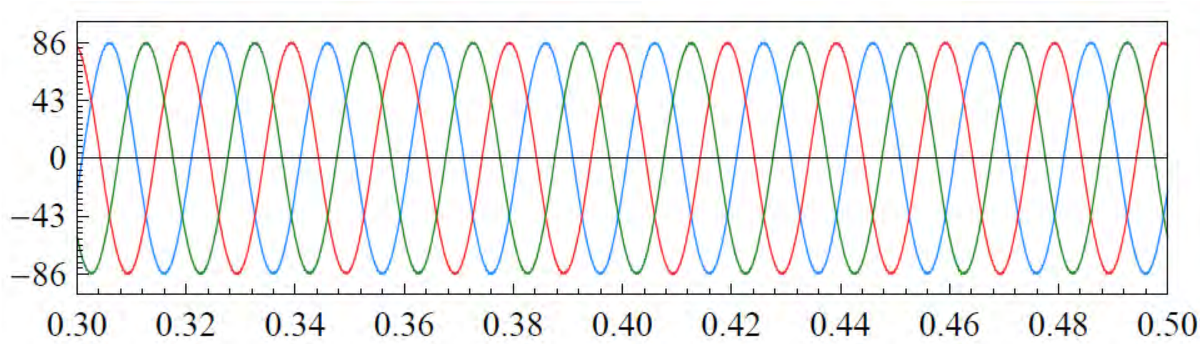

Figure 5-17: Three – phase load currents

To further cement the choice for this study, the proposed modulation for the MMLC was also verified on a phase-leg experimental prototype. The specifications for the laboratory prototype where clearly specified for the five sub-modules per arm that was built. The results from the laboratory prototype indicate the output phase voltage has eleven levels. While from the results of both the study simulations and the laboratory prototype, it is apparent that the amplitude of the output phase AC voltage signal is equal to half the DC voltage.

5.4.3. Converter Model Simulation

The following section presents the results from the simulation of the MMLC converter. The first simulations where performed on a single phase converter model with six sub-modules per arm and a total of 12 sub-modules in the phase leg. This results in a total of seven levels in the output phase voltage waveform. The chosen operating point for the simulation is the rated power at 30 MW. The simulation parameters for the MMLC are given in Table 5-3 below.

Table 5-3: MMLC converter simulation parameters.

Simulation Parameters	
DC Voltage	520.7 kV
R_{load}	7Ω
L_{load}	5 mH
Sub-module Capacitance	3.448 mF
Arm Inductance	3.8 mH
Sub-module Voltage	87 kV
Number of Sub-modules per arm	6
Number of Output Levels	7

After simulation of the converter with the above parameters on the single phase system, the voltage output of the converter is shown in Figure 5-18: 8 below. Similar to the results from the laboratory prototype done by Georgios S. K *et al* in the previous section, seven distinct levels are clearly observed from the simulation graph of the converter voltage output. Furthermore, the results of both the study simulations and the laboratory prototype indicate that it is apparent that the amplitude of the output phase AC voltage signal is equal to half the DC voltage.

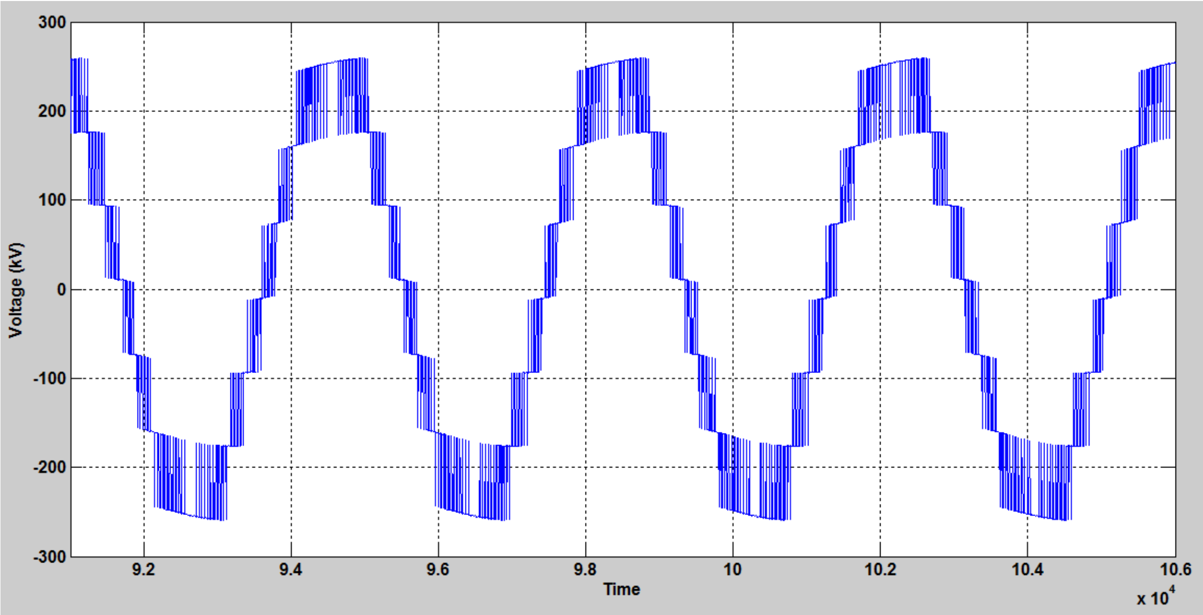

Figure 5-18: Single phase converter output voltage for a 7-level modulation.

After thorough simulations performed on the single phase operated MMC model, the MMC model has been implemented in full three phase system model. The purpose of using this model is to evaluate and validate the operation of the MMC in comparison with the simulation study as well as the laboratory prototype discussed in the previous section. The seven-level converter comprises of six in each arm, twelve sub-modules per phase leg and a total of 36 sub-modules for the three-phase topology. The increase in sub-modules allows relatively smaller voltage steps since each sub-module will be charged with a capacitor voltage of one sixth of the DC link voltage.

