An assessment of the potential of Solar Photovoltaic (PV) and hybrid renewable energy application in South Africa

Silas Khakhathi Mulaudzi

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School of Chemical Engineering & Advanced Materials

Newcastle University, Newcastle upon Tyne,
NE1 7RU, United Kingdom

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Abstract

More than 80% of the world's energy demand is satisfied by fossil fuels. Proven coal reserves are sufficient for the next 113 years, while natural gas reserve could last up to 55 years (Jain, 2010). More than 90% of South African electricity is generated from fossil fuels, mainly coal. South Africa has an average of 85% access to electricity. It is from this background that this study investigated the potential of solar PV, and hybrid energy system application to address energy security and poverty.

The primary data was collected from different stakeholders (Residential, government, power generators and solar PV installers) through interviews and completion of questionnaires. The secondary data was collected through publications and websites.

The "*Optioneering*" (Chapter 4) and household energy consumption survey (Chapter 6) lead to the same conclusion that Gauteng Province has the greatest solar PV potential. It has good solar irradiance and high electricity consumption, which solar PV could add value in the diversification of energy mix. Over 25% of South African electricity is consumed in this province, hence it is recommended for the construction of solar PV power plants and rooftop installation.

There is a potential of 2 million middle income and 0.5 million high income households, which consume 9.6 TWh/year and 3 TWh/year respectively and are interested to pay for electricity based on a green source. Approximately 45% of the high income residents are based in Gauteng. Thus, Gauteng is recommended as province with greatest solar PV potential taking into consideration chapter 4 and 6 findings.

There is good renewable energy potential in South Africa. However, these technologies will not replace fossil fuels soon. Fossil fuels will remain the main source of energy for the foreseeable future in South Africa because of the barriers that renewable energy technologies are facing in the country. Therefore, greenhouse gas emissions are most likely to increase at steady rate for the decades to come. Nonetheless, solar PV growth and development will continue to rise, mainly stimulated by the price reduction over time and improved efficiency with a low degradation rate.

Declaration

The content of this thesis is my original research work. I confirm that there is no collaborative or jointly-owned work in this thesis, whether published or not. Every form of support received in the course of this study and all cited texts have been duly acknowledged.

Part of this work has been presented at the 7th edition of International Renewable Energy Congress (IREC), 22-24 March 2016, Tunisia and the paper titled '*An assessment of the potential of Solar Photovoltaic (PV) application in South Africa'* and is published in IEEExplore - PES Section in the link below
http://www.ieee-pes.org/meetings-and-conferences/conference-calendar/monthly-view/166-technically-cosponsored-by-pes/475-irec

Dedication

To my beloved wife, Aluwani
And
My son, Mulisa and daughters, Otenda and Okhethwaho

Acknowledgement

I would like to take this opportunity to thank my supervisor, Professor Steve Bull for giving me the opportunity to undertake this exciting research project. His guidance, supervision and support throughout my studies has surely meant that I have completed my PhD to the very best of my abilities. It was indeed an honour, privilege and pleasure to work under his supervision. On the same note, I would also like to thank my second supervisor, Dr. Adrian Oila for being my co-supervisor throughout the journey of my PhD studies.

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CHAPTER 1: INTRODUCTION

1.1 Background

Energy is considered the life-blood of every development worldwide. The socio-economic growth, development and improved living standards of nations worldwide are directly linked to the increase in the use of energy (Bhandari and Stadler, 2011). Thus, energy resource, electricity in particular, plays a vital role in societal development across the world. On the other hand, growth in electricity demand is mainly caused by population increase, as well as favourable economic growth that continues to put pressure on the electricity supply sector.

The world benefits greatly from fossil fuel resources, notably coal, oil and gas. Coal, among other fossil fuels, has many uses fundamentally important to economic development and poverty alleviation. Its most significant use is electricity generation (Jain, 2010). The rapid reduction and depletion of fossil fuel resources across the world has compelled an urgent pursuit of alternative and sustainable energy sources to meet the present-day demand for energy. This is so because approximately 80% of the world's energy demand is satisfied by fossil fuel resources (Sahu, 2015).

Alternative energy resources such as solar, biomass, hydro and wind are possibly clean, safe and, most significantly available. Moreover, these are environmentally friendly renewable energy technologies, which pose little threat to the environment (Ekren *et al.,* 2008; Ekren and Ekren, 2009). In comparison, heavy reliance on, and consumption of, fossil fuels is anticipated to have major and irreversible consequences for the current and future generations. One of the primary concerns is that fossil resources are finite (they have a lifespan) and are being depleted at a rate which is significantly faster than their regeneration rate. Furthermore, it may not be accurately known for how long these fossil fuels will be available to future generations (Hofman and Li, 2008). However, Dudley (2014) estimated that the proven world coal reserves are sufficient to meet the demand for the next 115 years.

Many developed and developing countries have recently turned their attention to exploring and harnessing alternative and renewable energy resources. This is because the renewable energy sources such as solar are freely available and have remained largely untapped thus far in many parts of the world. Moreover, there is high risk in relying on fossil fuels to meet the ever-increasing electricity demand because of their limited lifespan. The other rationale for an increased interest in harnessing renewable energy from different nations is that the use of fossil fuels leads to long-term environmental problems, such as acid rain and greenhouse effects (Kumar and Tiwari, 2009). Consequently, global warming caused by greenhouse gas (GHG) emissions, mainly from the combustion of fossil fuels for the generation of electricity, has been an important environmental concern (Kannan *et al.,* 2006).

There is a pressing need to accelerate and advance the development of sustainable and clean energy technologies to address the global challenges of energy security, climate change and global warming. There is also global consensus on the exploration and utilisation of different renewable and sustainable energy sources to meet the electricity demand of the growing world population (Tiwari *et al.,* 2009). The bilateral and multilateral agreements and targets on the reduction of emissions among many nations across the world result in countries exploring possibilities of generating electricity from environmentally friendly technologies.

Solar Photovoltaic (PV) is one of the renewable energy technologies that generate electricity from the sun (Kusakana, 2014). It is becoming an increasingly favourable source of energy in many regions. This is true particularly in countries with daily average solar radiation levels in the range of 3–8 kWh/m^2/day (Dekker *et al.,* 2012). Solar energy, in comparison with other sources, is the most abundant energy resource on earth. The solar radiation that hits the earth's surface in one hour is the same as the amount consumed by all human activities in a year (Van der Hoeven, 2014). Hence, there is plenty of solar energy that has the potential to make a significant contribution to meeting electricity demands across the world.

1.2 South African electricity supply

South Africa grid connected electricity generation capacity is over 40000 MW, which is almost half of the African continent capacity of 90000 MW (Birol, 2014a). More than 90% of this electricity generation comes from Eskom Holdings, which is a state owned entity. Eskom Holdings is a vertically integrated company licensed to generate, transmit and distribute electricity in South Africa (Eskom, 2013b). South Africa is the second largest economy in the continent, second to Nigeria (Birol, 2014a). It is well developed and has substantial infrastructure in place compared to most other African countries. South Africa has an energy intensive economy mainly as a consequence of the exploitation of the country's mineral resources (DOE, 2015). The primary energy consumption in 2015 was 85 million tonnes oil equivalent for coal, followed by oil with 31.1 million tonnes oil equivalent (Dudley, 2016).

In 2015, South Africa generated 219979 GWh of electricity from Eskom power stations, which makes up to 95% of the country's power supply (Table 1.1). The country's total power generation capacity is 42810 MW from various sources, which 36441 MW comes from coal-fired power stations, 1860 MW comes from Nuclear (Koeberg power station), 2409 MW from gas-fired power station, 600 MW from hydro power station, 1400 MW from pumped storage schemes and 100 MW from the Sere wind farm (Eskom, 2016). There was an additional 2480 MW connected to grid lines in 2015 from the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) generating power from different renewable energy sources (DOE, 2015).

Table 1.1: Primary energy source and power production in 2015 (Source: Eskom, 2015)

Primary energy source	**GWh (2015)**
Coal-fired power station	199 888
Nuclear power	12 237
Open-cycle Gas Turbine	3 936
Hydro stations	688
Pumped storage stations	2 919
Wind	311
Total	**219 979**

The financial and policy instrument for renewable energy supply that South Africa has adopted is competitive bidding, through the REIPPPP, which was implemented in 2011. To date the programme has registered 6.3 GW of different renewable energy technologies, and 2.3 GW comes from solar PV technology (DOE, 2015).

South Africa is part of the Conference of Parties (COP) that convenes annually to discuss climate change and carbon emission policies, which become legally-binding agreements. According to COP 21 (2015), the 21th session of COP that took place from 29 November to 13 December 2015 in Paris, France aimed to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty. The parties agreed to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change. The parties further agreed to increase the ability to adapt to the adverse impacts of climate change and foster climate resilience and low Greenhouse Gas (GHG) emissions development, in a manner that does not threaten food production (COP21, 2015).

Therefore, South Africa is committed to reduce GHG emissions and its efforts were noticed when it implemented the REIPPPP to increase the uptake of renewable energy technologies in the total energy share. A reliable electricity supply of acceptable quality is essential for the economic development of South Africa (Eskom, 2013b). The transmission system plays a vital role in the delivery of a reliable, high quality electricity supply throughout South Africa. The transmission system needs to be well-maintained to deliver a reliable supply of electricity, and it also needs to be strengthened and upgraded to meet the additional power generated from the renewable energy technologies.

1.3 South African load profile and forecast

Load profile is fundamental to understand the power requirement. The availability of sufficient transmission network capacity in any country is important for economic growth (Eskom, 2013b). The typical winter load profile goes beyond 36000 MW in the evening (Figure 1.1). If winter becomes colder than usual, then it puts added pressure on the system. For every 1^0C decrease in winter temperature, the electricity demand increases by 600 - 700 MW during the evening peak. Similarly, a warmer than expected summer increases air-conditioning load and demand can increase by up to 400 MW (Eskom, 2012).

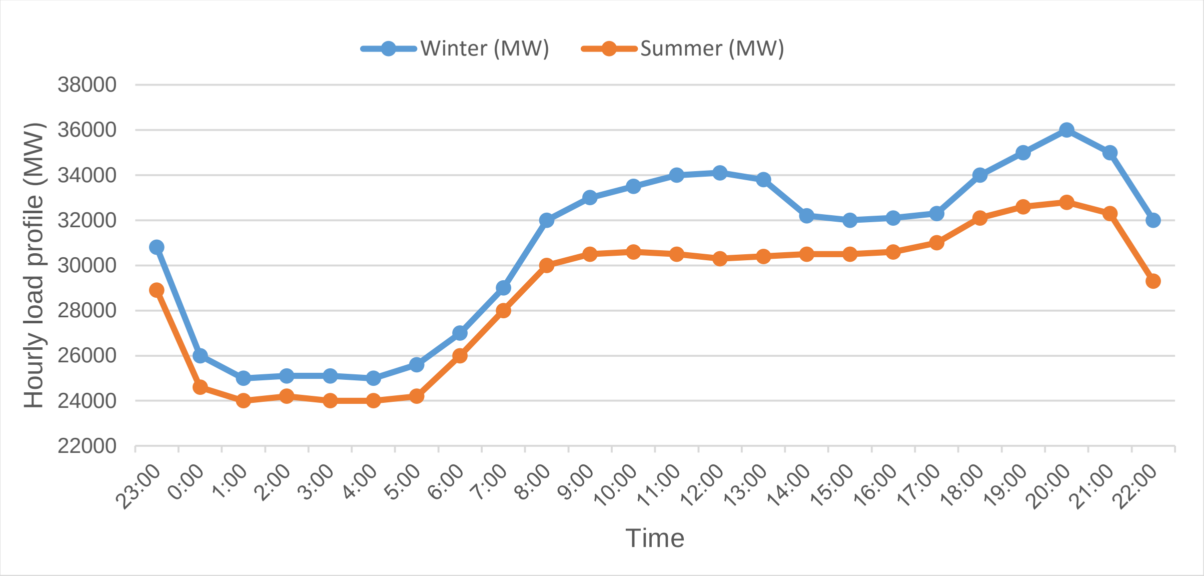

Figure 1.1: South African winter and summer load profile (Source: Eskom, 2012)

The Eskom energy profile forecast projected that by 2019 the peak MW capacity needed would be 46668 MW (Eskom, 2013). In 2015 the total power production was 219979 GWh from the available generating capacity of 42810 MW, it is therefore anticipated that in 2018 the power needed would be 307150 GWh, a growth of 87171 GWh in the 3-year period (Eskom, 2016). A steady growth of up to 46668 MW is projected by 2019 (Table 1.2). The forecast of 40923 MW for 2016 was incorrect as the generation capacity in 2015 was 42810 MW. This is the case because the synchronisation of Medupi Unit 1 and the REIPPPP was not incorporated in the forecast.

Table 1.2: South African annual electricity and peak demand forecast (Source: Eskom, 2013)

Year	Energy (GWh)	Peak (MW)
2016	277 860	40 923
2017	286 190	42 625
2018	307 150	45 667
2019	314 606	46 668

1.4 Solar photovoltaic energy

Solar PV energy is an arrangement of components designed to supply usable electric power for a variety of purposes. It uses the sun as source of power and generates electricity through the direct conversion of sunlight (Miller and Lumby, 2012). The basic building block of the PV system is the cell, which is a semi-conductor device that produces a photocurrent when exposed to the sun, hence converting solar irradiance into direct-current (DC) electricity (Bollen and Hassan, 2011). The PV cells are inter-connected to form PV modules, typically up to 200 Watts per module (Ölz, and Beerepoot, 2010). The PV modules differ in size and type; the crystalline module is four-cornered and sky blue in colour (Figure 1.2).

The solar PV system has become one of the most promising renewable energy technologies (Su *et al.*, 2012). It has substantial potential and its use has been growing fast in recent years, yet in many parts of the world it is still viewed with concern, largely about costs and doubt about its usefulness, effectiveness and efficiency. Society would gain substantially by understanding solar energy’s ability and potential to make an economic and social contribution to the total energy needs (Ölz, and Beerepoot, 2010).

Figure 1.2: Solar PV panels mounted on a roof-top in North West University, Potchefstroom (Photo taken by the author on 31 July 2014)

Solar PV generates electricity in over 100 countries across the world and remains the favourite and fastest growing power generation technology in countries with high solar irradiance. The grid-connected PV capacity has grown at an average annual rate of 60% since 2004 (REN21, 2014). For that reason, there has been substantial growth over the past decade in the development of the solar PV energy sector. The world installed solar PV capacity grew to 303 GW capacity in 2016 (Figure 1.3). It is anticipated that there will be further growth once other nations realise the benefits of solar PV, particularly developing countries.

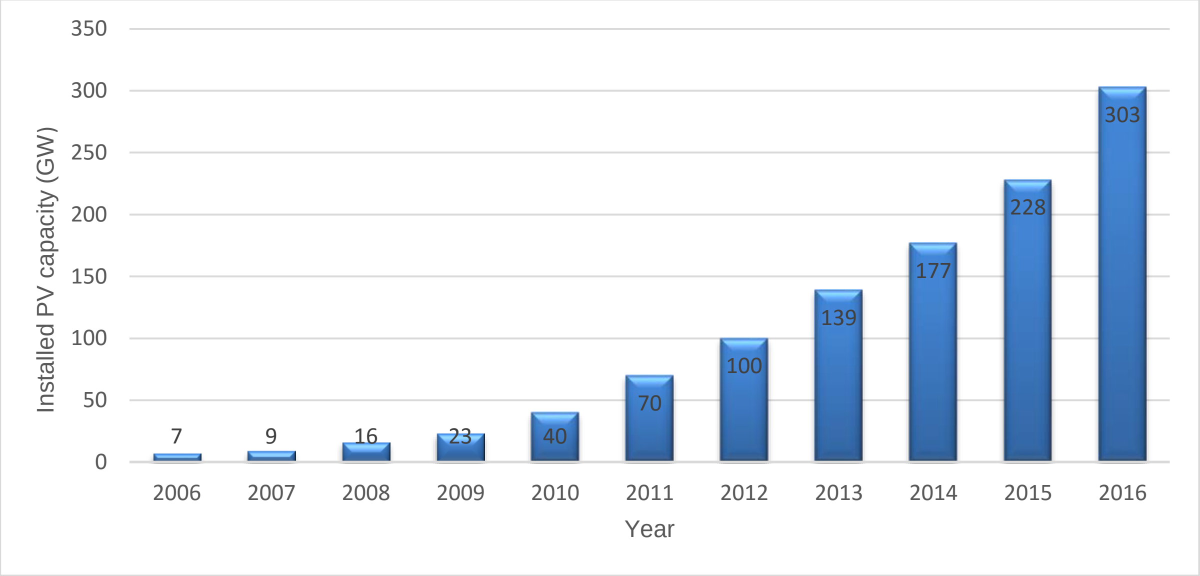

Figure 1.3: Existing world solar PV capacity from 2004-2014 (Source: REN21, 2017)

Solar PV energy comprises three main systems, namely: grid-connected solar PV, off-grid solar PV and hybrid renewable systems. These systems generate power for use in different ways and their suitability varies from one location to another, depending on different factors and characteristics.

1.4.1 The grid-connected solar PV system

In a grid-connected PV system is defined there is a link between solar cells and the national grid network system via a DC-to-alternating current (AC) converter. The grid-connected PV system feeds the electricity it generates directly to the national (utility) grid network and households (Figure 2.14). It is a power system energised by PV modules connected to the utility grid, thus the solar PV modules are generally connected together in series to produce strings of modules of higher voltage, and these strings are connected together in parallel to produce a higher current DC input to the inverters (Miller and Lumby, 2012). The grid-connected solar PV power system consists of panels, solar inverters, AC and DC converters, meter reading, power conditioning units and grid connection equipment. Electricity generated from solar PV can be used by the owner and the excess power goes to the grid network.

1.4.2 Off-grid solar photovoltaic system

Off-grid solar PV generation is an electrical power system energised by PV modules, which are stand-alone without any connection to the utility grid network (Figure 2.15). Off-grid systems are not new; they have been used for some decades to supply electricity in remote areas such as rural villages, islands and even small cities that are not connected to the national electricity grid supply. For renewable energy sources, in particular solar PV energy, applications of off-grid systems have been more common in developing countries than grid-connected systems until the mid-90s (Kempener *et al.,* 2015).

Furthermore, off-grid and mini-grid systems are used to supply remote industrial sites, telecommunication facilities or public applications such as lighthouses, national parks, schools or mountain shelters. It is estimated that more than two billion people in developing countries do not have a grid-connected electricity service (Saheb-Koussa *et al.,* 2009). The off-grid solar PV energy system consists of solar PV panels, a controller, batteries for power storage and an inverter.

Kempener *et al.* (2015) divided off-grid and mini-grid solar application into four categories, namely:

- Islands and remote communities;
- Commercial/industrial - mainly to ensure energy security up to 100% reliability and/or provide cheaper (in the long run) energy sources, especially if connected to heat production;
- Community/utility - often demonstration projects in the case of developed countries; and
- Institutional/campuses - hospitals, government buildings and other institutions with access to cheap capital and no short payback requirements.

1.4.3 Hybrid solar energy

Stand-alone/off-grid solar PV or wind energy systems have been promoted around the globe on a comparatively large scale. The challenge is that these independent systems, depending on size, are unable to provide continuous and uninterrupted power supply because of the fluctuation and variability characteristics of the power source. For example, a stand-alone solar PV energy system may not provide reliable power on cloudy/overcast days or at night. All things being equal, a stand-alone wind energy system cannot satisfy constant load demands owing to significant fluctuations in the magnitude of wind speed from hour to hour throughout the year (Muralikrishna and Lakshminarayana, 2008).