Figure 5-19: below shows the three phase voltage output of the converter where the simulation results show a progressive change in the voltage levels of almost 85 kV between successive voltage levels. This is the expected results as this changed is as a result of the sub-module voltage caused mainly by the sub-module capacitor.

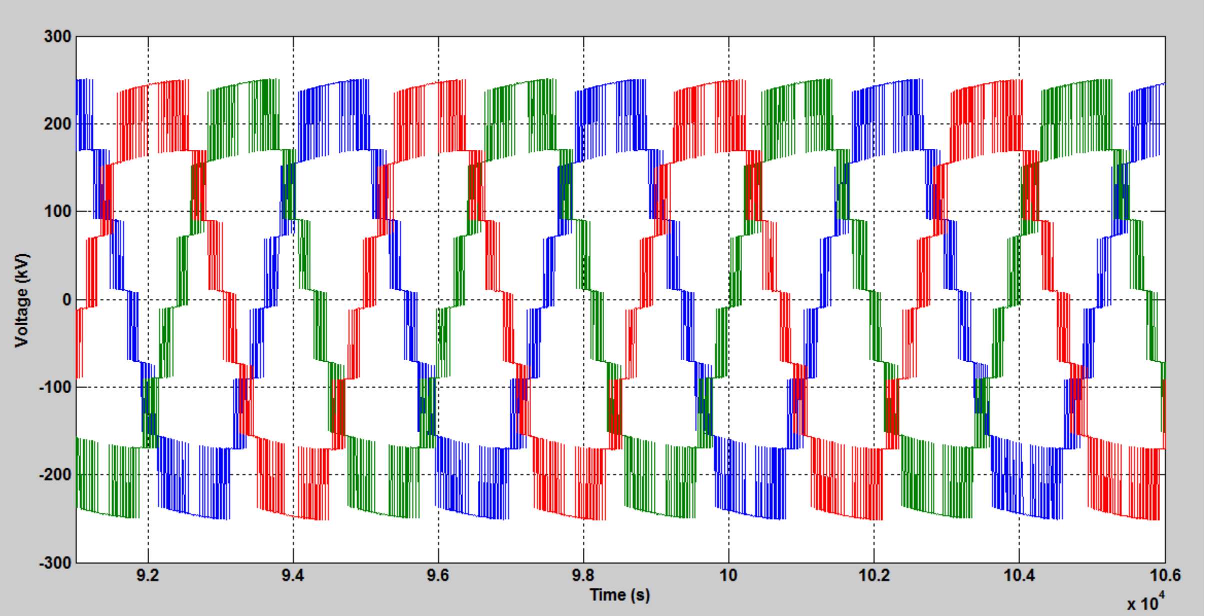

Figure 5-19: Three-phase converter output voltage for the 7-level modulation.

Figure 5-20: below shows the corresponding converter phase currents. These currents are filtered to some extent by the resistive load and the line impedances.

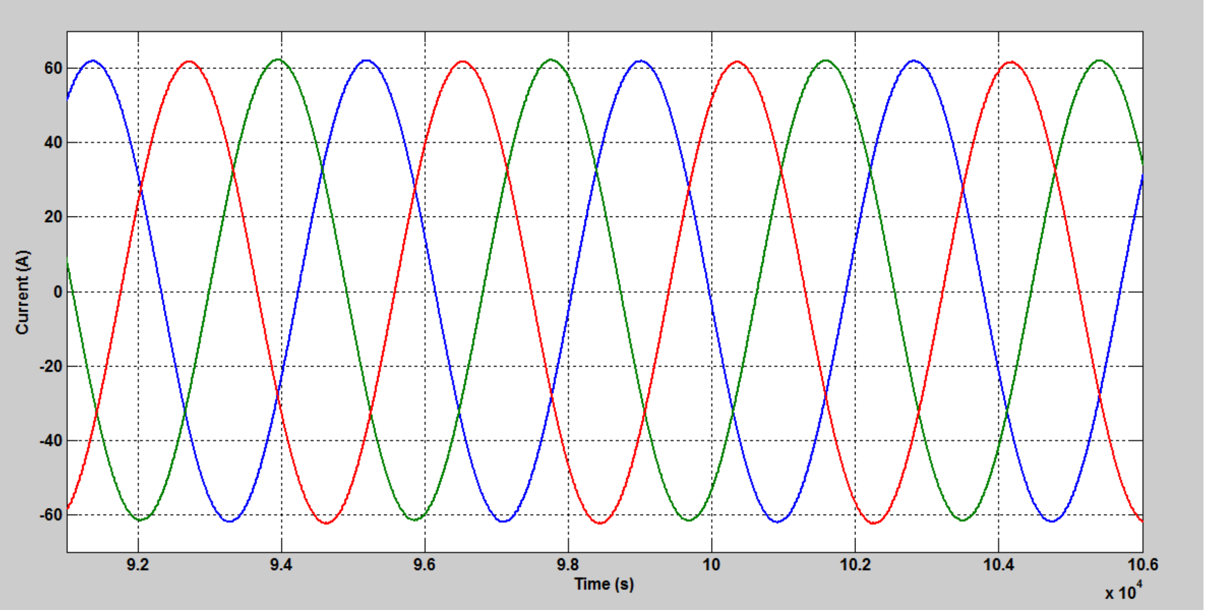

Figure 5-20: Three phase converter output currents

The simulations on the modular multilevel converter have shown the close relationship with the studies and the laboratory prototype built by Georgios S.K *et al* for both the converter output voltage and current. This validation of the converter performance to a greater extent assures that any variation in PV power output due to changes in temperature or solar irradiation shall result in a change in the converter output power.

5.5. The CAES Circuit Simulation Results

This section gives the variation of the key parameters over time during the simulation process of the CAES model. The two main physical properties of the model, the charging and discharging processes, are simulated separately as they depend on the solar irradiance and peak demand respectively. The total charging and discharging time is 13 hours and 6 hours respectively. Both the charging and discharging processes happen within 24 hours. These results show the iterative nature and dependency of model inputs, processes and outputs.

5.5.1. The Plant Charging Process

The cavern charging stage is the process of filling the storage cavern to its full volume capacity within the maximum pressure limit. The charging time, $T_{charging}$, is the time for the entire charging process and depends on the cavern volume, compressor ratings and compressor mass air flow rate. The initial conditions before compression are that the air is at ambient temperature 25 ºC (298.15 K) and atmospheric pressure is 1 bar. The cavern volume is 210 000 m^3 and the rock-salt and the air in the cavern are in thermodynamic equilibrium and having a temperature of T_{sc} = 298.15 K. The air mass inside the cavern before the commencement of the charging process is the same as it would be in a 210 000 m^3 container at ambient temperature and pressure. The air mass flow to the cavern is assumed to be constant at 140 kg/s. The mass can be calculated with the ideal gas expression given below (Hasan, et al., 2012)

$$m = \frac{pV}{RT} \qquad (5\text{-}2)$$

This gives an initial mass of 10.57 tonnes in the cavern at 1 bar and a maximum mass of 17.21 tonnes at the maximum pressure of 70 bars. The charging time, $T_{charging}$ is given by the equation 5-3 below:

$$T_{charging} = \frac{\Delta mass}{\dot{m}_c} \qquad (5\text{-}3)$$

$$T_{charging} = \frac{(p_{max} - p_{min})T}{RT} \qquad (5\text{-}4)$$

Where,

$\Delta mass$	Change between the minimum and the maximum cavern mass
$\dot{m}_c$	Compressor air mass flow rate

Figure 5-21: 1 below shows the variation of the cavern air mass during the charging process.

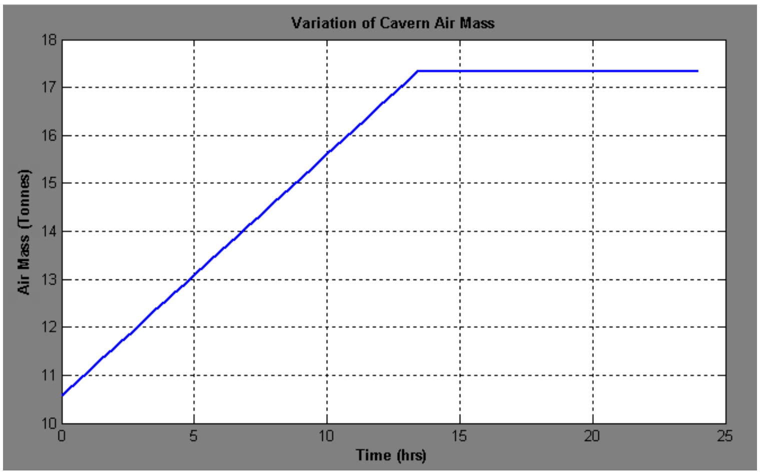

Figure 5-21: The variation of cavern air mass

The compression stage will stop once the pressure inside the cavern pressure reaches 70 bars, thus the compressor air mass flow rate will be equal to zero. Figure 5-22: 2 below shows the cavern air pressure during the charging stage.

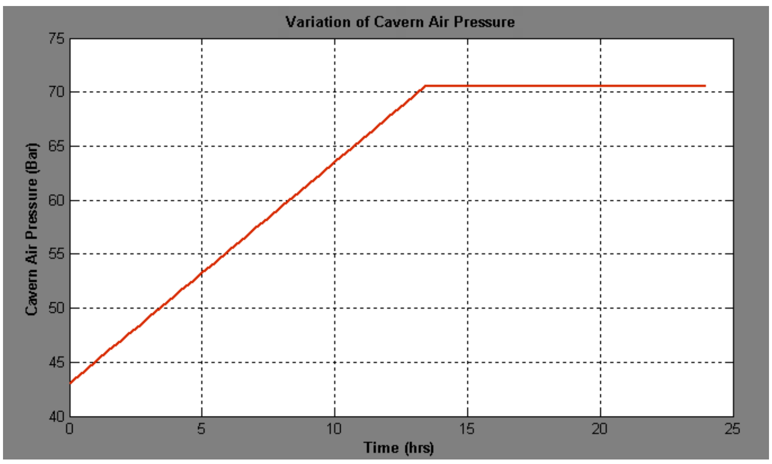

Figure 5-22: The variation of cavern air pressure

5.5.2. The Plant Discharging Process

During peak hours, a signal is received for the CAES system to generate electricity; this initiates the cavern discharge process. The air mass flow from the cavern is constant at 310 kg/s and the discharge process will run until the pressure reduces to 43 bars from 70 bars and over a period of 6 hours. The variation of the cavern pressure during the discharge process is shown in Figure 5-23: 3 below while Figure 5-24: 4 shows the variation of the cavern air mass over the discharging process.