Consequently, neither a stand-alone/off-grid solar PV nor wind energy systems can provide a continuous and reliable power supply to off-grid communities because of seasonal and periodical variance. A combination of solar PV energy, wind energy, batteries and diesel generator energy has been widely used for electricity supply in isolated locations far from the distribution and grid network (Saheb-koussa *et al.,* 2009). This system is commonly known as hybrid renewable energy (Figure 2.16). If, however, the system is properly designed, it provides reliable service and operates in an unattended manner for an extended period of time.

1.5 Statement of the problem

The extraction and exploitation of fossil fuel resources are associated with severe and irreversible consequences. The main consequences are environmental ones, including climate change and global warming. Furthermore, the supply of fossil fuels is limited and they will be depleted in the medium to long term (Clerici, 2013). South Africa is almost entirely dependent on fossil fuels for its primary energy sources. The 2014 and 2015 electricity shortage in South Africa should be seen as an opportunity to maximise utilisation of alternative energy sources. This is a serious problem, in particular with regard to the consequences of having more than 80% of primary energy source coming from fossil fuels (Dudley, 2016). The statement of problem includes both the environmental concerns and energy security.

1.5.1 Environmental concerns (climate change and global warming)

Climate change refers to the variation in global, regional, continental or national climate patterns (Thomas *et al.,* 2000). The change is attributed largely to increased levels of atmospheric GHG emissions (CO_2, CO, CH_4, NO_x), mostly produced by the use of fossil fuels. This is particularly the result of burning coal for power generation. The burning of coal causes a medium to long term change in weather patterns or average temperatures. The global change is a gradual increase in the overall temperature of the earth's atmosphere (Tanaka, 2011). The increase is generally attributed to the GHG emission effect caused by increased levels of emission of chlorofluorocarbons and other pollutants. The broad consequences and effects of climate change include*, inter alia*, drought, floods, global warming and other natural disasters (World Bank Group, 2012).

The total African CO_2 emissions in the electricity sector are dominated by a few main emitting countries, with South Africa, Egypt, Libya and Algeria representing over 80% of the total in 2008 (Pegels, 2010). It is anticipated that there could since have been some changes in the 80% due to development and expansion of energy related infrastructure in other African countries to meet the ever-growing demand for electricity. However, the overall emissions from the electricity sector in Africa remain small compared to other continents (Witi and Stevens, 2014). It mainly representing approximately 3.4% of total global emissions from electricity generation (Tanaka, 2011).

In 2010, the South African CO_2 emission was at just over 200 Mt (Eskom, 2012). South Africa was ranked seventh in the top ten countries producing coal across the world in 2013 (Birol, 2014a). It produced 251 million tonnes of coal in 2013 (Clerici, 2013; International Energy Agency, 2014). The energy sector is the main contributor of GHG emissions in South Africa. According to Dudley (2016) and Eskom (2016) approximately 93% of South African electricity was generated from coal in 2015. However, in 2010 South Africa was reported to have generated 94% of electricity from coal, followed by Poland with 93% (Figure 1.4). The slight decrease from 94% in 2010 to 93% in 2015 could be associated with the renewable energy sources from the REIPPPP, which approximately 1263 MW has been commissioned in 2015 (DOE, 2015). Nevertheless, the coal contribution is likely to increase due to 9000 MW coal-fired power stations (Medupi and Kusile) that are yet to be commissioned.

Coal production seems to be increasing every year; from 2011 to 2013 the production of coal increased in South Africa (Chapter 2, section 2.2.1). Consequently, the energy sector is the largest contributor of CO_2 emission in South Africa, with an average of 89.2% between 2000 and 2010. The livestock and waste sector contributed approximately 54.1% and 37.2% of the CH_4 and biomass burning contributed more than 80% of the N_2O in that period (Witi and Stevens, 2014).

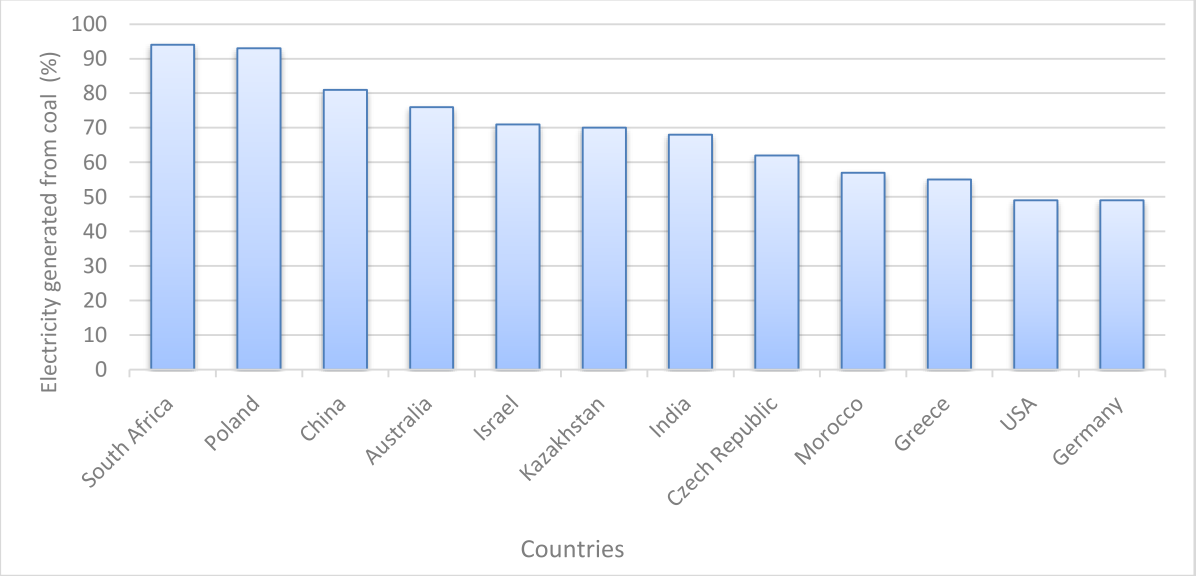

Figure 1.4: Coal used for electricity generation per country (Source: Jain, 2010)

It is concluded (from the previous paragraph) that the main challenge concerning GHG emission production is the performance of the electricity generation sector. Hence, with the binding COP agreements in Paris in 2015, a rapid and urgent transformation in electricity generation technologies is needed in South Africa. The main product of emissions in South Africa is CO_2 and the primary source is the electricity sector, which accounted for 55.1% of CO_2 equivalent between 2000 and 2010 (Witi and Stevens, 2014). In 2012, the total CO_2 emission from electricity generation grew to 231 Mt (Figure 1.5). However, the CO_2 remained constant from 2008 to 2012 with little increase. Overall, CO_2 is the main GHG emission, which has severe implications in the medium to long term, including its contribution to global warming. There is, therefore, a need for South Africa to scale up the generation of electricity from environmentally friendly and constantly available natural energy resources, such as solar power.

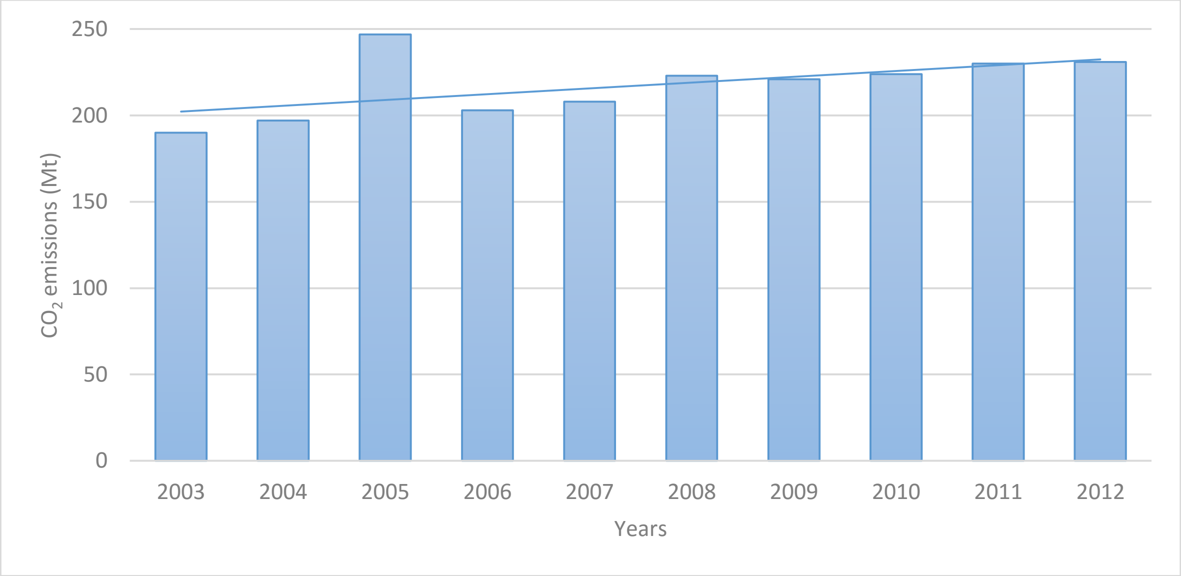

Figure 1.5: The CO_2 emission from electricity generation for a period of 2003-2012 (Source: Eskom, 2007; Eskom, 2012)

The GHG emission factors for electricity have remained relatively constant in South Africa between 2011 and 2017, it has been between 0.30 to 0.37 kg CO_2/MWh (Eskom, 2017). However, the highest was in 2014, which was 0.37 carbon emission kg/MWh (Figure 1.6).

The process of generating electricity in South Africa is GHG inefficient because of the high reliance on coal powered plants. Thus, the GHG emissions resulting from electricity generation in South Africa are generally higher than for other countries in electricity generation.

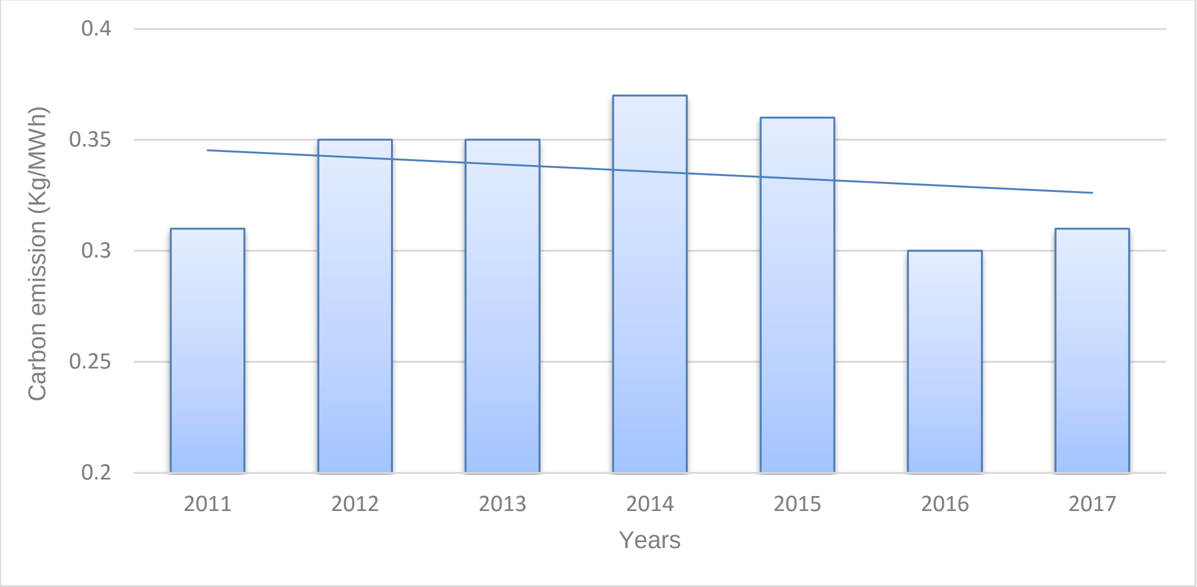

Figure 1.6: South African electricity grid connected kg CO_2/kWh (Source: Eskom, 2010; Eskom, 2017)

It is anticipated that kg CO_2/GWh may rise in South Africa due to the two coal-fired power stations that are yet to be commissioned. The 9000 MW two coal-fired power stations are likely to add emissions despite the renewable energy technologies that have come online, which a total of 6300 MW has been registered thus far. However, it also depends on the coal characteristics and power station design parameters, which will be more efficient and reduce emissions during operation. The extent to which this will affect emission is not yet known. The country has committed to reduce emissions at the COP21, there is a political will and interest to move towards nuclear as a measure to reduce emissions and comply with the commitment made in COP21.

South Africa has the highest tCO_2 per capita in Africa. In 2013 it was at 7.91 tCO_2/capita, followed by Libya with 6.97 tCO_2/capita, other countries such as Botwana, Democratic Republic of Congo, Kenya have less than 1 tCO_2/capita (Birol, 2015). The leading developing or newly industrialized countries, which are Brazil, Russia, India, China and South Africa (BRICS), which are countries that are distinguished by their fast-growing economies and significant influence on regional affairs, South Africa is the second highest with Russia being the highest with 10.79 tCO_2/capita, Brazil has the lowest tCO2/capita of 2.26 in the BRICS countries (Birol, 2015).

1.5.2 Energy security

Fossil fuel resources are diminishing with time, and the remaining crude oil, gas and coal are concentrated in a smaller number of countries (Tanaka, 2008). This raises concern about energy security and the volatility of oil prices, which has the potential to harm economic growth. Coal has an important role to play in meeting the demand for a secure electricity supply. It is the most abundant source of energy.

In the estimate of proven fossil fuels reserves at the end of 2008, coal had reserves to maintain the production ratio for about 128 years (Jain, 2010). Nonetheless, the Reserve to Production Ratio (R/P) has been demonstrated to be relatively stable over the years; South Africa with the highest coal reserve in the continent has a 39 R/P ratio (Dudley, 2017). Taking into account the uptake of renewable energy, solar in particular having increased its global capacity from 228 GW to 303 GW from 2015 to 2016, the coal reserve may be relatively stable for many more years to come.

However, coal is a finite resource and with the increase in population growth and economic development, which lead directly to an increase in demand for electricity, the consumption of coal has grown rapidly over the past seven years (2008-2015). This growth in consumption does not take into account the innovative ways of generating electricity and improved efficiencies in renewable energy technologies such as solar PV, therefore, coal is most likely to last for more than the estimated 128 years. The question is for how long the world would in general, and South Africa in particular, keep using coal, and how long the coal resource would last at future usage rates? Any economic development and advancement requires secure and reliable access to electricity to support its growing prosperity (Birol, 2014a).

In 2014 and 2015 many parts of South Africa faced power shortages, despite many provinces of South Africa having good solar and wind power potential that remained underutilised. With the increasing shortage of electricity across the country, South Africa could benefit by exploiting the potential of off-grid, grid-connected, stand-alone and hybrid renewable energy technologies that have the ability to meet energy needs and provide sustainable and long-term energy solutions. Renewable energy improves energy security by reducing the heavy reliance on imported fuels (such as oil) and helps diversify the power mix (Birol, 2014a).

South Africa imports a large amount of crude oil and a limited quantity of natural gas is available in the country, mainly in the Karoo area of the Western Cape Province, in 2015 South Africa imported 649 thousands of barrels per day (Dudley, 2016). This dependency on fossil fuels makes the country more susceptible to an energy crisis with an insecure electricity supply, which is dangerous to the economy. South Africa is well-endowed with sustainable and renewable energy resources, notably solar energy (Pegels, 2010). Nonetheless, it still relies on fossil fuels as a primary energy source, with coal providing 88.2 million tonnes oil equivalent and oil 27 million tonnes oil equivalent of the fossil fuel based energy supply and renewable energy contributing only 0.1 million tonnes oil equivalent of the primary energy supply (Fig 1.7).

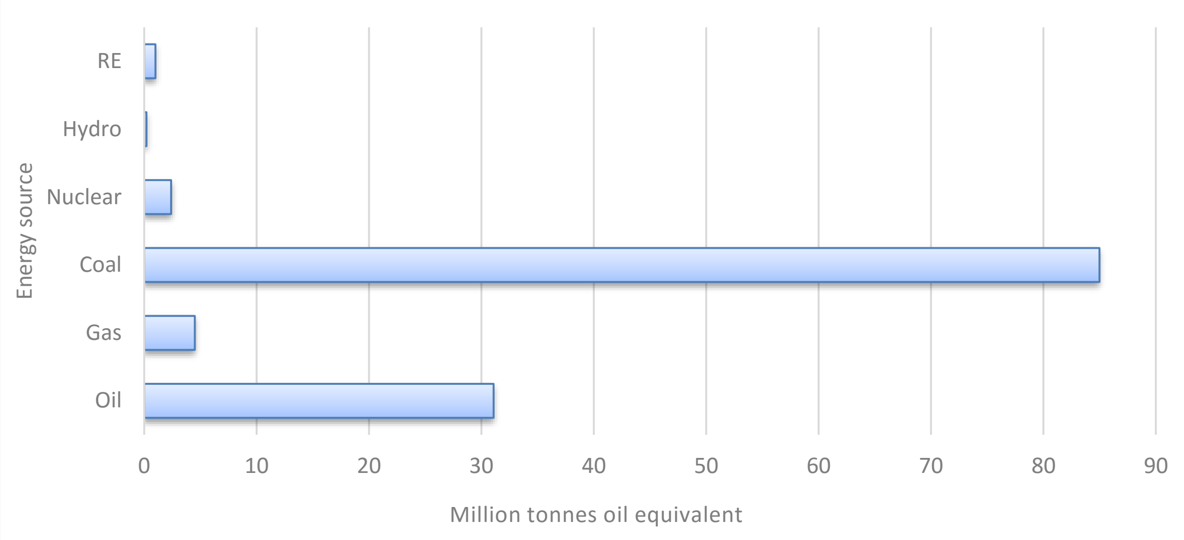

Figure 1.7: South African energy consumption by fuel in 2015 (Source: Dudley, 2016)

The newly constructed Kusile and Mepudi coal-fired power stations will contribute to electricity provision in the short to medium term; however, they are coal-fired power stations, and this resource has a limited lifespan. The construction of these power stations does not solve the energy security issue, though.

1.5.3 Existing gaps in solar PV and hybrid research in South Africa

Although some research on solar energy such as PV, Concentrated Solar Power (CSP), Solar Water Heating (SWH) has been carried out in South Africa, no single study has been carried out that identifies and determines the potential of solar PV using a set of pre-defined critical parameters in different scenarios. Moreover, no study that has investigated the household energy use patterns in different provinces across various income categories. Then, the aim of the project is to identify and assess solar PV using an appropriate set of parameters in each province, employing specific and suitable software to analyse the potential. Moreover, the technical potential for the different types of solar PV technology has not yet been researched in South Africa, taking into consideration the efficiency of the technologies (crystalline and thin film) and degradation rate.

The existing studies in the field of hybrid energy have mainly focused on economic and financial viability using the Hybrid Optimisation Model for Electric Renewables (HOMER) GIS software. One criticism about this literature is that studies are rather insufficient and biased towards the quantification of solar PV potential and the hybrid energy system. Moreover, there is inconsistency in identifying hybrid energy systems; some studies use methods that are inadequate and lack key parameters input that determines the viability of hybrid energy system in different provinces. Moreover, energy consumption pattern at a household level (for different income household) for grid-connected electricity and off-grid solar PV has not been done in South Africa. Thus, this research seeks to obtain answers to these questions.

One criticism of much of the literature regarding the identification of the potential of solar PV and hybrid energy system is that the software used relies almost entirely on solar irradiance data, yet there are other equally important factors and parameters that should be considered in modelling solar PV and hybrid energy system potential. All the studies reviewed so far have, however, suffered from the fact that the software used is unable to provide different scenarios informed by weightings on different parameters to create an enabling environment for informed decision-making. The methods used in previous research are as follows:

- ***Potential of concentrated solar power (CSP): Fluri, 2009)***

Fluri (2009) measured the potential for CSP using solar radiation data derived from the satellite imagery of the United States National Renewable Energy Laboratory (NREL) and the United States National Aeronautics and Space Administration (NASA) and appropriate GIS software analysis.