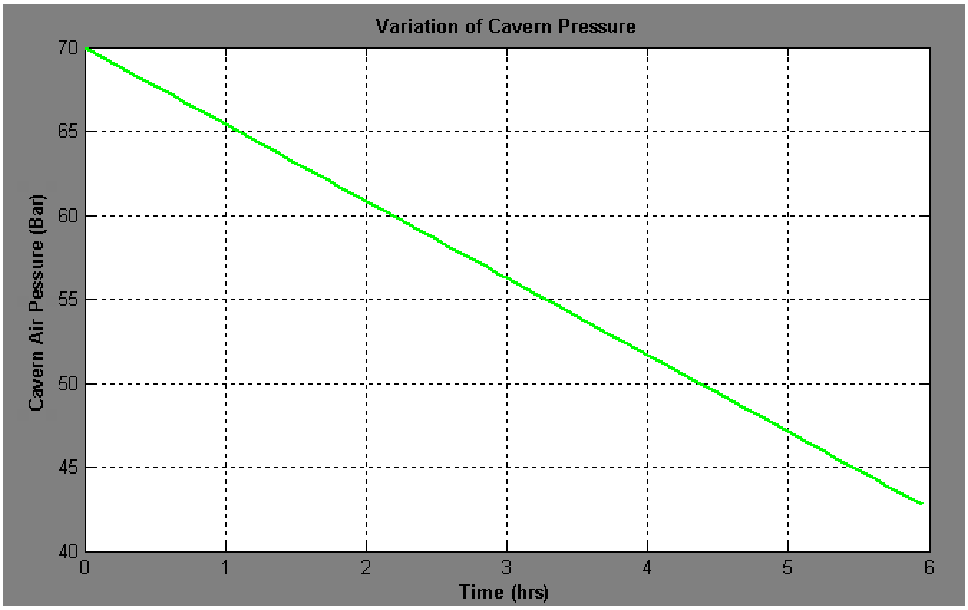

Figure 5-23: The variation of cavern air pressure

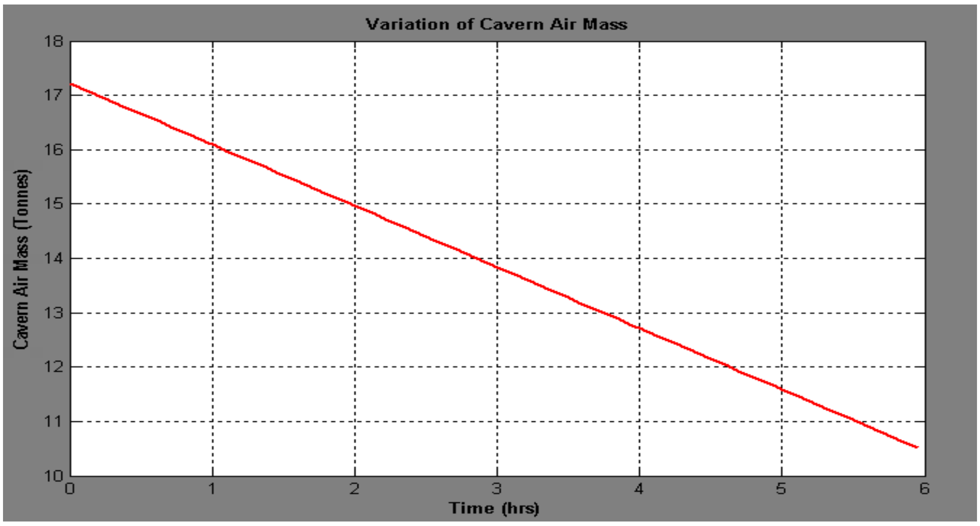

Figure 5-24: The variation of cavern air mass

5.5.3. CAES Model Efficiency

The overall model efficiency is given by the round trip efficiency. This basically compares the CAES model's electricity consumption and production. The electricity consumed by the compressor is given by:

$$P_c = \frac{1}{\varepsilon_c} * \dot{m}_c * \dot{c_{p,a}} * T_{c,in} * \left(1 - \beta^{\left(\frac{k-1}{k}\right)}\right) \quad (5.5)$$

The total power consumed during the charging process is quantified by Figure 5-25: 5 below:

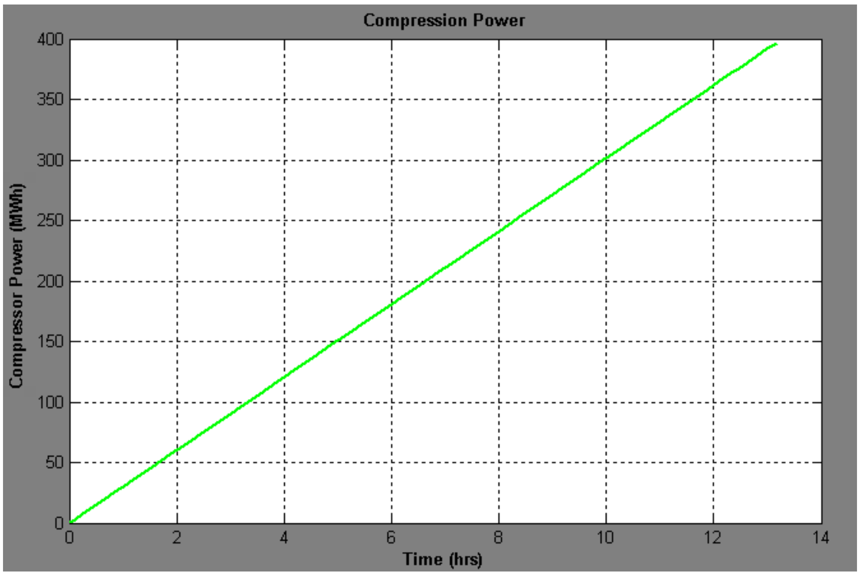

Figure 5-25: The accumulation of consumed power

Similarly, the electricity generated by the turbine is given by:

$$P_t = \varepsilon_t * \dot{m}_t \dot{*} c_{p,a} * T_{t,in} * \left(1 - \beta^{\left(\frac{m-1}{m}\right)}\right) \quad (5.6)$$

The total power generated during the discharging process is quantified by Figure 5-26: 6 below:

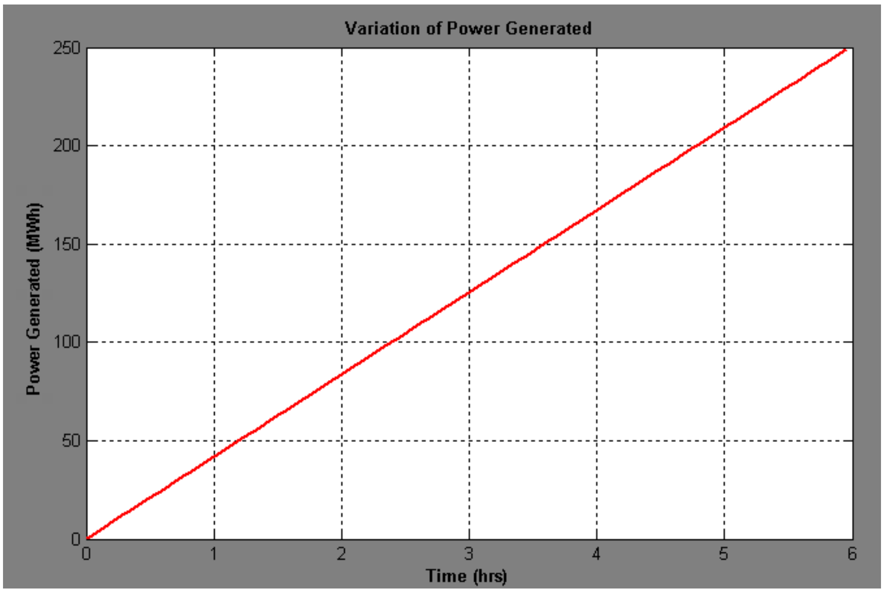

Figure 5-26: The accumulation of generated power

Now the overall model efficiency is determined by

$$\varepsilon_{overall} = \frac{P_t * T_{dischar}}{P_c * T_{char}} \quad (5.7)$$

$$\varepsilon_{overall} = \frac{248.8885}{395.1}$$

$$\varepsilon_{overall} = 0.63$$

The model round-trip efficiency of 63% is within the expectation of typical CAES systems with efficiency ranges between 50% and 75%.

5.6. Summary

The results presented in this chapter are obtained from the Matlab/Simulink simulations that were carried out for all the system components namely the PV plant, the maximum power point tracking scheme, the modular multi-level converter and the compressed air storage for grid integration. The behaviour and performance of the PV panels were simulated and compared with the manufacturer's data early in this chapter. This was done in order to confirm the validity of the developed PV model as a basis for the entire system simulation. The characteristic curves of the simulation PV model closely matched those of the manufacturer and hence the model was used as the foundation for the 30 MW PV plant that was then tested in this thesis. The functionality of the MPPT was demonstrated with the increase in power generated by the PV plant. The geographical location of Witkop substation makes it for solar power generation as the irradiation and temperature levels are around the optimal operation of the PV panel.

Analysis of the results obtained from the research and prototype developed by Georgios S.K *et al* against the performance results from the simulations of the MMLC showed minimum deviation, thus the three results closely matched. It can be concluded that the performance of the simulation model is a true reflection of the practical behaviour of the converter when implemented with the same parameters. In addition, the compressed air energy storage technique proved suitable for large-scale power systems as well as for integration with PV plant coupled to the MMLC systems.

The simulation results shown in this chapter have demonstrated that, when a PV plant is located at an idea geographic area with high irradiation and good temperature, the solar generated electricity is a viable option in South Africa. The work in this report has shown that it can be concluded with confidence that CAES system on a PV plant effectively reduces the intermittence nature of solar generated electricity and instead introduces more electricity supply reserves, demand control and system stability.

CHAPTER 6

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusion

An analysis of PV systems was carried out, resulting in the development, based on the mathematical model, of the PV cell in Matlab/Simulink. The model was then customised to simulate the SunPower E20/330 PV module, based on the manufacturers' module specifications, to check validity of the developed model for further use in the study. The validation process entailed keeping the module working temperature constant at 25 ºC while varying the irradiance intensity (1 200, 1 000, 800, 600, 400, 200 and 100 W/m^2). The model demonstrated that for a given solar irradiation, the model returns particular Current – Voltage and Power –Voltage graphs. A comparison of these graphs with the manufacturers' graphs illuminated that the photovoltaic module short-circuit current and the maximum output power increased as module irradiation intensity increases. Matlab/Simulink graphics were used to represent these findings. This outcome substantiated the validation of using the developed model for the research study.

This research study had to check the viable and feasibility of large-scale PV systems in South Africa and based on the weather data received from ARC, the PV system demonstrated satisfactory performance in the electricity generated by the 30 MW plant at Witkop substation. Significant improvements were apparent on introduction of the MPPT control. Therefore, the PV systems can be a consideration as a viable electricity generation alternative into the grid.

A comprehensive analysis of the MMLC system was conducted in this study, and a control scheme with multiple control objectives to fulfil the requirements raised by the MMLC distinctive topology was presented. The MMLC demonstrated a modular solution with full flexible scaling in voltage, power and energy levels. This ability of having many degrees of freedom offers the MMLC its competitive edge against other multilevel converters. The converter functionality and control structures were also demonstrated in this study.

This research study presented a mathematical model of CAES system to show the ability of CAES in reducing the intermittent effects of solar energy. The CAES simulation results show that, the compression and expansion pressure directly depends on the compression and expansion ratios, airflow rate and air mass into and out of the cavern. These attributes also affected the system efficiency. Therefore, increasing these will increase the system efficiency. However, the CAES parameters defined in the research study proved to be sufficient to meet its objection of storing and supplying electricity when necessary. This had excellent indication and further applications are anticipated as it addresses the South African electricity problem of elevated peak electricity demands that quickly erode the reserve margin.

6.2. Recommendations

In a quest to make the most out of the PV panel, the most efficient PV panel must be considered for further research as well as installation. This can be done by considering the recent and most efficient PV module on the market. Additionally, the potential of PV systems in South Africa is enormous and the applications need not be limited to peak periods only but can be proposed for back-up power systems and energy management systems.