The parameters used in this study were:

- Proximity to the transmission lines (km);
- Solar radiation, available area (km^2);
- Land use profile and slope; and
- Water availability.

Although this was for CSP and not PV, this method relies heavily on solar radiation and lacks crucial parameters such as electrification backlog, electricity consumption and population, which are key in determining sites that are more suitable for CSP. Moreover, it does not provide more than one scenario as options for decision-making.

- ***Redrawing the solar map of South Africa for photovoltaic applications: Munzhedzi and Sebitosi, 2009***

This research used the Meteonorm and PVDesignPro software packages to redraw the solar map of South Africa for PV application. The rationale was to map areas and locations where there is good solar PV application (Munzhedzi and Sebitosi, 2009). The following software was used:

Meteonorm: This software takes in a location as a set of coordinates of latitude and longitude and generates climate data for the selected or preferred locations.

PVDesignPro: This is a solar design software package that simulates solar PV system operation on an hourly basis for a year, based on a user-selected climate and system design. The parameters that Meteonorm software considered relevant for the performance of solar PV were generated at hourly intervals for the duration of a year, namely dry-bulb temperature/air temperature, wet-bulb temperature, dew-point temperature, wind direction, wind speed, global radiation, diffuse radiation, cloud cover fraction and relative humidity.

All input parameters are entered into the software, the only variable being climate, and the solar fraction is calculated. The fraction gives an indication of the percentage of load that would be supplied by a specified number of panels in a specific location. Hence, maps were generated indicating the solar PV potential in a specific location. Again, this software is good to map solar PV performance for a particular area to give economic and market potential and it further provides sites with good theoretical solar PV potential. However, it omits critical parameters such as land space, which is not modelled, and does not give different scenarios for informed decision-making.

- ***Economic analysis of PV/diesel hybrid power systems in different climatic zones of South Africa: Dekker et al., 2012***

This research modelled the economic feasibility of a hybrid energy system using climate data (kWh/m^2/day) to predict certain outputs of the system based in different geographical locations around South Africa. Moreover, the average/annual load profile of a typical residential house is used to obtain the correct size and type of solar PV modules, charge controller, batteries and converter and the size of the diesel generator to meet the load.

The software used for Dekker *at al. (2012)* study was the HOMER GIS in different climatic zones of South Africa. The HOMER is crucial for the design of a hybrid renewable energy system in a particular location especially comparison of different simulations around energy yield and economic feasibility, but not for determining potential in a particular location. HOMER GIS is mainly a step forward after determining the renewable energy potential in a particular province. It is then used to design a suitable system that would be economically and financially viable in a particular area.

The technical potential, which usually considers the type of PV technology as well as its efficiency, has not been investigated in South Africa, though Dekker *et al.* 2012 touched slightly on the PV technology, but did not investigate deeper, as the HOMER software focuses on economic and financial aspects of the solar plant. This study modelled solar PV and hybrid potential using the Design Matrix Methods Application software version 1.0 © 2009 by John Dalton (John.Dalton@ncl.ac.uk)[1]. The modelling was based on the following set of key parameters that have not yet been considered simultaneously in any software: Solar radiation, wind energy, electricity tariff, population, land space, electricity consumption and electrification backlog.

Moreover, these parameters were modelled in different weightings and in three different scenarios. This study sought to achieve the following regarding investigation of the solar PV and hybrid potential in South Africa, which previous research studies failed to resolve:

- Investigating and modelling the solar PV potential in different provinces;
- Investigating and modelling the hybrid energy potential in the three coastal provinces;
- Calculating the technical potential using two types of solar PV technology (thin-film and crystalline modules) and assessing the variation in order to determine the technology impact;
- Investigate different household energy pattern from low, middle and high income categories in different provinces; and
- Determining the monthly variation in solar PV output in respect of different seasons.

1.5.4 Significance and opportunities for the study

Solar PV energy offers an opportunity to contribute to solving the problem outlined in section 1.5.1 and 1.5.2. Moreover, this research intends to close the gap outlined in section 1.5.3. South Africa's abundant renewable energy sources, solar energy in particular, remain untapped thus far. Solar radiation levels in South Africa are among the highest in the world: average daily solar radiation varies between 4.5 and 7 kWh/m^2 (Banks and Schaffler, 2006; Kusakana, 2014) [Figure 1.8]. Solar PV energy could significantly contribute to the emission reduction in the country, energy security and meeting the renewable energy target. Moreover, it could boost the country's economy.

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[1] John Dalton
Director, Engineering Design Centre, School of Chemical Engineering and Advanced Materials,
Merz Court, University of Newcastle upon Tyne Newcastle upon Tyne, NE1 7RU United Kingdom
Telephone: +44(0)191 208 8556

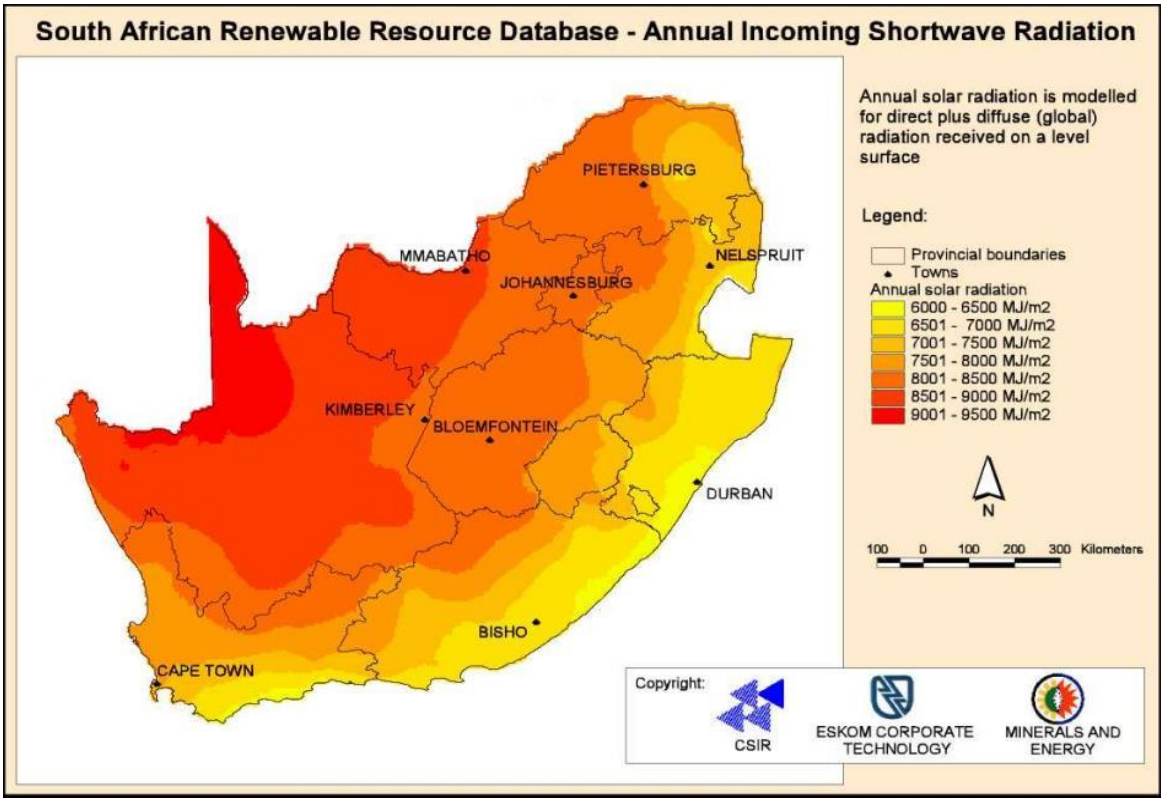


Figure 1.8: Solar energy resource database (Source: Department of Minerals and Energy *et al.,* 2001)

Jain (2010) and Clerici (2013) estimated that most parts of South Africa receive in excess of 2 500 hours of sunshine per year, so it has average solar radiation levels ranging from 4.5 to 6.5 kWh/m^2/day and has an annual 24-hour global solar radiation average of about 220 W/m^2. The country is considered to have high solar energy potential (Figure 1.8).

The barriers for the PV uptake in some sectors such as residential is because of the absence of Renewable Energy Feed-in-Tariff (REFIT) in South Africa. The middle and high income may afford to install solar PV for own use, however, it has to be off-grid as they would not be able to inject the surplus power back in a grid connected environment. South African government has opted for the competitive bidding policy, which is mostly suitable for the generators.

1.6 Objectives of the study

1.6.1 General objective

To investigate and establish the potential of solar PV energy for both off-grid and grid-connected application across South Africa and to explore the viability of the hybrid energy system in coastal areas.

1.6.2 Specific objectives

- To investigate and determine the solar PV potential and seasonal variation across South Africa;
- To investigate the viability of hybrid energy system application in the coastal provinces;
- To investigate the households' energy use pattern in different provinces; and
- To investigate the barriers hampering solar PV and hybrid application and associated risks.

1.7 Research questions

- Which provinces in South Africa have good solar PV potential?
- What is the total technical potential of solar PV in South Africa?
- To what extent can the technical potential contribute to GHG emissions reduction in South Africa?
- What could the contribution of solar PV energy be in the South African renewable energy target?
- Can the off-grid solar PV and hybrid energy systems provide a sustainable solution for communities that are not electrified and reduce the effective electrification backlog in South Africa?
- What are the impediments facing South African solar PV and hybrid energy system development and how can they be addressed?
- What are the solar PV plant development risks and how can these be minimised, prevented and avoided (mitigating measures)?
- What is the household energy utilization pattern in different provinces and how does this impact on renewable energy take-up?

1.8 Thesis layout

This thesis contains seven chapters that are structured as follows:

Chapter 1: Introduction

It contains the background information and introductory remarks on renewable energy, solar PV and hybrid energy in particular, different types of solar PV energy and their definitions. It describes the rationale and significance of the study. This chapter further comments on what previous studies have stated regarding the identification of solar PV energy and gaps in the field. The research objectives and questions are outlined in this chapter.

Chapter 2: Literature review

This chapter gives an overview of the current literature on renewable energy, solar energy and the application of grid-connected, stand-alone systems, as well as the hybrid energy system in developing countries. The chapter includes literature on the rationale and factors influencing the use of solar energy and the trend of solar PV energy from a global, continental (Africa), regional (Southern Africa) and South African perspective. This chapter identifies the potential of solar PV energy and comments on various types of potential, discussing the findings of other research done in South Africa and elaborating critically on the implications. Different types of solar PV barriers are reviewed.

Chapter 3: Research methodology

This chapter outlines the type of research method used and the sampling techniques employed for primary and secondary data. Furthermore, the four sectors from which data was collected are discussed in this chapter. This chapter further elaborates on the quantitative data method for secondary data, the modelling and software used as well as the *‘optioneering’* technique for the analysis of data.

Chapter 4: Potential of solar PV energy application in South Africa

This chapter presents the solar PV energy potential results in three different scenarios, consequent to the modelling process. The technical potential was presented using two types of solar PV technologies. Moreover, the seasonal and monthly variation of solar PV output was discussed and analysed. The discussion section covers results found from other research; comparison, contrast and explanation are provided. The potential contribution of solar PV energy in the total energy mix in South Africa is discussed.

Chapter 5: Potential of hybrid energy system application in the coastal provinces

This chapter presents the hybrid energy potential in the three coastal provinces. The results are presented in three scenarios, which are compared and discussed. The hybrid energy system experience and lessons learnt in South Africa are discussed in this chapter. Grid-connected and off-grid household energy consumption figures are compared. The villages identified for the hybrid energy system are discussed in this chapter.

Chapter 6: Households energy utilization patterns in different provinces

This chapter investigates the household energy use in different income classes across the provinces. The chapter identifies to what extent does household income determine energy consumption, and the level of solar PV awareness and willingness to utilize solar PV in different income households.

Chapter 7: Barriers and opportunities in the solar PV and hybrid energy sector in South Africa

This chapter presents the existing barriers on the development and growth of solar PV and hybrid systems in South Africa. The barriers in four sectors are discussed (government, solar PV installers and distributors, IPPs and community members). This chapter also analyses the risks associated with the development of solar PV generation and opportunities for the development of hybrid energy systems.

Chapter 8: Conclusion and recommendations

This chapter summarises the key findings and elaborates on energy implications in the short, medium and long term for South Africa. Various recommendations are made on the development and growth of solar PV and hybrid systems, taking into consideration critical aspects of the technologies and parameters.

References

This section contains a list of references used in the thesis

Appendices

This section contains information that was used for data collection and the hybrid energy experience in South Africa

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter reviews PV energy technologies and hybrid energy system applications in different parts of the world. Various research projects undertaken in different regions particularly Europe, Asia and Southern Africa are reviewed and; their strengths and weaknesses are analysed. The key factors for the successful implementation of renewable energy projects, such as the regulatory frameworks, policies and financial mechanisms in different countries, are reviewed and evaluated. The different techniques and methods used to quantify and measure the potential of solar PV systems are investigated and critically analysed. The potential was found to differ from region to region, depending on the solar irradiance (kWh/m^2/day), among other parameters, in a particular area.

Energy resources are categorised into fossil fuels, non-fossil fuels (nuclear) and renewables. Different types of technologies carriers are investigated, their merits and demerits are analysed and reviewed. Some solar PV potential types were found to be common worldwide; however, other types were abundant in specific regions such as in developing countries, and unfortunately remained largely untapped thus far. Furthermore, solar PV challenges and barriers are investigated and examined. There are common barriers that persist in developing countries, such as finance and the regulatory framework. Others are prominent in both developing and developed countries.

2.2 Fossil fuel energy resources

There is rapid growth in global energy supply and demand. The investment in the energy sector reached US$1600 billion between 2012 and 2013. This investment is needed to satisfy the global energy needs, growth and demand (Van der Hoeven, 2013). There is consistent and steady growth in global energy requirements. Since energy demand increases with population growth. Global electricity consumption reached 21000 TWh by 2014, and growth of 37% is projected by 2040 (Ashby, 2015;

Birol, 2014). Consequently, global primary energy consumption increased by 2.3% in 2013 alone, an acceleration of at least 1.8% over 2012 (Dudley, 2014). The consumption and production of electricity increased for all fuel types, reaching record levels for every fuel type except nuclear power over the past years; for each of the fossil fuels, global consumption rose more rapidly than production (Dudley, 2015). Clearly, it is of serious concern when consumption grows faster than production; there is high medium to long-term energy risk. The worldwide average annual growth rate in energy demand reached 4.4%, whereas that of power consumption reached 5.2% from 1989 to 2009 (Van der Hoeven, 2013). Energy demand in sub-Saharan Africa rose by approximately 45% from 2000 to 2012, which accounts for 4% of the world total (Birol, 2014a). Access to electricity remains low in many populations, with a ratio of two out of every three not having access in sub-Saharan Africa (Birol, 2014).

Population growth has significant implications for the development of the energy sector in Africa. The growth is rapid; the population increased by 270 million people from 2000 to around 940 million in 2013, for that reason it is expected to reach one billion before 2020 (Birol, 2014a). This has direct impact on energy demand and supply on the continent. This trend has continued over the past years and is expected to increase over time. In actual terms, energy demand grew faster than electricity generation over the past years in Africa, and this is not sustainable. The question would be what is the main driver behind such rapid increase of energy consumption? What are the swift interventions needed to neutralise and/or slow down consumption and increase production?

Approximately 80% of the world's energy demand is satisfied by fossil fuel (Sahu, 2015). In 2015, 85% of the global primary energy source was met by fossil fuels (Figure 2.1). Fossil fuels remain at the heart of global energy use (Van der Hoeven, 2013). Fossil fuels are predicted to account for about 89% of primary energy supply by 2025 (Yue and Huang, 2011). This prediction could be a reality, particularly considering the current rapid increase in energy consumption; however, in view of extensive research into alternative energy sources and the climate change concerns and emission reduction targets and commitments, the production of electricity from fossil fuels may slow down and may not reach 89% by 2025. Consumption will most certainly increase. According to REN21 (2013) fossil fuels contributed 82% of the total global primary energy supply resources, while renewable energy (excluding hydro energy) contributed only 11% in 2011.

In 2015 world energy consumption reached over 13147 million tonnes oil equivalent and 4331 million tonnes oil equivalent came from coal resources; the renewable sources, excluding hydro energy, contributed 279 million tonnes oil equivalent (Dudley, 2016). Hence, fossil fuels are still dominating the total global energy shares. Coal is the world's largest source of electricity, accounting for around 40% of global electricity production (Sahu, 2015). It is the world's second largest source of primary energy after oil (Figure 2.1).

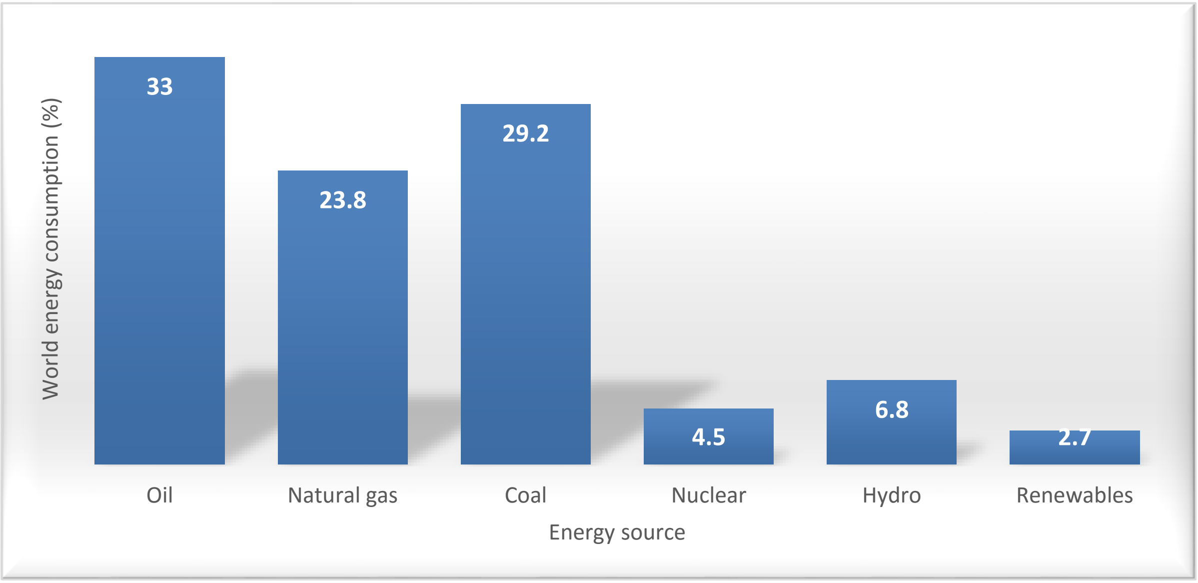


Figure 2.1: World Energy consumption by fuel, 2015 (Source: Dudley, 2016)

The energy sector is at the heart of future development in Africa. However, the continent remains one of the poorest in the world. The African continent is large and is approximately the size of the USA, China, India and Europe combined. It currently has more than sufficient energy resources to meet domestic needs, yet more than two-thirds of its population does not have access to modern energy (Birol, 2014a). The section below outlines the characteristics, availability, scarcity and viability of the energy resources.

2.2.1 Coal

Coal remains central to the global energy system (Clerici, 2013). Most of the world's coal resources are well monitored and recorded. Europe has the largest coal reserves of 310538 million tonnes with most reserves in Russia, followed by Asia with 288328 million tonnes (Dudley, 2016). Africa and the Middle East have 32936 million tonnes of coal reserves (Figure 2.2). In Africa, more than 90% of coal resources come from South Africa, which produces 30156 million tonnes of anthracite and bituminous coal, followed by Zimbabwe, with 502 million at the end of 2015 (Dudley, 2016).