The commitment by the government of South Africa to renewable energy is highly commendable as it provides numerous platforms for penetration into the previous closed electricity generation industry while allowing the maximization of the abundantly available renewable resources. However, several measures are to be put in place before the full realisation of the benefits of the renewables are attained. Some of these measures are the need for government to create an enabling environment through the introduction of fiscal and financial support mechanisms within an appropriate legal and regulatory framework to allow renewable energy technologies to compete with fossil-based technologies.

Technically, the PV panels are very sensitive to obstructions of any nature and magnitude resulting in significant drops in their performances. Therefore, the PV panels should be regularly cleaned to remove any dust as well as the environmental obstructions. Additionally any shading of the PV panels should be avoided.

6.3. Contribution to Body of Knowledge

This project needs to be treated as a base for system design and implement as well as a baseline for continuous improvement of the PV system with a multilevel converter coupled to a CAES for grid integration. The simulation models can be used for analysis of other system configurations that may be advocated for by various renewable energy techniques and energy storage philosophies. The results of this research study can be used as foundation for further study and research as well as highlight the avenues available for the potential of large photovoltaic-based electricity generation plant in South Africa.

6.3.1. Contribution to Academia

- The results of integrating the PV system, the MMC and CAES to the grid present a platform for the simultaneous utilization of two or more energy resources within a hybrid power system for future research.

6.3.2. Contribution to Society

- The research study demonstrated the capability of the PV systems as an alternative source of electricity based on the developed 30 MW PV plant. This presented the potential of the penetration of PV systems as an option to alleviate the present electricity constraints currently experienced in the country;
- The success of this study further increases the awareness around PV systems and this has the possibility of increasing PV applications in off-grid stand-alone systems;
- A reliable storage system, CAES in particular, will ensure availability of solar generated power during periods of high power demand;
- An efficient and reliable solar-based energy system will go a long way in providing more reliable power supply to the South African society and reducing reliance on conventional fossil fuel generated electricity.

6.3.3. Contribution to Eskom and Industry

- An efficient PV system with improved energy storage that can be easily integrated to the South African grid will help alleviate power shortage and meet the government targets in alternative power generation technologies;
- In isolated areas where utility power is not available, PV systems with small-scale CAES can be considered as an alternative hence reducing pressure on the Eskom electricity grid while promoting the energy industry;
- A reliable storage system will ensure a smooth and continuous supply of electricity especially during peak periods even when the sun has set.

6.4. Further Work and Development

Further work in research and development is needed in the examination of the photovoltaic technologies and the CAES energy storage systems of the future generation of plants to be built to harness the great amount of solar irradiation in South Africa. These studies will focus on the detailed assessment of the cost and performance basis for these plants in terms of:

- Analysis of the industry projections for technology improvement and plant scale-up, including a detailed assessment of the cost and performance projections;
- Assessment of the level of cost reductions and performance improvements that are most likely to be achieved and a financial analysis of the cost of electricity from such future PV systems;
- The state of the technology and development costs of the CAES systems has to be closely analysed.

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APPENDICES

APPENDIX [A] ESKOM MEDIA STATEMENT

Eskom

MEDIA STATEMENT

Eskom calls on all customers to reduce electricity usage

Tuesday, 19 November 2013: The power system is severely constrained today due to the loss of additional generating units from our power station fleet and the extensive use of emergency reserves. This has necessitated the need for Eskom to declare an emergency in terms of the approved regulatory protocols.

Eskom is now following the protocol in terms of its emergency procedures in order to secure the power system. We have alerted our key industrial customers and have required them to reduce their load by a minimum of 10%.

While we will make every effort to avoid load shedding, we are hopeful that by applying these measures we will achieve the required load reduction necessary to protect the national grid. Eskom calls on all its customers to urgently switch off geysers, pool pumps, air conditioning and all non-essential appliances from 5pm to 9pm. As workers leave office buildings this evening we ask that they please switch off lights with the exception of the security lighting.

As a precautionary measure, we will be publishing load shedding schedules for Eskom direct customers on our website from 5pm today (http://loadshedding.eskom.co.za/). Customers can also contact our call centre 0860 037 566 for additional information. Load shedding schedules will only be utilised for the duration of the constraint and Eskom will provide regular updates on the status of the power system.

Consumers are urged to switch off pool pumps, geysers and unnecessary lights from 5pm to 9pm tonight. Where possible we recommend that you switch off air conditioning unless necessary, in which case it should be set at 23°C. Remember to watch out for the Power Alert and the Power Bulletin on television to obtain near real-time status of the system. For tips on how to trim 10% off your consumption, visit http://www.eskom.co.za/sites/idm/Residential/Pages/Residential.aspx

ENDS

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APPENDIX [B] ESKOM SYSTEM STATUS BULLETIN

CONSERVE ELECTRICITY ESPECIALLY BETWEEN 5-9 PM – ESKOM

June 23, 2014

Power supply tonight is expected to be tight due to higher demand with the colder weather conditions, Eskom said in a statement today, 23 June.

"The system is very tight tonight over the evening peak and is expected to remain tight over the evening peaks (5 – 9 pm) for the rest of the week due to higher demand with the colder weather conditions," Eskom pointed out in its system status bulletin.

Today Eskom also again called on all consumers to beat the peak over the next few months by using electricity sparingly, particularly between those hours.

"We request all electricity customers to save at least 10% of their electricity usage and sustain these savings. Residential and commercial customers can make the biggest difference by switching off geysers and pool pumps during peak hours [by] switching off non-essential lights; using space-heating efficiently and responding to the Power Alerts messages."

The capacity available to meet this evening's peak demand is 35 191 MW (including open cycle gas turbines), while demand is forecast 35 244 MW.

Last Wednesday, the parastatal declared a system emergency, saying the national power grid was severely constrained.