The proven world coal reserves in 2013 was reported to be sufficient to meet 113 years of global production, which is by far the largest ratio for any fossil fuel (Clerici, 2013). Clerici (2013) estimated that 869 billion tonnes of coal reserves, which is based on 2012 proved reserves, should last for around 115 years, significantly longer than conventional oil and gas reserves. Thus, as coal is predicted to meet the global energy need for a period of 113-115 years, this may mean that coal reserves are depleted by 2130, which is of concern, taking into consideration its current massive global economic contribution. However, taking into account the R/P ratio, coal may last longer than the predicted period.

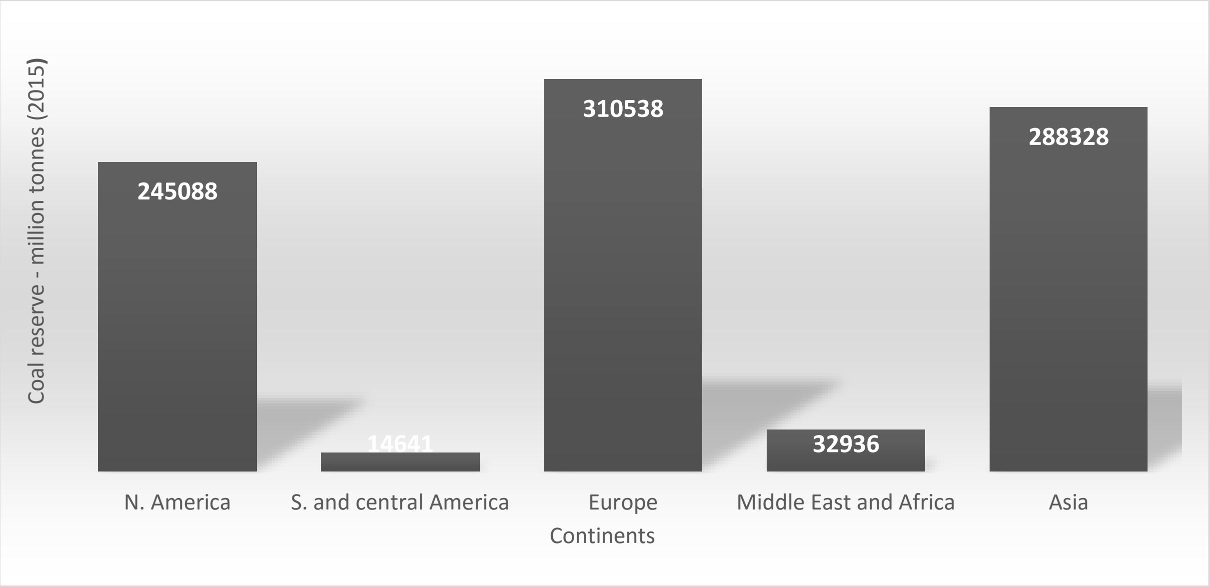


Figure 2.2: Proven coal reserves at end 2015 (Millions of tonnes) [Source: Dudley, 2016]

Coal remains an important source of energy that has significant contribution to electricity supply worldwide, in spite its well-known negative environmental credentials. According to the International Energy Agency (2014), the five largest coal producers and users are China, the USA, India, Indonesia and Australia, with South Africa being the seventh after Russia (Table 2.1). With regard to production, China was the largest coal producer in 2015 with 1827 million tonnes oil equivalent more than any other country across the word (Dudley, 2016).

Since 2000, global coal consumption has grown faster than consumption of any other fuel at 4.9% per year (Clerici, 2013). In 2013, coal consumption grew by 3%, which was below the 10-year average of 3.9%. However, growth in its use is still the fastest of any fossil fuel (Dudley, 2014). Furthermore, consumption decreased by 2% on average in all Organisation for Economic Co-operation and Development (OECD) countries. This may be because of the growth in alternative energy sources in the OECD countries, notably solar PV and wind energy. Nonetheless, outside the OECD, coal consumption increased by 8.6%, predominantly owing to demand for greater electricity generation in China and India (Clerici, 2013). Another factor that contributed to this massive growth is the substantial coal reserves in Asia.

Table 2.1: Top ten hard coal producer countries (Source: International Energy Agency, 2014)

Country	Production (million tonnes)	World’s production (%)
China	3561	45.5
USA	904	11.6
India	613	7.8
Indonesia	489	6.3
Australia	459	5.9
Russian Federation	347	4.4
South Africa	256	3.3
Germany	191	2.4
Poland	143	1.8
Kazakhstan	120	1.5
Rest of the world	740	9.5

The binding commitments that are made in the annual Conference of Parties (COP) meetings to reduce carbon emissions and technological development and advancement of alternative energy sources are likely to curb coal utilisation. Therefore, coal utilization is most likely to decrease in the next two decades. South Africa is a case in point with two coal fired-power stations that will account for 9000 MW combined capacity, which are expected to be in full operation by 2018. However, a commitment has been made that these will be the last two coal-fired power stations to be constructed in the country, future electricity demand would be met with other forms of energy such as nuclear.

Despite this, coal is anticipated to continue meeting energy demands in the foreseeable future in South Africa. The production and consumption of coal has increased over the years, therefore most South African primary energy is provided by coal (Witi and Stevens, 2014). Nonetheless, consumption is relatively constant while production has shown slight increase in 2014 and 2015 (Figure 2.3).

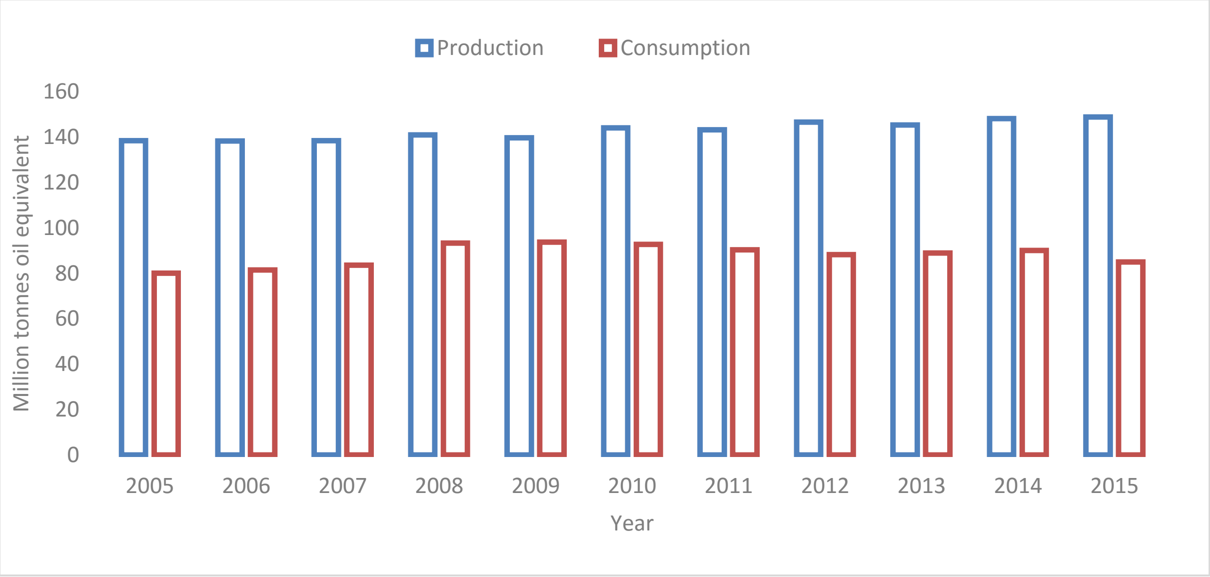


Figure 2.3: South African coal production and consumption (Source: Dudley, 2016)

Dependency on coal may have severe consequences for future electricity generation. Coal is not a sustainable solution for electricity generation in South Africa. While coal boosts economic development and foreign revenue due to export, it is considered wise to explore alternative and sustainable energy resources (solar, wind, hydropower and biomass) that will contribute equally to socio-economic development in South Africa.

2.2.2 Crude oil

According to Jain (2010), crude oil is a naturally occurring mixture consisting predominantly of hydrocarbons that exist in a liquid phase in natural underground reservoirs. It is recoverable as liquids at typical atmospheric conditions of pressure and temperature. Oil plays an important role in the global energy balance, accounting for 32% of energy consumption in 2010 (Clerici, 2013).

Jain (2010) concluded that it is unknown what the recoverable quantities of oil and gas resources are, or to what extent the demand will grow over time and depends on human actions. The crude oil resource is in great demand and it is finite. Moreover, it is known that 100% of the oil or gas in the ground cannot be recovered and that the actual percentage will depend on the recovery processes applied. Therefore, in view of all these uncertainties about the availability of crude oil, there is a need for the development of alternative energy sources, since the uncertainties reflect the high degree of energy risk that the world is running.

Africa is the continent with second-least oil reserves, with 129 thousand million barrels after Asia with 42 thousand million barrels (Figure 2.4). The majority of this reserve mainly comes from Nigeria, which has substantial oil resources. However, regulatory uncertainties and militant activities that go along with oil theft in the Niger Delta prevent investment and production (Birol, 2014a). The Middle East has the largest proven oil reserves: ~800 thousand million barrels at the end of 2015 (Dudley, 2016).

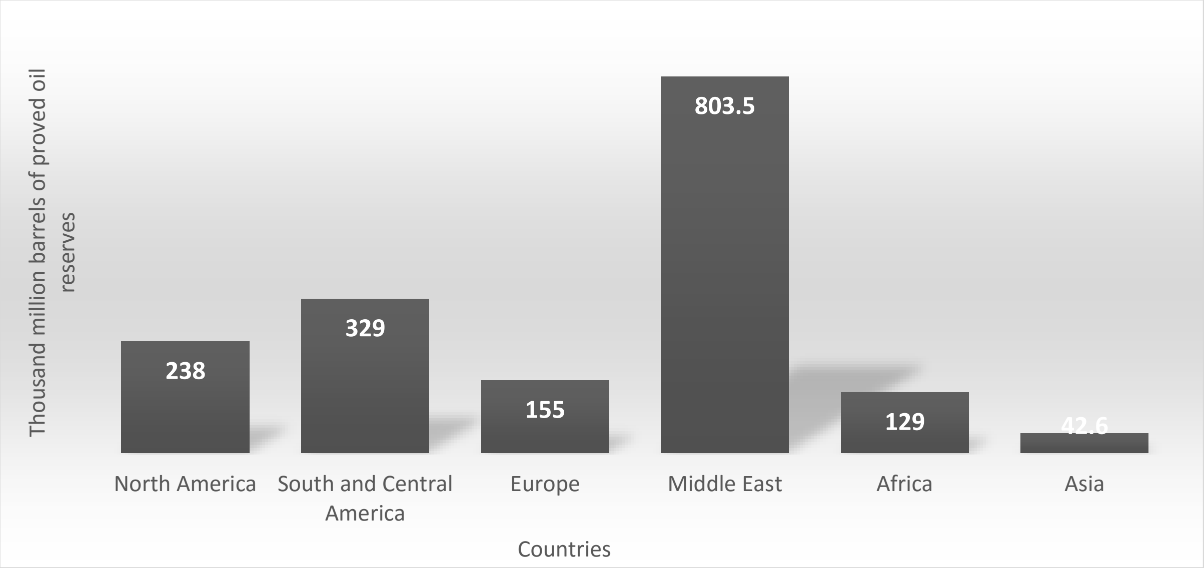


Figure 2.4: Thousand millions of barrels of proven oil reserves per continent at the end of 2013 (Source: Dudley, 2016)

Africa consumed 3866 thousand barrels of oil daily in 2015 (Dudley, 2017). The consumption pattern in the three largest oil consumers (Egypt, South Africa and Algeria) is increasing over the years (Figure 2.5). South Africa is the second highest oil consumer in the continent with 560 thousand barrels daily, followed by Algeria that consumed 412 thousand barrels daily in 2016 (Dudley, 2017). Egypt was the biggest consumer with 853 thousand barrels daily (Dudley, 2017).

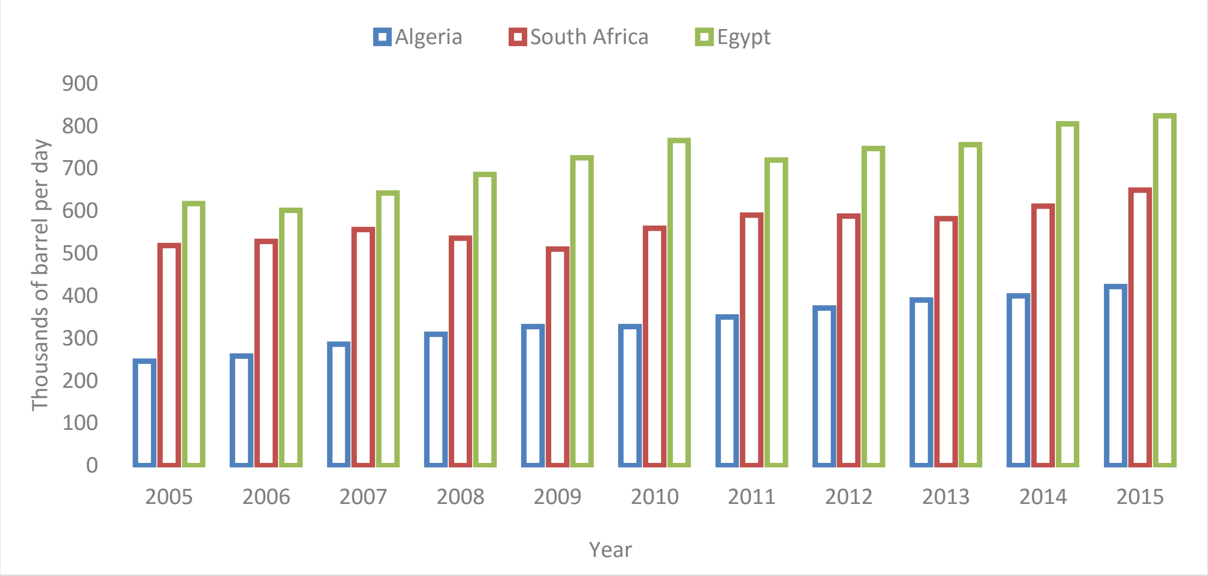


Figure 2.5: Oil consumption in thousands of barrels per day (Source: Dudley, 2016)

Crude oil and natural gas are scarce resources in South Africa and are mainly imported from other countries. South Africa does not have oil resources and hence imports a large amount of this resource from the Middle East. This becomes expensive for the country, with petrol and jet fuel prices that often increase frequently, especially when the consumption pattern is increasing every year. Consequently, crude oil is not a sustainable and future energy option for South Africa. Moreover, it is unknown how long the reserves of this resource will last.

2.2.3 Natural gas

Natural gas is a mixture of hydrocarbons, of which by far the largest component is the simplest hydrocarbon, methane (CH_4). Methane is an odourless, colourless, non-toxic gas that is lighter than air (Clerici, 2013). The world's largest reserves of natural gas are held by the Russian Federation, Iran and Qatar (Dudley, 2016). The natural gas reserves are sufficiently abundant to cover global gas demand for many decades (Jain, 2010). Technological development and higher energy prices have increased the volumes of economic reserves, as well as the diversification of sources.

Clerici (2013) reported that proven natural gas reserves were recorded in all regions across the globe, with the highest volumes in the Middle East (41%), Europe, including the Russian Federation (27%), and Asia (15%). Moreover, Dudley (2016) claimed that proven natural gas reserves at the end of 2015 stood at 186.9 trillion cubic metres (tcm), which is anticipated to meet the energy demand for the next 55 years. The Middle East has the highest reserves with 80 tcm, followed by Europe with 56.8 tcm (Figure 2.6). At a country level, Iran is the highest with 34 tcm followed by Russia with 32 tcm; the two countries hold the largest proven reserves (Dudley, 2016). Africa holds about 14.1 tcm of proven natural gas reserves (Figure 2.6).

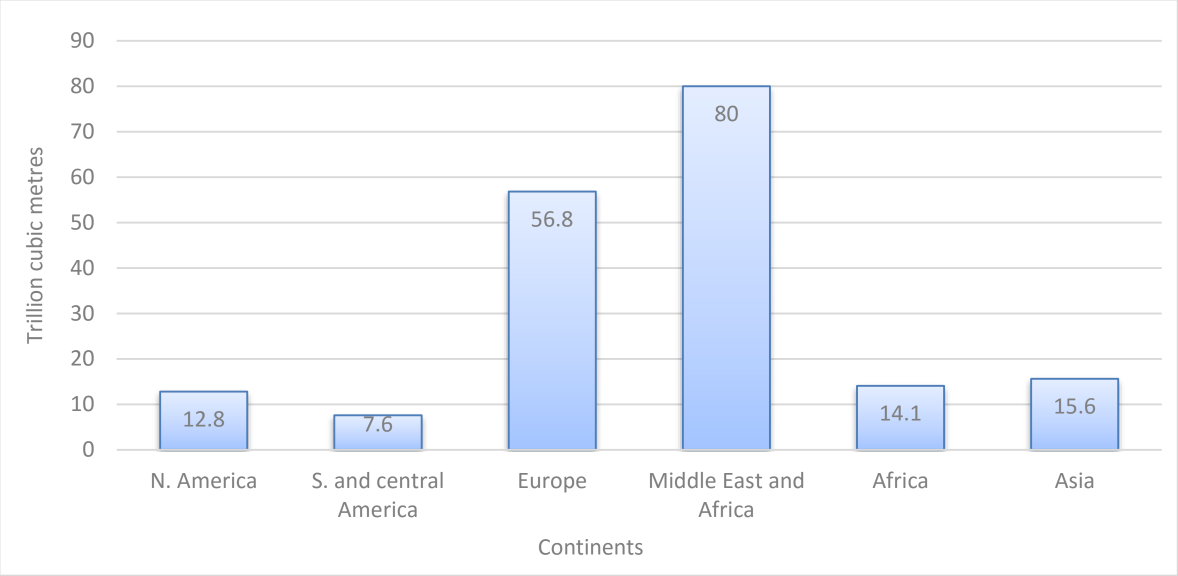


Figure 2.6: World natural proved gas reserves at the end of 2013 (Source: Dudley, 2016)

Just like crude oil, Africa produced the second least amount of natural gas globally, which was 211 billion cubic metres in 2015 (Dudley, 2016). Much of the gas is produced and consumed in Nigeria. Nonetheless, much of the attention regarding implementation of the new gas projects are shifting to the east coast of Africa (Tanzania) and to the massive offshore discoveries in the southern part of Africa in Mozambique (Birol, 2014a). Europe produced the highest quantity of natural gas (989.8 billion cubic metres) in 2015, with almost half (573.3 billion cubic metres) from Russia; the second highest natural gas producer was North America with 984 billion cubic metres (Dudley, 2016).

South Africa is the third (on the continent) largest natural gas consumer, with 5 billion cubic metres, after Egypt and Algeria that consumed 47 and 39 billion cubic metres respectively in 2012 (Dudley, 2016). Africa has relatively low natural gas reserves and hence it is not a sustainable source of energy for South Africa, where most of the natural gas is imported at high cost. South Africa imported about 2.9 billion cubic metres of natural gas from other African countries in 2013 by pipeline (Dudley, 2013). The implication of such high dependence on the import of fuel is high import cost, political pressure and many other factors that put the country at high energy risk.

Fracking is the process of injecting liquid at high pressure into subterranean rocks, boreholes, in order to force open existing fissures and extract oil or gas (Baker, 2014). The Karoo in the Western Cape of South Africa is the focus of future hydraulic fracturing. The estimates on the gas in the Karoo vary. However, the Energy Information Administration (EIA) estimating reserves of 390 trillion cubic feet, which would make South Africa the 8th largest reserve in the world. These figures were nonetheless, based on desktop research and would only be refined through an extensive exploration programme (Blaine, 2014). The government of South Africa proposed to pursue fracking, nevertheless, the environmental non-profit organisations objected the proposal citing environmental damages such as water contamination and pollution consequent to fracking. Therefore, fracking is regarded as high environmental risk in South Africa.

2.2.4 Nuclear energy

Nuclear energy is used to produce electricity all over the world. Nuclear power generation is the harnessing of the energy created by a nuclear reaction, uranium is the source of power, which comes through a process known as fission (Eskom, 2015). The nuclear industry has grown slowly over the past decades to an annual output of 2600 TWh in the mid-2000, despite the two nuclear incidents including Chernobyl (former Ukrainian Soviet Socialist Republic) and Fukushima in Japan (Clerici, 2013). Nuclear energy contributes 2.6% of the global energy sector by 2013, with Europe and North America being the highest continents leading in the nuclear industry (REN21, 2014; Dudley, 2016). In a global scale, Europe is the highest nuclear consuming continent, followed by North America. However, Africa is the second lowest nuclear consuming continent with 2.4 million tonnes oil equivalent by 2015 (Figure 2.7).

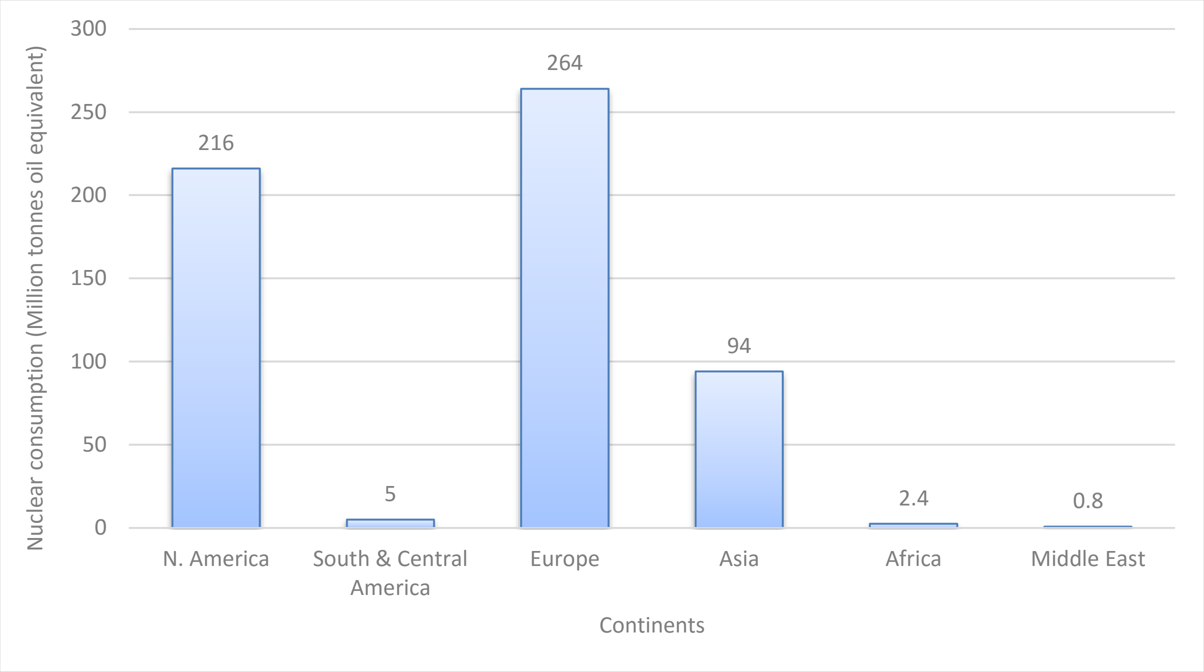


Figure 2.7: Continental nuclear energy consumption (Source: Dudley, 2016)

The US is the highest country in the world that consume approximately 189.9 million tonnes oil equivalent in 2015, followed by France with 99 million tonnes oil equivalent (Figure 2.8). Africa has consumed 2.4 million tonnes oil equivalent, which is mainly South Africa in the continent (Dudley, 2016).

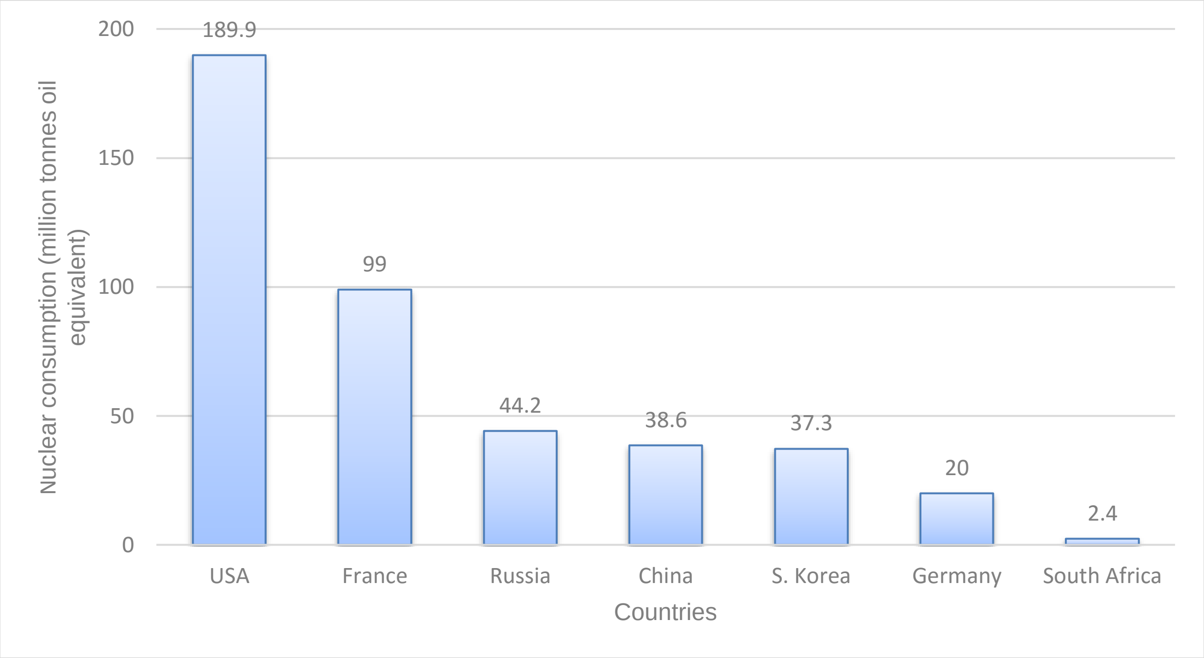


Figure 2.8: Nuclear energy consumption in different countries (Source: Dudley, 2016)

Nuclear energy is highly efficient, and a clean source of electricity without CO_2 emission production. However, nuclear electricity generation has negative effects such as high capital cost and rising compliance costs, public concerns regarding its operations and final waste disposal and liabilities in case of accidents (Clerici, 2013). In South Africa, 1860 MW of electricity production capacity comes from Nuclear energy in Koeberg power station. Due to the risks and capital costs that come with nuclear energy, plans to expand Keoberg or building more nuclear power stations in South Africa are strongly objected by the opposition political parties, despite the government proposal to build a second nuclear power station.

2.3 Renewable energy resources

Renewable energy harnesses naturally occurring non-depleting energy sources, including solar, wind, biomass, hydro, tidal, wave, ocean current and geothermal sources, to produce electricity, liquid fuel, heat or a combination of these energy types (DME, 2003). The supply of sustainable energy is anticipated to remain the main challenge that humankind faces in the foreseeable future, particularly because of the need to address energy security matters and environmental concerns such as climate change, pollution and environmental degradation (Clerici, 2013). However, the steady increase in hydropower energy and rapid expansion of wind and solar power have paved the way for renewable energy to be a vital part of the global energy mix (Birol, 2012).

2.3.1 Global overview

Renewable energy technologies provided an estimated 19.2% of global final energy consumption in 2014 (Figure 2.9). Out of the total share of 19.2%, traditional biomass, which is currently used primarily for cooking and heating in remote and rural areas of developing countries, accounted for about 8.9%, and the modern renewable sources increased their share to approximately 10.3% (REN21, 2016). In the 10.3% of modern renewable sources, biomass accounted for 4.2%, hydropower for 3.9%, wind and solar power for 1.5% and biofuel with 0.8 (REN21, 2016).

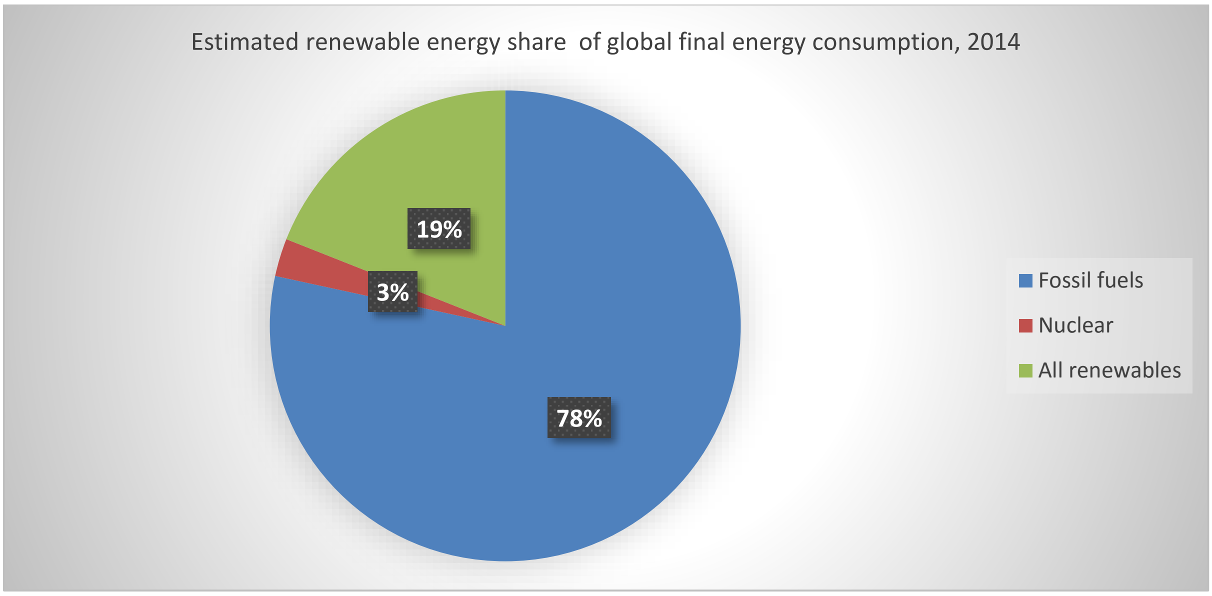


Figure 2.9: Global estimated renewable energy consumption in 2012 (Source: REN21, 2014 and REN21, 2015)

Africa’s grid-connected power generation capacity was 90 GW in 2012, almost half of this capacity (40 GW) being in South Africa alone. Furthermore, 45% of Africa’s total capacity comes from coal (mainly in South Africa where almost 90% of its electricity is generated from coal), 22% comes from hydro power, which is abundant in the Democratic Republic of Congo, 17% from oil and 14% from gas, which is mainly found in Nigeria, Angola and Mozambique (Birol, 2014a). Thus, there is limited grid-connected renewable energy in Africa. Many of the off-grid and hybrid mini-grid projects that involve high usage of diesel generators are in central Africa, for example in Mali (Franz *et al.,* 2014).

Solar PV energy had the highest annual growth rate in 2015 compared to other renewable energy technologies. It grew by 38% in 2015 (REN21, 2016). Geothermal energy had the lowest growth with only 2.4% (Figure 2.10). For that reason, solar PV energy is the most favourable renewable energy source across the globe. Nevertheless, hydro and onshore wind may be cheaper, depending on site. Many developing nations intend to grow the renewable energy sector. In 2011, renewable energy contributed around 8% of the Chinese total energy consumption. Nevertheless, the Chinese government aims to increase its renewable energy target to 15% by 2020, with solar energy envisaged to play a crucial role in achieving the target (Fang and Li, 2013). Commitment on this target has been witnessed when China generates 39.2

TWh of electricity from renewables in 2015, which is up about 57% over 2014 (REN21, 2016).

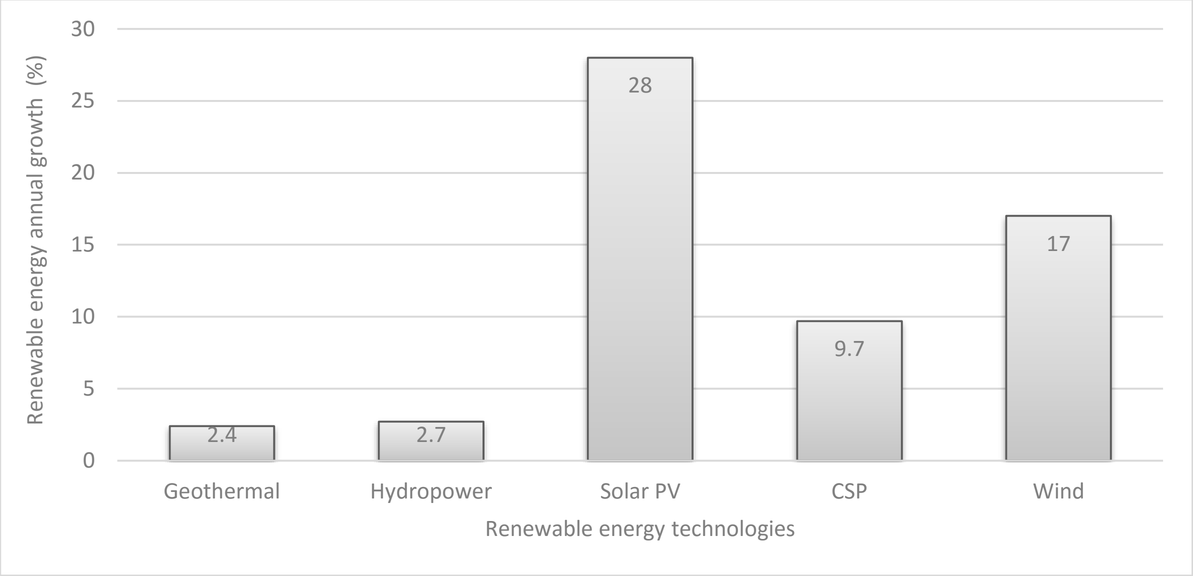


Figure 2.10: Annual renewable energy growth rate in 2015 (Source: REN21, 2016)

Solar PV is seen as having good potential and ability to transform energy spectrum of many countries across the globe. The 28% annual growth rate in 2015 presents an opportunity for further growth in the solar PV industry for many more years to come. Moreover, the continued PV price reduction and improved energy module efficiency are expected to be key in the viability of solar energy development and growth.

2.3.2 South African overview

South Africa is the second largest economy after Nigeria on the continent (Birol, 2014a). The South African energy utilization pattern and sources have been explained in detail in Chapter 1 (section 1.5.2, figure 1.7). The high solar irradiance suggests that solar PV technology can have a major impact and potentially be a competitive energy source in South Africa (Makrides *et al.,* 2010).

2.3.2.1 Renewable energy technologies

- **Hydropower**

The global hydroelectric output grew by 2.4% in 2015, which the top countries being China, Brazil, the United States, Canada, Russia, India and Norway, that together accounted for about 63% of global installed capacity by the end of 2015 (Dudley, 2016). An estimated 28 GW of new hydropower capacity was commissioned in 2015, increasing the total global capacity by about 4% to approximately 1064 GW (REN21, 2016). China alone, commissioned 16 GW of new hydropower projects, other countries such as Brazil, where more than 70% of electricity is generated from hydro, added 2.5 GW in 2015, which led to the year-end total of 91.7 GW (REN21, 2016).

Moreover, there are several countries where hydropower accounts for over 50% of electricity generation; these include Iceland, Canada, Nepal and Mozambique (Clerici, 2013). Some setbacks are drought in other nations; Finland, Norway and Sweden dropped the hydropower output by a combined 14.5% in 2012 (Clerici, 2013). In Africa, the technical hydropower potential is estimated at 283 GW, with more than half of this untapped potential situated in Central and East Africa, particularly in Cameroon, the Congo, Democratic Republic of Congo and Ethiopia (Birol, 2014a).

South Africa has two conventional hydropower stations and three pumped storage schemes. However, the pumped storage schemes are meant to meet the demand during peak hours; these schemes are the Palmiet, Ingula and Drakensberg pumped storage schemes, which have total capacity of 2732 MW. Drakensberg pumped storage scheme has a rated output of 1000 MW and rated voltage of 420 kV, with an average production of 2041 GWh (Eskom, 2005). Palmiet pumped storage scheme has a rated power output of 400 MW. The Gariep hydroelectric power station has four 90 MW units, which is a total of 360 MW capacity, the average production is 889 GWh. The Van der Kloof hydroelectric power station has an installed capacity of 240 MW, with an average production of 628 GWh.

South Africa is a water-scarce country with relatively low levels of water resources and is susceptible to drought. This means that there is limited hydro potential. The country's Integrated Resource Plan (IRP) has allocated hydropower electricity a capacity of 1143 MW and 1183 MW by respectively 2022 and 2023 as imported hydro power because of the unavailability of internal water resources. Consequently, hydroelectricity is not anticipated to contribute significantly as an alternative power source, rather meeting the peak demand from the pumped water storage schemes.

- **Wind energy**

On a global scale, wind energy generation has grown significantly over the past years. In 2015, 54.4 GW capacity was added, which brought the global total to above 433 GW (REN21, 2016). The annual growth rates of cumulative wind power capacity have averaged 25% since 2008, and the global capacity has increased eightfold over the past decade. It is expected to dominate the growth in renewable energy production in the coming years (Apt, 2015). The global wind capacity has grown from 59 GW in 2005 to 433 GW in 2015 (Figure 2.11).

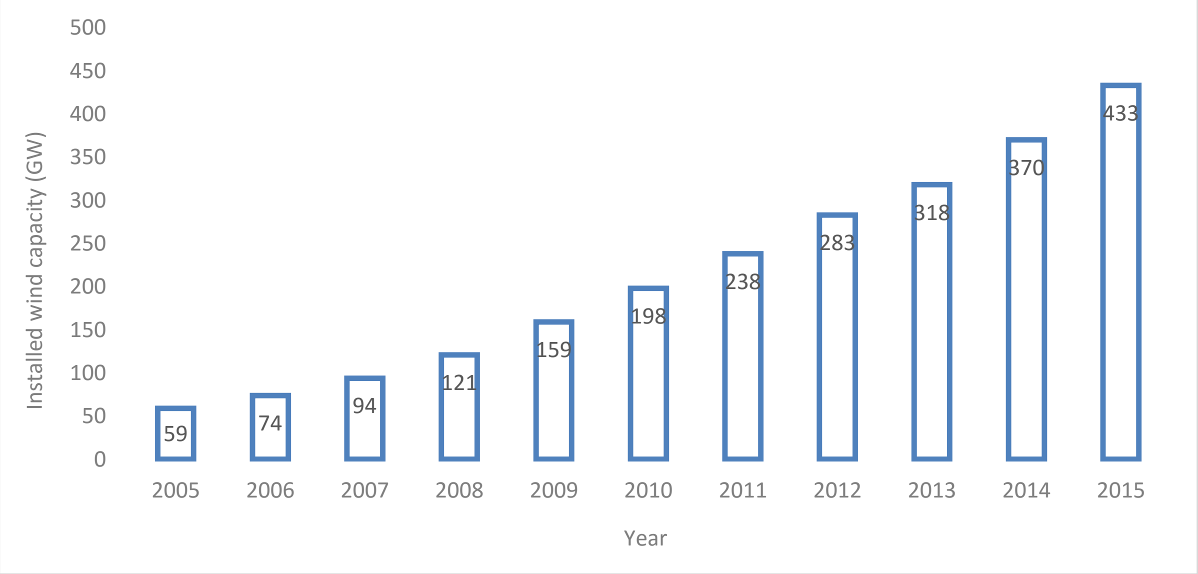


Figure 2.11: Global total wind energy capacity from 2005-2015 (Source: REN21, 2016)

China had the highest growth having installed 30.8 GW wind power capacity in 2015 (REN21, 2016). The top five countries with most wind energy capacity are led by China, with a total of over 145 GW, followed by the USA with 74 GW, Germany with 45 GW, India with 26 GW and Spain with 22 GW (REN21, 2016). However, Denmark, with just over 3 GW, has the highest level per capita, with production that corresponds to about 42% of Danish electricity consumption (Clerici, 2013; REN21, 2016). Ashby (2015) argued that more 20% of electricity generated from solar or wind would require grid scale storage due to variability and fluctuation; the Scandinavian power connection network allows Denmark to source power from Norway or Sweden when wind power is lower than the demand.