In the past Eskom customers experienced power cuts as two units at Duvha and Kendal power stations tripped and a portion of the capacity normally imported from Cahora Bassa became unavailable.

APPENDIX [C] 2011 IRP COMMITMENTS BEFORE NEXT IRP REVISION

	New build options							
	Coal (PF, FBC, imports, own build)	Nuclear	Import hydro	Gas – CCGT	Peak – OCGT	Wind	CSP	Solar PV
	MW	MW	MW	MW	MW	MW	MW	MW
2010	0	0	0	0	0	0	0	0
2011	0	0	0	0	0	0	0	0
2012	0	0	0	0	0	0	0	300
2013	0	0	0	0	0	0	0	300
2014	500[1]	0	0	0	0	400	0	300
2015	500[1]	0	0	0	0	400	0	300
2016	0	0	0	0	0	400	100	300
2017	0	0	0	0	0	400	100	300
2018	0	0	0	0	0	400[4]	100[4]	300[4]
2019	250	0	0	237[3]	0	400[4]	100[4]	300[4]
2020	250	0	0	237[3]	0	400	100	300
2021	250	0	0	237[3]	0	400	100	300
2022	250	0	1 143[2]	0	805	400	100	300
2023	250	1 600	1 183[2]	0	805	400	100	300
2024	250	1 600	283[2]	0	0	800	100	300
2025	250	1 600	0	0	805	1 600	100	1 000
2026	1 000	1 600	0	0	0	400	0	500
2027	250	0	0	0	0	1 600	0	500
2028	1 000	1 600	0	474	690	0	0	500
2029	250	1 600	0	237	805	0	0	1 000
2030	1 000	0	0	948	0	0	0	1 000
Total	6 250	9 600	2 609	2 370	3 910	8 400	1 000	8 400

Firm commitment necessary now

Final commitment in IRP 2012

1. Built, owned & operated by IPPs 2. Commitment necessary due to required high-voltage infrastructure, which has long lead time 3. Commitment necessary due to required gas infrastructure, which has long lead time 4. Possibly required grid upgrade has long lead time and thus makes commitment to power capacity necessary

APPENDIX [D] ESKOM'S UPDATE ON STATUS OF IPPs

Dear Guardians

THE GAU FOR IPPs AND GENERATORS ACHIEVES GREAT MILESTONES

Since its inception, the Grid Access Unit (GAU) for Independent Power Producers (IPPs) and generators under the leadership of Mr Gabriel Kgabo has achieved great milestones to ensure the realisation of grid access to the Eskom network by the IPPs. Specifically, on the current Department of Energy (DoE) Renewable Energy IPP Procurement Programme (REIPPPP), the GAU Front Office in partnership with the Transmission and Distribution Group, and also the Group Customer Services (Pricing and Contracts), have gone to great lengths to ensure that over 300 cost estimate letters (CEL) to all IPP bidders for Bid 1 and 2 were issued on time.

Following the two bidding rounds, a total of 47 preferred bidder projects that collectively signify renewables capacity of 2 459.4 MW had been announced by the DoE; 28 bidders in Bid 1 (one project to connect to the municipality grid) and 19 bidders in Bid 2.

Impressively, the Budget Quotes (BQ) and all associated agreements (connection, use of system, self-build and direct) for all 27 preferred bidders of Bid 1 were issued on time as per the DoE timeline. So far, only seven IPPs have signed their respective agreements and submitted them back to Eskom. The process to issue BQs for the 19 projects of Bid 2 is presently in progress.

The GAU is currently facilitating the issuing of over 350 CELs for Bid 3. However, the applications might increase due to the recent DoE public announcement that the third bid submission date will be postponed from 1 October 2012 to 7 May 2013 due to, amongst others, the immediate need to focus on Bid 1 and 2 financial close processes, and to update the Request for Proposals (RFP) and finalise the new determination for additional megawatts.

The excellent work done by this team was acknowledged and awarded at the Group Customer Services Manager's Awards held recently.

For further enquiries, please contact the GAU on GridAccessUnit@eskom.co.za

APPENDIX [E] SUNPOWER PV MODULE CHARACTERISTIC

SUNPOWER E20/333 and E20/327 SOLAR PANELS

20% EFFICIENCY

SunPower E20 panels are the highest efficiency panels on the market today, providing more power in the same amount of space

TRANSFORMERLESS INVERTER COMPATIBILITY

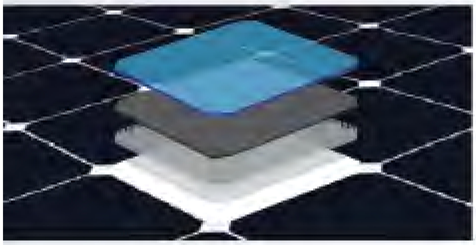
Comprehensive inverter compatibility ensures that customers can pair the highest-efficiency panels with the highest-efficiency inverters, maximizing system output

POSITIVE POWER TOLERANCE

Positive tolerance ensures customers receive the rated power or higher for every panel

RELIABLE AND ROBUST DESIGN

SunPower's unique Maxeon™ cell technology and advanced module design ensure industry-leading reliability



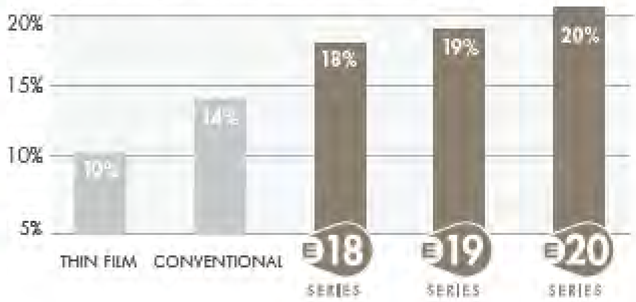
MAXEON™ CELL TECHNOLOGY

Patented all-back-contact solar cell, providing the industry's highest efficiency and reliability.