Wind energy generation has grown competitively at an international level and is emerging as one of the viable energy options for South Africa. The Sere wind farm in the Western Cape is generating at its full capacity of 100 MW from March 2015 (DOE, 2015). The 5 MW Darling wind farm serves as a good indication that wind energy is one of the viable forms of renewable energy in South Africa. South Africa has registered just over 3 200 MW of wind energy through the REIPPP, 790 MW plant are generating from 2015, and are mainly based in the coastal provinces (Western, Northern and Eastern Cape) [DOE, 2015].

Thus, wind energy is a good option that can supplement other renewable energy technologies in the provision of clean energy in South Africa. Despite the negative environmental effects associated with wind energy such as noise and possible disturbance to wildlife, especially birds, wind remains one of the main sustainable source of energy for South Africa. Wind energy has the potential to contribute a significant amount of energy to satisfy South Africa’s energy needs, especially in the coastal areas of the country. However, the business model for the generators to make a profit can be problematic at current South African electricity prices, in absence of REFIT.

- **Concentrated Solar Power (CSP) energy**

CSP is a renewable energy technology that uses mirrors or lenses to focus and concentrate sunlight into a relatively small area of PV cells that generate electricity (REN21, 2013). CSP has not seen much development compared to other renewable energy technologies. The total global capacity is 3425 MW (REN21, 2014). The USA became the leading market in 2013, adding 375 MW, followed by Spain that added 350 MW in the same year.

South Africa remains one of the most active markets for CSP in Africa. Fluri (2009) found that the Northern Cape Province has good CSP potential; however, lack of water in the Northern Cape is one of the biggest setbacks and likely to channel much of the CSP potential into other provinces of South Africa. CSP has been largely criticised for the fact that it requires many resources that may not be available in most states; it requires significant land and water resources (REN21, 2016). South Africa is a water-scarce country, hence not much potential can be realised from the CSP technology.

South African policies and programmes support CSP development. Through the REIPPP, a total of 600 MW has been registered (DOE, 2015). The first CSP plant was brought online in 2015, which is 100 MW, and an additional 50 MW was commissioned in 2016 (REN21, 2016). The potential of further CSP is limited in South Africa because of its water requirements. Hence, it is not an ideal option for South Africa, but it does supplement other renewable energy resources.

- **Solar thermal energy**

Solar thermal technology contributes significantly to hot water production in many countries and progressively to space heating and cooling (Singh, 2013). Solar thermal technology uses the sun’s energy to generate low-cost and environmentally friendly thermal energy. This energy is used to heat water or other fluids and can also power solar cooling systems. Solar thermal energy differs from solar PV systems, which generate electricity rather than heat.

Globally, most solar thermal systems are used for domestic water heating and they typically meet 40–80% of the demand. There is a trend towards larger domestic water heating systems for sectors such as hotels, schools, multi-family homes and other large complexes. In Jordan, water heating accounts for 20% of the total energy consumption in the residential sector and about 7% of commercial buildings (Ashhab *et al.,* 2013). According to REN21 (2014) the use of solar thermal systems for space heating has been gaining ground over the years, particularly in Central Europe, where 100% solar-heated buildings have been demonstrated (although typically solar power meets 15–30% of the space heating demand).

The bulk of solar heat capacity is in China, which accounted for 86% of the world market and 64% of total capacity in 2012 (REN21, 2014). In 2013, an estimated 57.1 GW (81.6 million m^2) of gross capacity was added worldwide, bringing the operating global solar thermal capacity to about 330 GW. A large number of Australian households heat water with solar thermal systems, with the highest number in New South Wales (REN21, 2014). In the Middle East, Israel leads with a total capacity of about 85% of households using solar water heaters, followed by Jordan and Lebanon. SWH is competitive and has become an attractive industrial sector in China; it has a total share of 22% of China’s hot water heater market (Fang and Li, 2013).

The government of South Africa supports solar thermal technology for water heating in the residential sector as a way to reduce the demand for electricity. The government allocates funding for SWH programmes through a Division of Revenue Act, which is currently rolled out in various municipalities (City of Tshwane, Sol Plaatje and Naledi municipalities). However, the main SWH programme that is unfolding is managed by Eskom. As part of integrated demand management, Eskom is managing the SWH programme, where the residential sector that installs solar water heaters in houses gets a rebate.

Solar thermal technology has been criticised in South Africa for many reasons, such as that it has not been proven that the technology works for 20 years and the low pressure system is prone to damage from storms and hailstones (Donev *et al.,* 2012). Recently (2014 and 2015) South Africa has experienced massive hailstorms that caused severe damage to properties, therefore SWH could be vulnerable to such weather conditions in South Africa. Some systems develop cracks and corrosion as time goes on.

Solar thermal technology plays a crucial role in reducing the demand for energy. Nonetheless, on its own it is insufficient, as people would still need electricity. The SWH is an excellent demand side management control measure and reduces power consumption significantly, as the residential sector of South Africa consumes over 20% of the power production. Further research on how the SWH programme could be rolled out with minimum risks should be conducted, but it is good initiative for South Africa, which enjoys good solar irradiance.

- **Biomass energy**

Biomass consumption continues to increase worldwide for the provision of heat and electricity. Approximately 60% of the total biomass used for energy purposes is traditional biomass. This comprises fuel wood (some converted to charcoal), crop residues and animal dung that is gathered by hand and usually combusted in open fires or inefficient stoves for cooking, heat for dwellings, and some lighting (REN21, 2014). In 2014, biomass accounted for about 10% of global primary energy supply. Almost one in five of the world's population lacks access to modern energy services such as electricity and approximately 2.6 billion people around the world depend on traditional use of biomass for cooking (Van der Hoeven, 2013). Then biomass is an available and affordable source of energy for many nations, especially developing nations.

Most primary biomass used for energy is in solid form and includes charcoal, fuel wood, crop residues (predominantly for traditional heating and cooking), organic municipal solid waste, wood pellets and wood chips (predominantly in modern and/or larger-scale facilities). Biomass is also used to make biogas through pyrolysis and gasification (REN21, 2014). A number of large-scale plants that run on biogas are operating across Asia and Africa, including many for industrial process heat. Biogas is also produced in small, domestic-scale digesters, mainly in developing countries, including China, India, Nepal and Rwanda, and is combusted directly to provide heat for cooking (REN21, 2015).

The South African government supports the biogas projects at a small scale in rural communities that are not electrified, and some industrial companies. However, more work still needs to be done to enable the technology to reach a commercial stage. Gasification and pyrolysis are still in the research phase, with pilot and small-scale projects that have been implemented in some parts of South Africa. Therefore, biogas has not been commercially implemented thus far. Thus, biomass is useful as a source of energy to supplement other renewable sources in the shorter to longer term.

- **Solar photovoltaic energy**

The Clerici (2013) has estimated that oil, gas, coal and nuclear material will provide less than 15% of world energy consumption, while solar thermal and PV sources are anticipated to supply about 70% by 2100. This could be true, particularly taking into account the lifespan of fossil fuel resources. Solar PV is expected to increase its global electricity share to approximately 16% by 2050 (Van der Hoeven, 2014). Indeed, the prediction is achievable, taking into account the PV current growth prospects. Solar energy generation is growing more rapidly than any other renewable technology, with the total installed capacity of 23 GW in 2009 increasing to approximately 277 GW in 2015 (REN21, 2016).

Solar PV plays a substantial role in electricity generation in many countries, meeting an estimated 7.8% of annual electricity demand in Italy, nearly 6.5% in Greece, 6.4% in Germany and much higher daily peaks in many countries in 2014 (REN21, 2016; Van der Hoeven, 2014). In late 2013 the global installed PV capacity was 138 GW, which is around 0.4% of the world’s electricity generation (Ashby, 2015). Both PV grid connected and off-grid are playing massive role in electrification across the world, China has achieved 100% electrification by 2015 mainly due to off-grid electrification (REN21, 2016). This was also contributed to by the mass migration from rural to urban areas in China.

In 2014, Germany was the top country with 37.9 GW capacity installed. However, it was overtaken by China with a massive 16 GW installed in 2016 to bring the total to 44 GW (Figure 2.12). China is leading in the PV industry with 30% of the global installed PV, followed by Japan, United Kingdom with 15% and 7% respectively (REN21, 2016). By the end of July 2013, there were 1 900 projects with a total of 60 GW solar generation capacity worldwide, of which 630 projects were large-scale PV, with capacity ranging from 15 MW to 300 MW, and more countries indicated increasing interest in large-scale PV (Shah *et al.,* 2015).

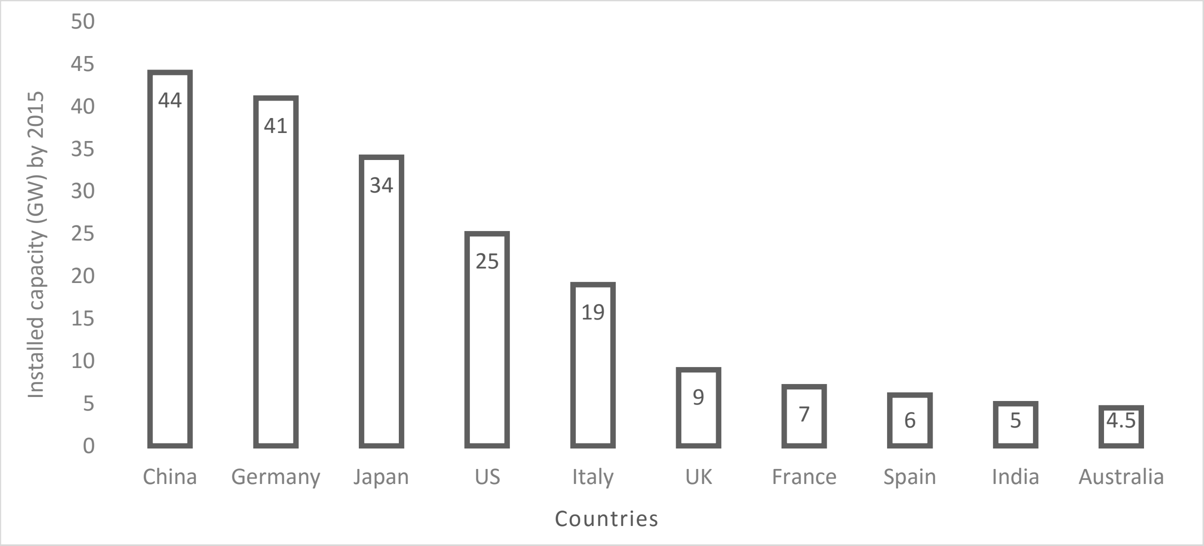


Figure 2.12: Top ten countries with highest installed solar PV by 2015 (Source: REN21, 2016)

The South African government supports solar PV. The Integrated Resource Plan (IRP) allocated solar PV a 300 MW yearly from 2012 to 2024. The government has already procured 2322 MW of solar PV in 4 bidding windows for the REIPP programme, and over 1 GW had been commissioned by mid-2015 (DOE, 2015). Unlike CSP and wind energy, solar PV energy is applicable and viable in all sectors: residential, commercial, industrial, mining and agriculture. There are agricultural, residential and commercial operators that have set up solar PV on a small scale. Solar PV generation is a viable source of electricity, taking into consideration various parameters such as solar radiation, policy and the legal and regulatory framework (Table 2.2).

By comparison with other renewable energy technologies, solar PV generation is the most viable option for the South African energy sector (Table 2.2). It has the potential to make a significant contribution in the total energy mix. It is flexible and applicable to many sectors in all small, medium and large scale applications. The irradiance in South Africa is favourable for solar PV implementation.

Africa has particularly good solar energy potential, with most parts of the continent having an average of more than 320 days per year of bright sunlight and with solar irradiance of almost 2000 kWh/m^2/year, which is twice the average level in Germany (Birol, 2014a). Solar energy is the most abundant energy resource on earth. There are many good reasons for developing solar energy technologies while fossil fuels still dominate the global economy's energy balance. Table 2.2 summarises the rationale for the merits of solar PV application.

Table 2.2: Comparison analysis of the viability of renewable energy technologies in South Africa

Parameters	**Renewable energy technologies**					
	Hydropower	**CSP**	**Biomass**	**Wind**	**Solar thermal**	**Solar PV**
Potential	Moderate	Excellent	Good	Excellent	Excellent	Excellent
Sectors applicable	Commercial	Commercial	Residential, agricultural, commercial	Commercial	Residential, agricultural, commercial, industrial	Residential, agricultural, commercial, industrial
Policy support	IRP, RE policy	IRP, Minister's determination, RE policy	IRP, Minister's determination, RE policy	IRP, Minister's determination, RE policy	Government SWH programme, RE policy	IRP, Minister's determination, RE policy
Legislation support	Energy Act	Energy Act	Energy Act	Energy Act	Energy Act	Energy Act
Scale flexibility (small/large)	Small and large	Large	Small and large	Large	Small and large	Small and large
Land and water requirements	Too much water and land required	Too much water and land required	Too much land required	Too much land required	Less land and no water required	Less land and no water required

Nfah and Ngundam (2008) estimated that about 2 billion people in small villages in developing countries lack grid-based electricity services. Most of the remote villages lack access to modern energy. It is almost impractical to extend grid transmission lines to these villages because of, *inter alia,* the terrain, landscape and cost of grid extension (Lau *et al.,* 2010). Solar energy is an inexhaustible energy source that has unlimited potential of continuously supplying power to these remote communities.

The sub-Saharan African region is in a similar position. It is poor compared to other regions in developing countries in terms of access to modern energy; countries in this region rely mostly on traditional biomass for cooking. More than 90% of the population of countries such as Liberia, Bukina Faso and Tanzania rely on traditional biomass for cooking, and access to modern energy systems for cooking is very low (Brew-Hammond, 2010). These are countries where alternative and flexible energy sources such as solar PV energy are required.

As in many parts of Asia, off-grid, stand-alone PV and hybrid energy systems have become a better energy solution for most parts of Sub-Saharan countries. It is anticipated that if alternative source(s) of energy such as solar PV or hybrid energy are not made available to these communities, the number of people relying on traditional biomass for cooking is likely to increase rapidly, which could result in deforestation and loss of biodiversity (Brew-Hammond, 2010). This is likely, taking into consideration the population growth in such countries, which increases energy demand. Traditional biomass offers only a limited energy solution for these communities.

2.4 Solar PV technology and trend in South Africa

Solar PV technology is best known as a method for generating electric power by using solar cells to convert energy from the sun into a flow of electrons (Singh, 2013). The PV system thus directly converts solar energy into electricity. The PV cells are inter-connected to form PV modules with a power capacity of up to several hundreds or thousands of watts, when PV cells are combined to form a PV system (Van der Hoeven, 2011). Thus a solar PV system is an electricity generation mechanism and hence it is one of renewable energy technologies that are clean, non-depleting and do not emit GHGs as they generate energy directly from the sun by means of a PV effect (Chua and Oh, 2012).

The PV system usually requires an inverter, which transforms the DC of the PV modules into AC, most usage being run on AC (Figure 2.13). PV systems are highly modular, where the modules can be linked together to provide power ranging from a few watts to many megawatts (MW), they are easy and fast to install and accessible to the general public (Van der Hoeven, 2011). The large variety of PV applications allows for a variety of different technologies in the market, from lower cost ones with lower efficiency technologies to high-efficiency technologies at higher cost.

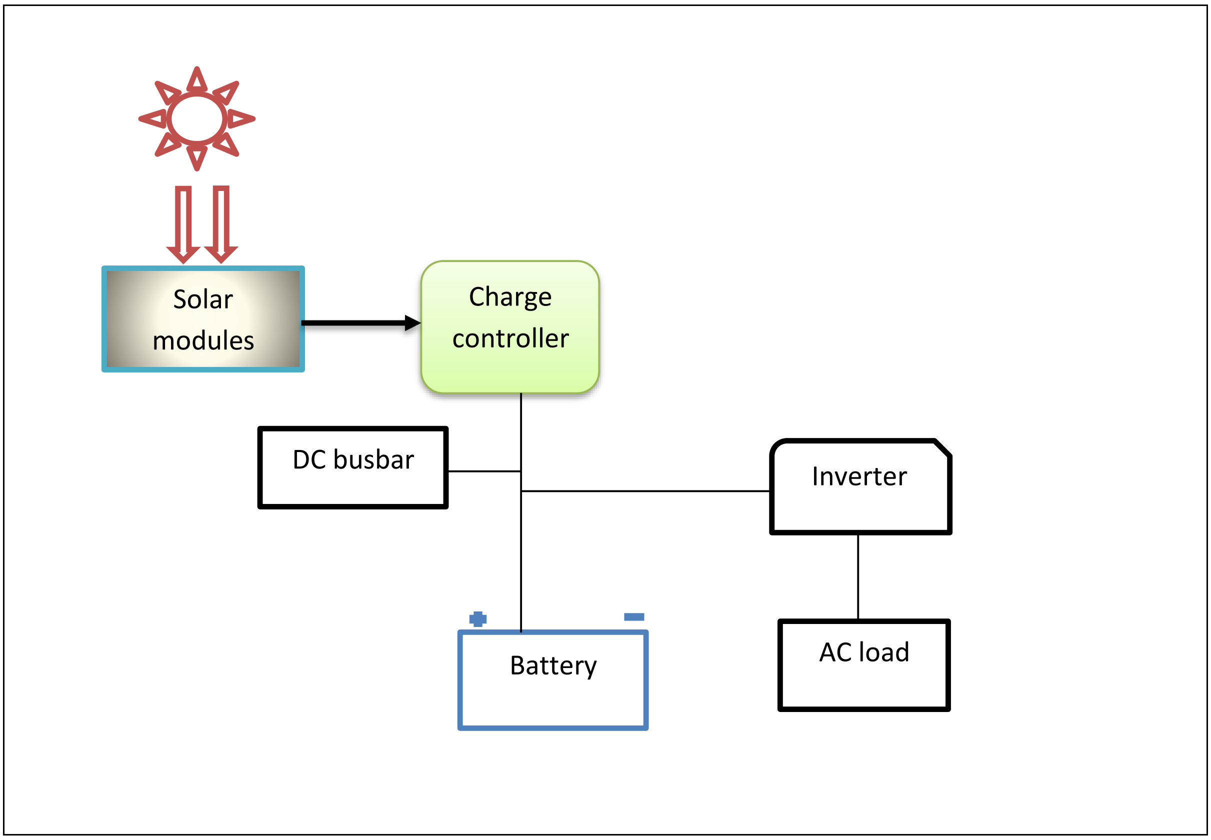


Figure 2.13: A typical solar PV system comprising of various components

The solar PV system comprises various components, which perform different functions. The components and their roles are illustrated below:

Module: It is an essential component of a solar PV system that converts sunlight directly into DC electricity.

Solar charge controller: It regulates voltage and current from solar arrays, charges a battery, prevents the battery from over-charging and also maintains control over discharges.

Battery: It stores electricity that is produced from solar arrays for use when sunlight is not visible, at night or for other purposes. It is intended for electricity storage.

Inverter: It is a critical component of a solar PV system that converts the DC power output of solar arrays into AC, for AC appliances.

Lightning protection: It is an essential component that prevents electrical equipment from damage caused by lightning or induction of a high voltage surge. It is normally required for large-sized and critical solar PV systems and includes efficient grounding.

2.4.1 Categories of solar PV systems

The solar PV energy system comprises various categories, namely:

- Grid-connected solar PV;
- Off-grid solar PV; and
- Hybrid renewable energy system.

The application of these systems depends on many factors, such as available infrastructure, technical expertise, solar energy potential (irradiance), wind energy potential and distance to the grid line, energy demand, terrain pattern and landscape of a particular area.

- **Grid-connected solar PV system**

The grid-connected solar PV system is a power energised by PV modules that are connected to the grid line (Singh, 2013). The grid-connected PV system supplies electricity directly to households; during daylight the PV modules produce DC current, which runs through an inverter that converts the current into AC electricity. The AC electricity is suitable for electrical appliances and export to the main electricity grid (Figure 2.14).

During the day when solar radiation is available, the grid-connected PV system generates AC power; if the PV system is installed in a domestic household(s), the AC power is fed into the main electrical distribution panel of the house(s) to which it provides power for on-site consumption; the excess is supplied to the utility grid (Hermann *et al.,* 2014).

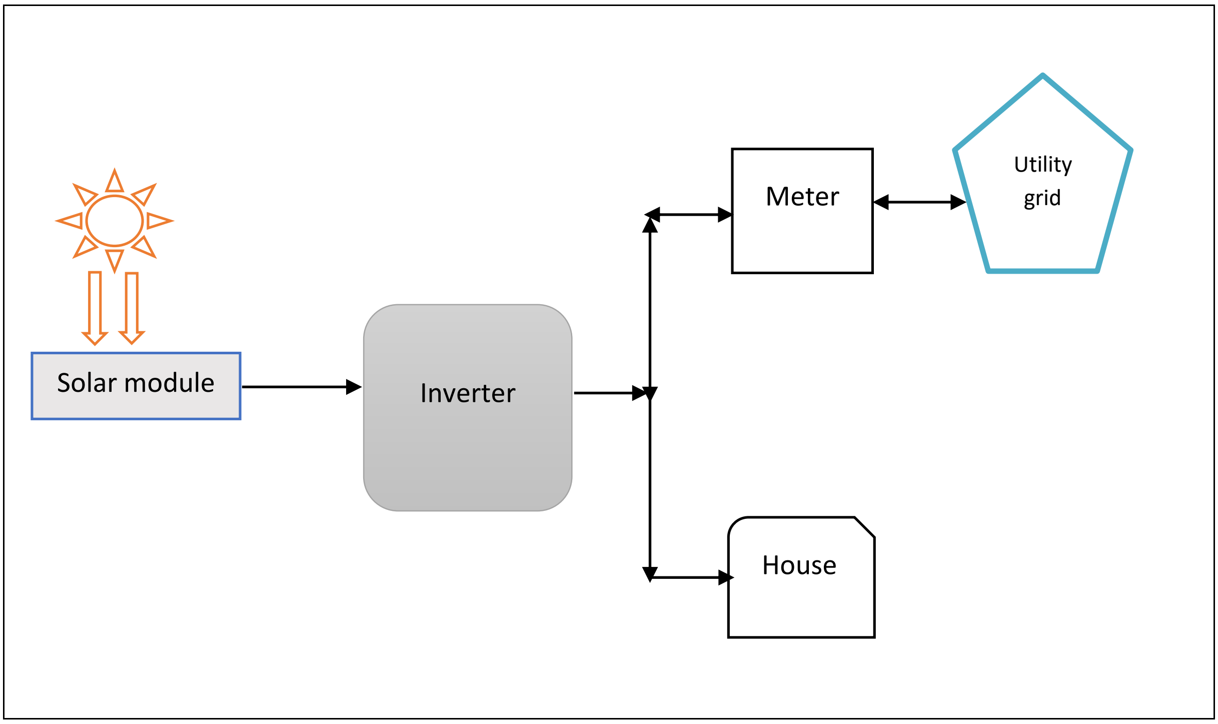


Figure 2.14: A grid-connected solar PV system

The grid-connected solar PV has a number of advantages, including reducing both energy and capacity losses in the utility distribution network. It further avoids or delays upgrades and maintenance of the transmission and distribution network where the average daily output of the PV system corresponds with the utility's peak demand period (Mondal and Islam, 2011).

The grid-connected solar PV system is beneficial and adding value in South Africa. Medium to high income groups can afford the PV system at a residential household application; however, because of the regulatory framework that does not allow feeding surplus power back to the grid, it becomes a setback as the country has opted to go for the renewable energy competitive bidding process instead of Renewable Energy Feed-In Tariff (REFIT), which is designed for the renewable energy power producers, and not the residents (Eberhard, 2014). One way of applying solar power is off-grid at residential level. There are, however, IPPs that implement the solar PV grid connected through the government procurement programme in South Africa.

- **Off-grid solar PV system**

Off-grid solar PV is an electrical power system energised by PV modules, which are stand-alone, without connection to the utility grid. This is an independent power system that is not connected to the grid. In most cases it is installed with a battery for power storage, as there is no grid connection for back-up (Figure 2.15). The advantage of the off-grid system is that it provides power in any area where there is no grid connection.

Living in an area that is off the grid means being disconnected from the electricity grid network line, the off-grid power systems usually cost less than extending transmission lines to some remote location. A typical solar PV off-grid system consists of various main components, including an array of solar modules, a charge controller, battery bank, inverter and generator. Off-grid solar PV power generation has been most useful in remote applications with small power requirements where the cost of running distribution lines was not feasible (Singh, 2013).

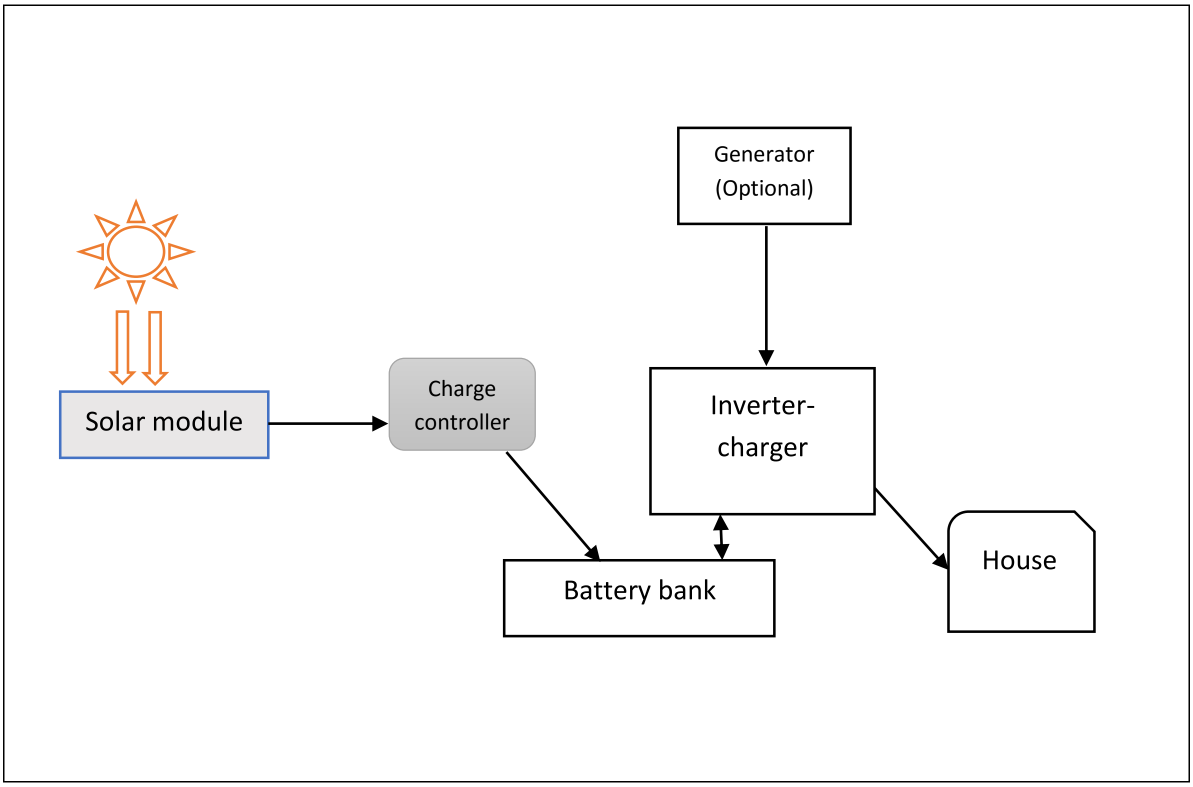


Figure 2.15: An off-grid solar PV system

There are cases where grid extension is impractical because of many factors, such as diverse and dispersed population dwelling patterns, rugged terrain and high cost of grid connection (Franz *et al.,* 2014). Thus, off-grid electricity offers an avenue to narrow down the electrification backlog in most rural parts of developing countries. The off-grid PV system is further valuable in countries where the grid extension is at a slower pace than the population growth. Even though the system can generate a small amount of electricity for a limited number of appliances, it contributes significantly to a better quality of life in remote locations (Kempener *et al.,* 2015).

- **Hybrid renewable energy system**

A hybrid energy system is a combination of two or more renewable energy sources such as wind and solar power, and a conventional system such as a diesel generator and storage batteries (Parida *et al,* 2011; Essalaimeh *et al.,* 2013; Singh, 2013). It uses a variety of energy sources to ensure continuous power supply without any interruption (Figure 2.16). Hybrid energy systems have elicited a lot of attention in the green energy field (Ashhab *et al.,* 2013). This energy system can be grid-connected or a stand-alone application.

  - *Stand-alone hybrid application*

The system needs to have sufficient storage capacity to handle power variation from the alternative energy sources involved (wind, solar, diesel generator). This system can be regarded as a micro-grid, with its own generation sources and loads, equipped with power electronics interfaces to regulate voltage and frequency and ensure proper load sharing among various sources (Dali *et al.,* 2010).

  - *Grid-connected hybrid application*

The alternative energy sources in the micro-grid have the ability to supply power to both local loads and to the utility grid. The capacity of the storage device can be smaller, since the utility grid can be used as a back-up. Nevertheless, when connected to the grid, important operation and performance requirements such as voltage, frequency and harmonic regulation are imposed on the system (Dali *et al.,* 2010).

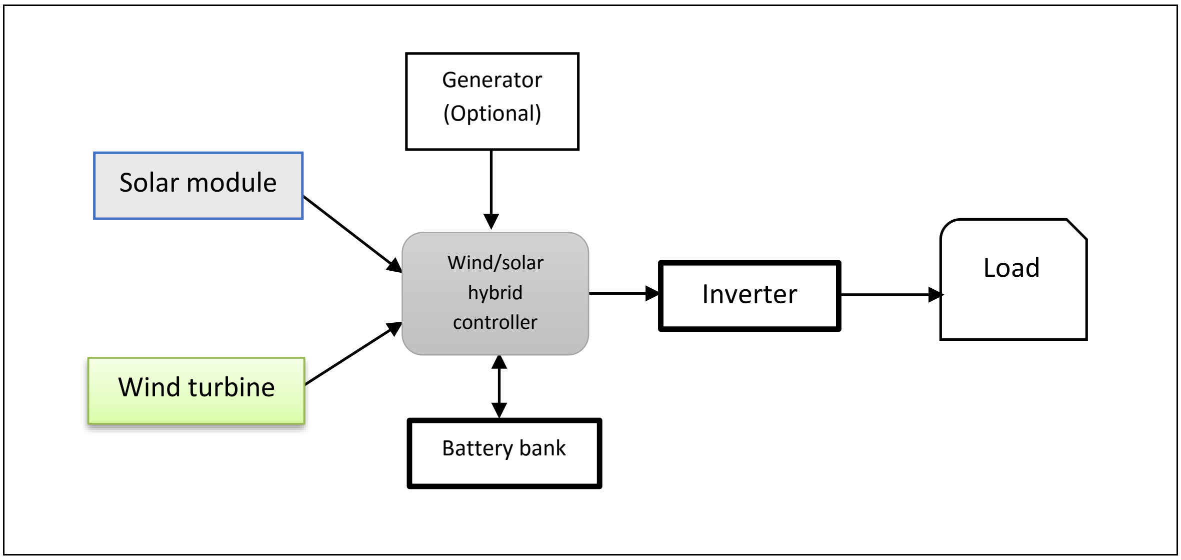


Figure 2.16: A hybrid energy system

The principal advantage of a hybrid energy system is the enhancement of system reliability when solar, wind and diesel power production are used together (Singh, 2013). It provides a more reliable and sustainable power supply than a single source, such as a stand-alone wind or solar PV system. The hybrid energy system can be optimised regarding sizing of components, such as a PV panels, battery, diesel generator, charge controller and inverter, in order to achieve the desired power output and achieve the most economically viable energy solution for the isolated remote location (Dekker *et al.,* 2012).

A hybrid energy system requires less maintenance than a stand-alone diesel generator system, which supplies the same amount of load, because supplying the same load with a diesel stand-alone generator requires more diesel, and the generator would run for as long as power is needed. Furthermore, a hybrid system turns on the diesel generator if the solar irradiance is insufficient and the power stored in the battery is exhausted. Therefore, a hybrid system has a high level of reliability in terms of power supply.

A common renewable hybrid energy system relies mostly on solar and wind energy as the primary power resources. These power resources are backed up by the battery in case of break-down or power shortage due to intermittency. The batteries are used for power storage owing to the stochastic characteristics of the system inputs, solar radiation, wind speed and electricity consumption of the place (Ekren and Ekren, 2009). The potential energy resources, such as solar and wind resources, are non-controllable variables and the behaviour of these variables is non-deterministic. The diesel generator is part of the hybrid renewable energy system that provides ultimate backup power if wind and solar power and batteries are exhausted. So the generator and battery power storage are critical aspects of the hybrid renewable energy system.

Essalaimeh *et al.* (2013) conducted a feasibility study for the introduction of a hybrid energy system in Jordan. It was concluded that it is technically feasible to implement a hybrid energy system of 1.2 kW solar PV array, 1 kW of wind generation, diesel generator and batteries for power storage. It has been proven to be a viable option that has the potential of supplying power to more than 500 households. The well-designed hybrid energy system keeps the output of the generator constant to ensure efficient and effective operation and minimise diesel consumption, while maximising the utilisation rate of the PV panel and minimising the storage capacity of the battery (Dekker *et al.,* 2012). Therefore, the hybrid energy system has been proven to provide effective and efficient power, which could be used in many parts of the world.

The hybrid energy system is suitable for different locations that are not electrified around the world. The utilisation of a hybrid energy system was not known in Cameroon, which had a population of 70% in rural areas that were not connected to the grid or had independent generating power projects in 2006 (Nfah and Ngundam, 2008). However, the subsequent introduction of hybrid energy system resulted in many parts of Africa having energy. The hybrid energy system reduces emissions and pollution, reduces costs and ensures more efficient use of power (Lau *et al.,* 2010).

2.4.2 Solar PV trend in South Africa

Since the introduction of the Renewable Energy Independent Power Producer Procurement (REIPPP) programme in 2011, the South African solar PV industry has shown accelerated growth. The solar PV companies are affiliated with an organised South Africa Photovoltaic Industry Association (SAPVIA). The SAPIA association is described in detail in Chapter 3 section 3.3.1.2. There are two solar PV manufacturing companies that began operation in South Africa in 2015 (REN21, 2016). However, the main solar PV trend driver is REIPPP, which has registered approximately 6.3 GW at the end of 2015 (DOE, 2015).

The REIPPP that is being rolled out in South Africa has seen many international and regional companies investing in the solar PV sector. The solar PV companies are scattered all over the country, mainly having their main or head offices in major cities such as Johannesburg, Durban and Cape Town. Moreover, these companies often have the satellite or branches in smaller cities or where they are constructing solar PV plants such as in Upington, Northern Cape Province.

The government of South Africa has collaborated with ARTsolar, which is a South African-owned (PV) module manufacturing plant. The facility has the capacity to produce 250 000 PV modules a year (DOE, 2015). These locally manufactured PV modules adhere to stringent International Electro-technical Commission (IEC) specifications. The operation of the ARTsolar is anticipated to reduce dependency on the PV imports mainly from China. The challenge with heavy dependence on importation of the final product is market volatility and costs. The lack of skills, capacity and expertise in the country remain the challenges for dependence on importation. It would seem that there is solar PV import duty exemption, however, there is 14% tax on sales.

2.4.3 Solar PV market trends

The global PV market has experienced vibrant growth for more than a decade, with an average annual growth rate of 40% (REN21, 2015). The solar PV market grew exponentially from less than 5 GW in 2004 to 227 GW in 2015 globally (REN21, 2016). It is expected that the solar PV market will continue to grow significantly in years to come, owing to a decline in the cost of solar PV modules and global pressure to increase the renewable energy contribution in the total energy mix.

Great advances were made in the development and growth of solar PV technologies over the years. For example, efficiencies have improved and will continue to improve. The cost of PV modules has been brought down by orders of magnitude (Clerici, 2013). Much of the newly added capacity was driven by accelerated tariff changes, imminent policy expirations and drastic price reduction. The solar PV capacity in operation at the end of 2011 was about 10 times the global total just five years earlier, and the average annual growth rate exceeded 58% for the period from the end of 2006 through to 2011.

About 7.5 GW was installed in the EU bringing the region to approximately 95 GW in 2015 (REN21, 2016). The three countries that played bigger role being the UK (3.7 GW), Germany (1.5 GW) and France (0.9 GW) and this accounts for 75% of EU grid connected capacity (REN21, 2016).

Beyond the EU, the largest PV markets are China, USA, Japan and Australia. Japan is the third market globally in terms of total operating capacity in 2015. The commercial and utility scale projects drove the PV market in Japan in 2015, the developers have turned into the abandoned farmland and golf courses to set up large scale PV projects due to shortage of land space (2016). Then PV accounted for 10% of Japanese electricity demand, and it represents 3% of the total power generation in 2015 (REN21, 2016).

Understanding how the costs of energy and the technologies change and improve over time is paramount for the decision makers (Rubin *et al,* 2015). As the technology matures, cost reductions are expected. The future cost reductions are estimated by projections of historical trends (Candelise *et al.,* 2013). The solar PV module price keeps on reducing whilst the cumulative global PV installation increased (Figure 2.17). As the solar PV cost declined over the years, the cumulative capacity increased (Schaeffer, 2004). In 2009, the solar PV cost was 2.4 US$/Wp and has declined to 0.65 US$/Wp in 2015 (Figure 2.17).

Swanson’s law is the observation that the solar PV module price drops by 20% for every doubling of cumulative shipped volume (Wesoff, 2012). In 2010 the production rate for the price of PV modules was estimated to be around 20% to 24% (23% to 24% for thin films and 19% to 20% for crystalline silicon); PV module costs have declined by 20% to 22% from 2000 to 2010 (Gielen, 2012). Accurate data on global average PV module prices are difficult to find and there is a wide range of prices in different countries, depending on the cost structure of the manufacturer, market features and module efficiency.

Apart from Gielen (2012), Gan and Li (2015) studied the relationship between the emergence of low-cost Chinese PV modules in the global market and cumulative production, silicon prices, and supply and demand imbalances. It was found that the PV module cost declined over time, from 32% to 14% over periods from 1976 to 2006, indicating lower costs of production as PV technology matured (Gan and Li, 2015).