THE WORLD'S STANDARD FOR SOLAR™

SunPower™ E20 Solar Panels provide today's highest efficiency and performance. Powered by SunPower Maxeon™ cell technology, the E20 series provides panel conversion efficiencies of up to 20.4%. The E20's low voltage temperature coefficient, anti-reflective glass and exceptional low-light performance attributes provide outstanding energy delivery per peak power watt.

SUNPOWER'S HIGH EFFICIENCY ADVANTAGE



sunpowercorp.com

SUNPOWER E20/333 and E20/327 SOLAR PANELS

MODELS: SPR-333NE-WHT-D, SPR-327NE-WHT-D

ELECTRICAL DATA

Measured at Standard Test Conditions (STC): irradiance 1000W/m², AM 1.5, and cell temperature 25° C

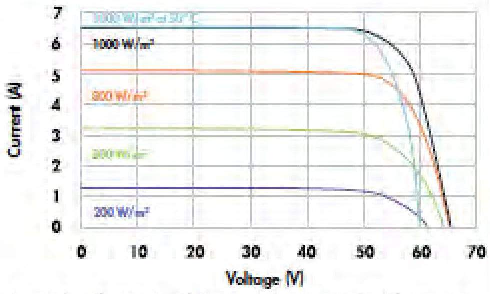
Nominal Power (+5/-0%)	P_{nom}	333 W	327 W
Cell Efficiency	η	22.8%	22.5%
Panel Efficiency	η	20.4%	20.1 %
Rated Voltage	V_{mpp}	54.7 V	54.7 V
Rated Current	I_{mpp}	6.09 A	5.98 A
Open-Circuit Voltage	V_{oc}	65.3 V	64.9 V
Short-Circuit Voltage	I_{sc}	6.46 A	6.46 A
Maximum System Voltage	IEC	1000 V	1000 V
Temperature Coefficients	Power (P)	– 0.38%/K	
	Voltage (V_{oc})	– 176.6mV/K	
	Current (I_{sc})	3.5mA /K	
NOCT		45°C +/– 2°C	
Series Fuse Rating		20 A	
Limiting Reverse Current (3 strings)	I_R	16.2 A	
Grounding		Positive grounding not required	

ELECTRICAL DATA

Measured at Nominal Operating Cell Temperature (NOCT): irradiance 800W/m², 20° C, wind 1 m/s

Nominal Power	P_{nom}	247 W	243 W
Rated Voltage	V_{mpp}	50.4 V	50.4 V
Rated Current	I_{mpp}	4.91 A	4.82 A
Open-Circuit Voltage	V_{oc}	61.2 V	60.8 V
Short-Circuit Voltage	I_{sc}	5.22 A	5.22 A

I-V CURVE



Current/voltage characteristics with dependence on irradiance and module temperature.

TESTED OPERATING CONDITIONS

Temperature	– 40° C to +85° C
Max load	550 kg/m² (5400 Pa), front (e.g. snow) w/specified mounting configurations
	245 kg/m² (2400 Pa) front and back (e.g. wind)
Impact Resistance	Hail: 25 mm at 23 m/s

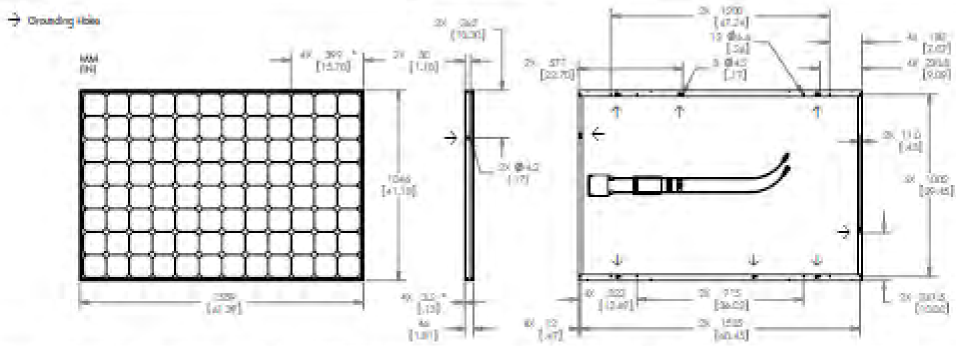
WARRANTIES AND CERTIFICATIONS

Warranties	25-year limited power warranty
	10-year limited product warranty
Certifications	IEC 61215 Ed. 2, IEC 61730 (SCII)

MECHANICAL DATA

Cells	96 SunPower Maxeon® cells
Front Glass	High-transmission tempered glass with anti-reflective (AR) coating
Junction Box	IP-65 rated with 3 bypass diodes
	32 x 155 x 128 mm
Output Cables	1000 mm cables / Multi-Contact (MC4) connectors
Frame	Anodised aluminium alloy type 6063 (black)
Weight	18.6 kg

DIMENSIONS



Please read safety and installation instructions before using this product, visit sunpowercorp.com for more details.

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APPENDIX [F] TOP 10 WORLD'S MOST EFFICIENT SOLAR PV MODULES

The table below shows the Top 10 of the current commercially available mono-crystalline silicon solar PV modules with the highest module efficiency. This information has been collated from public sources such as product datasheets online.

	Manufacturer	Module Efficiency	Module Type
1.	Sunpower	20.40%	E20 / 333 SOLAR PANEL
2.	AUO	19.50%	PM318B00
3.	Sanyo Electric	19.00%	HIT-N240SE10
4.	Jiawei	18.30%	JW-S100
5.	Crown Renewable Energy	18.30%	Summit 100LM
6.	Idea Solar	17.50%	IS-W234
7.	Winaico	17.15%	WSP-285M6
8.	PVT Austria	16.88%	PVT-2xxMAE-A255
9.	JA Solar	16.84%	JAM5(L)-72-215/SI
10.	Zytech	16.84%	ZT 215S