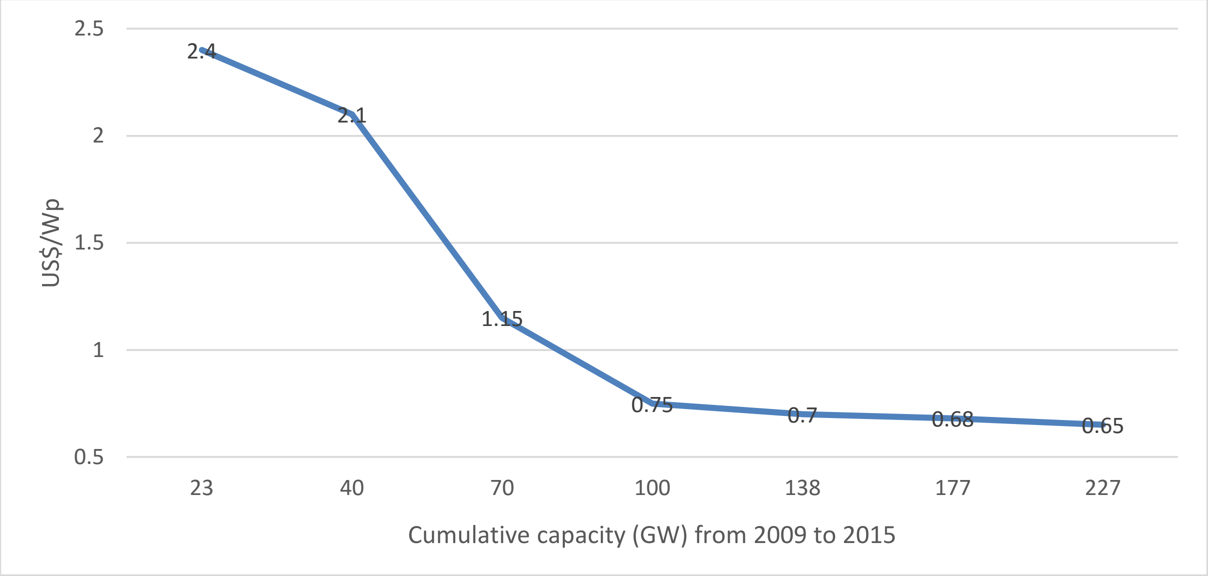


Figure 2.17: Solar PV market trends (Source: Chung *et al.* 2015 and REN21, 2016)

2.4.4 Solar PV cost

The solar PV prices rapidly reduced over the past years (Chung *et al.,* 2015). The solar PV module price reduced from US$2.40/W in 2009 to US$0.65/W in 2015 (Figure 2.18). PV costs in the UK have experienced a sharp decline of nearly 70% between 2010 and 2015. In UK the 4kW system reduced from around £5000/kW when the FIT scheme started in April 2010 to around £1880/kW in April 2014, this represents an average annual cost reduction of around 16%, it is anticipated that the cost reductions are likely to continue over the coming decade (KPMG, 2015). The module price is a major cost element accounting for around 35–55% of total PV cost (Candelise *et al.,* 2013).

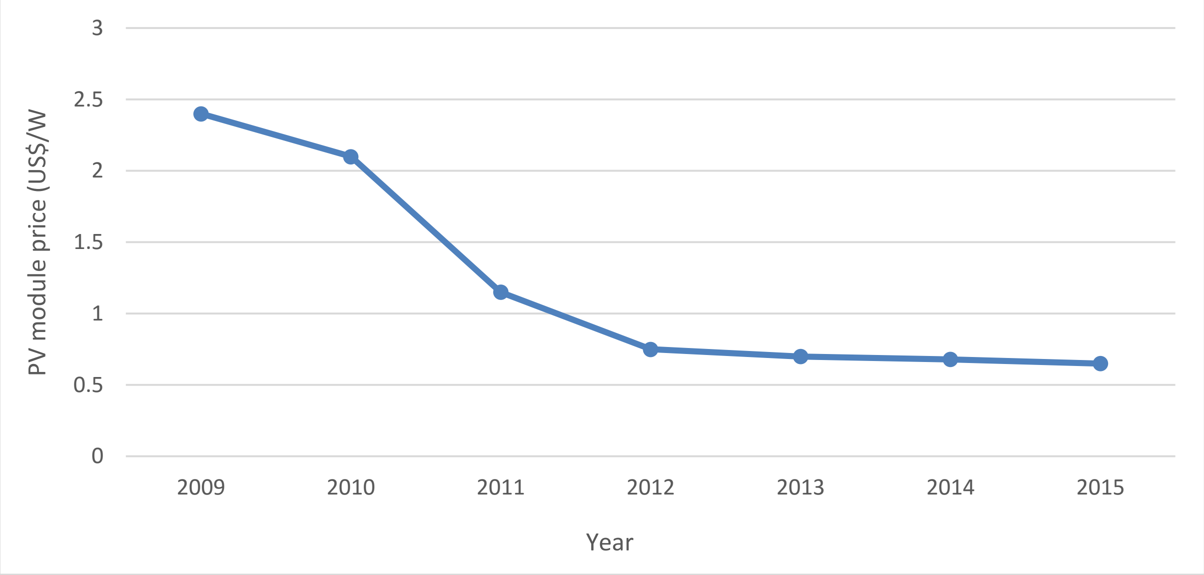


Figure 2.18: Solar PV module average price in the USA (Source: Chung *et al.,* 2015)

It should, however be noted that the prices in figure 2.18 are for the PV module only. A complete system would be higher, rather it could go up to US$5.71/Wp for residential sector (Gielen, 2012). The other factors that add on price for the complete PV system whether for residential, commercial or utility are labour, installer profit, inverter, hardware and electrical labour, site preparation. In 2015, the module price further decreased to less than US$1/Wp, hence the installation cost including labour, sales tax and other was reported to have declined to US$ 3.09/Wp (Chung *et al.,* 2015). Then it is anticipated that solar PV is likely to be economically competitive option for meeting the US peak power needs, and an estimated 39% utility capacity was added in 2015 (REN21, 2016).

The US solar PV market has grown at 76% annual growth rate between 2010 and 2014, which went up to 7458 MW installed capacity (Figure 2.19). The main drivers behind such growth has been the rapid decline in equipment costs, and system installation prices (Chung *et al.,* 2015). The installation is mainly in the residential, utility and commercial sectors. The continuous price reduction has positive impact in the uptake of solar PV in the USA (Figure 2.19).

Elsewhere in the world, the PV market growth is influenced by a number of factors, system design modifications, which include the reduction of the number and balance of system parts, improving mechanical and electrical integration of PV modules, and improving mounting systems for easier, faster and cheaper installation have contributed to decline of PV cost (Candelise *et al.,* 2013). However, in other countries across Europe the policy and regulatory framework has largely contributed to the uptake of PV technology. The introduction of Renewable Energy Feed-in-Tariff (REFIT) in countries such as Germany, UK, Malaysia, and Japan has brought significant uptake of PV technology (section 2.9.1.1)

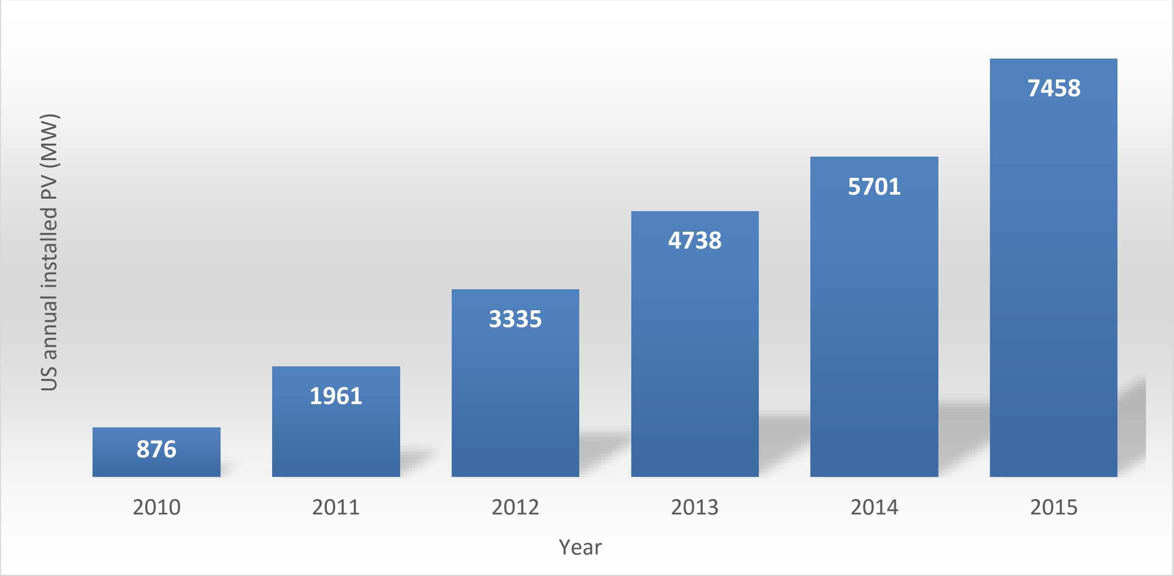


Figure 2.19: Annual USA solar PV installed MW (Source: Chung *et al.,* 2015)

Low material costs (particularly for polysilicon) combined with improved manufacturing processes and economies of scale have reduced manufacturing costs far faster than targeted by the industry, with top Chinese producers approaching costs of US$0.50/W in 2013 (REN21, 2014). The price of raw materials for PV modules (copper, steel and stainless steel) has been more volatile. Approximately 45% of solar PV system price reduction was experienced from 2008 to 2011, but the more recent reduction is smaller due to price volatility. However, the costs of different materials for solar cells are decreasing owing to research and development in the area of materials science (Tyagi *et al.,* 2013). Installation costs have decreased at different rates depending on the type of application and maturity of the market in the country.

The global price reduction brings technology closer to cost-effectiveness for grid-connected applications, considering the long lifetimes of PV systems (over 25 years), no fuel costs and generally low maintenance costs, which include cleaning dust from the modules (Van der Hoeven, 2011; Tyagi *et al.,* 2013). Moreover, the continued reduction in PV module prices is largely due to the following factors:

- Economies of scale associated with rising production capacities;
- Improvement, and innovation in material technology;
- Competition among manufacturers;
- Improvement in efficiency by the help of new technology;
- Lifespan of PV system;
- Policy in favour of renewable energy; and
- A large drop in the price of silicon and its deployment due to research and development

2.4.5 Types of solar PV technologies/modules

Technologies for the development of PV modules are rapidly emerging and there is a diverse portfolio of such technologies across the world. There are various types of solar PV technology, which are at different stages of maturity; most significantly, they all have potential for improvement (Van der Hoeven, 2011). However, sustained research and development commitment is still needed in order to continue the cost reduction of solar PV technology.

2.4.5.1 Crystalline PV modules

The crystalline PV module is a preferred economic and commercial choice for grid-connected applications (Makrides *et al.,* 2010). Solar PV modules absorb up to 80% solar radiation; however, only 5-20% is converted into electricity, depending on the type of PV module (Fang and Li, 2013; Vermaak, 2014). Current modules have good efficiency close to 20% (Makrides *et al.,* 2010; Pavlovic´ *et al.,* 2013). However, this can be increased using solar tracking technology. The crystalline silicon technologies comprise mono-crystalline or polycrystalline modules. These modules dominate the market share, with close to 90% (Van der Hoeven, 2014).

Polycrystalline silicon has an ordered crystal structure, with each atom ideally lying in pre-determined position (Figure 2.21). Mono-crystalline PV modules exhibit predictable and uniform behaviour (Figure 2.20), and are more efficient when compared to polycrystalline (Tyagi *et al.,* 2013). However, these modules are the most expensive type of silicon because the manufacturing processes are slow, require highly skilled operators and are capital, labour and energy intensive (Table 2.3).

Figure 2.20: Mono-crystalline PV modules (Source: http://energyinformative.org/solar-basics)

Figure 2.21: Polycrystalline PV modules (Photo taken by the author)

These modules are usually guaranteed for a lifetime of 25-30 years. The polycrystalline cells are suitable materials needed to reduce the cost of developing a PV module, though their efficiency is lower compared to that of mono-crystalline cells. There are various merits and demerits of the crystalline PV modules (mono-crystalline and polycrystalline), which are outlined in table 2.3 below.

Table 2.3: Merits and demerits of mono-crystalline and polycrystalline cells (Source: Miller and Lumby, 2012; Tyagi *et al.,* 2013)

	Mono-crystalline	**Polycrystalline**
	More expensive than polycrystalline	Cheaper that mono-crystalline
	It has been around for a long time, proving its longevity and durability.	The process used to make polycrystalline silicon is simpler and costs less.
	It is not hazardous to the environment.	The amount of waste silicon is less compared to mono-crystalline technology
	Its silicon solar modules are space-efficient; these solar modules yield the highest power outputs and require the least amount of space compared to any other types	
Demerits	It is more expensive than polycrystalline	It is less efficient than mono-crystalline solar cells.
	If the solar panel is in partially shaded or covered with dirt or snow, the entire circuit can break down.	Lower space efficiency. It needs to cover a larger surface area to provide output of the same electrical power as a solar panel made of mono-crystalline silicon

Various approaches to reduce the cost of crystalline PV cells and modules have been taken, this include research for more efficient PV cells. It is believed that the cost will continue to reduce as time goes on. Techniques for the production of polycrystalline silicon are simpler and therefore cheaper than those required for mono-crystalline material. Nevertheless, the material quality of polycrystalline is lower than that of mono-crystalline material owing to the presence of grain boundaries (Tyagi *et al.,* 2013).

In conclusion, both mono-crystalline and polycrystalline modules are suitable for the residential, commercial, industrial and agricultural sectors. These modules are more suitable for areas with predominantly direct sun radiation (Pavlovic´ *et al.,* 2013). They have the potential to provide substantial solar power output, with good efficiency. The challenge of high cost remains unsolved thus far; however, technological advancement is expected to reduce costs in the coming years, but it is not yet known to what extent this affect module prices.

2.4.5.2 Thin-film PV modules

Thin-film module production manufacturing processes operate at a much lower temperature than those of crystalline silicon. This reduces the embodied energy per watt-peak (Makrides *et al.,* 2010). The thin film is made from semi-conductors deposited in thin layers on low-cost backing (Van der Hoeven, 2011). Thin-film technology is less expensive, as it uses few materials and fewer manufacturing processes (Miller and Lumby, 2012; Tyagi *et al.,* 2013). Thin films represent about 10% of the total PV market share, which has decreased from 16% in 2009 (Van der Hoeven, 2014).

A significant advantage of thin films over crystalline cells has been affordability (Makrides *et al.,* 2010). Another manufacturing advantage is that thin films can easily be deposited on a wide variety of both rigid and flexible substrates including glass, steel and plastics (Figure 2.22). However, the most important challenge of thin-film technologies remains the improvement of the technology so as to increase the efficiency of industrially produced cells.

Figure 2.22: Thin-film modules (Source: http://energyinformative.org/wp-content/uploads)

The thin film PV system is in a downward trajectory over the last few years because they are far less efficient compared to crystalline technology (table 2.4). Moreover, the technological performance and improvement of these films is relatively poor. The thin film requires nearly twice as much space for the same amount of power that is generated by crystalline modules. Moreover, they may pose problems at the end of their lifecycle when they need to be disposed of. Their performance also degrades faster over time compared to crystalline silicon modules.

Table 2. 4: Merits and demerits of the thin-film modules (Source: Makrides *et al.,* 2010; Miller and Lumby, 2012)

Merits	**Demerits**
They are cheap and affordable	They are far less efficient than mono-crystalline and polycrystalline technology.
They can be applied to almost any surface, such as metal, glass or plastic.	They require nearly twice as much space for the same amount of power.
They are flexible and can be bent without breaking.	They contain toxic substances (such cadmium telluride) that does not pose a significant risk while on the roof; however, it may pose problems at the end of its life-cycle when it needs to be disposed of.
High temperatures and shading have less impact on solar panel performance	Its performance degrades faster over time.
It performs well in indirect light	
Its homogenous appearance makes it look more appealing	

Thin-film solar modules are more suitable for areas with predominantly diffuse solar radiation (Pavlovic´ *et al.,* 2013). They are not ideal for the residential sector, as the warranty is shorter and the efficiency is lower than those of mono-crystalline and polycrystalline silicon modules. Moreover, the high space needed makes them unsuitable for many sectors such as residential use and locations where there is not much land space.

Because the thin-film solar modules degrade faster, this may send a wrong message to consumers. The advantage of lower cost makes them favourable in terms of capital cost, but problematic over time, because of less power generated and faster degradation. The output of both thin-film and crystalline modules is subject to loss caused by dirt, dust or snow on the modules, DC/AC conversion losses, conduction losses in cables as well as a gradual decrease in performance during the lifetime of the modules (Monforti *et al.,* 2014).

2.4.5.3 The Concentrating photovoltaic technology and hybrid PV thermal panels

The Concentrating PV (CPV) seems to be a promising approach for achieving better efficiency by using greater portions of the solar spectrum. Concentrating PV (CPV) technology is rapidly gaining popularity, as it offers several economic advantages over existing technologies (Makrides *et al.,* 2010). Just like CSP, the CPV uses mirrors or lenses and sometimes a combination of both to focus solar radiation. Its highly efficient cells are usually made of several layers, each capturing a specific wavelength of the solar light spectrum (Van der Hoeven 2011). Many CPV activities are still in the research phase, hence it is much more likely to be implemented as pilot project in many parts of the world (Makrides *et al.,* 2010). This is a promising solution for the solar PV industry in the near future across the world. When it becomes commercially viable, it will boost the solar industry and increase the contribution of clean energy in the total global energy mix.

The hybrid PV thermal panel maximises energy efficiency per surface area of the receiving panel; moreover, it generates electricity from the PV effect and heat simultaneously (Van der Hoeven, 2011). It is a system that converts solar radiation into thermal and electrical energy. These systems combine a PV cell, which converts electromagnetic radiation (photons) into electricity, with a solar thermal collector, which captures the remaining energy and removes waste heat from the PV module. The capturing of both electricity and heat allows these devices to receive higher energy and thus be more energy-efficient overall than an ordinary solar PV or solar thermal device alone. These systems are currently under development, nonetheless, the complexity of the system may increase the PV prices. Just like CPV, when it becomes commercially viable it will boost the solar industry.

2.5 Application of the solar PV system

Solar PV systems are applicable in different sectors with different energy needs and goals. Solar PV can be designed to suit a variety of applications (Muhammad-Sukki *et al.,* 2012). Moreover, this technology is applied in a diverse range of applications, including residential systems, mining, and agriculture, commercial and large-scale utility sectors. According to Miller and Lumby (2012), solar PV systems are categorised into four main groups, namely:

- Off-grid domestic (providing electricity to households, locations and villages that are not connected to the utility electricity network);
- Off-grid non-domestic (providing electricity for a wide range of applications such as telecommunication, water pumping and navigational aids);
- Grid-connected distributed/mini-grid (providing electricity to specific grid-connected/mini-grid customers); and
- Grid-connected centralised (providing centralised power generation for the supply of bulk power into the main/national grid network).

Solar PV systems have been implemented in both developed and developing countries. For instance, Bhandari and Stadler (2011) have found that solar PV technology is well accepted in Nepal, a developing nation, especially in the residential sector for lighting, charging cell phones and other domestic purposes. Because of the successful PV promotional programmes implemented by the Nepalese government as well as the private sector, the expansion of PV systems is expected to increase in the near future in Nepal. It is anticipated that the continued trend of lower prices will promote the expansion programme in many developing nations.

The biggest advantage of solar PV devices is that they can be constructed as stand-alone systems to give outputs with MW capacity. Hence, they have been used as power sources for many appliances, such as calculators, watches, water pumping, buildings in remote locations, communications, satellites and space vehicles, and even multi-MW scale power plants. With such a vast array of applications, the demand for PV modules is increasing every year (Clerici, 2013). In 2012, over 31000 MW of PV modules were sold for terrestrial use and the worldwide market has been growing at a phenomenal rate since 2000 (Clerici, 2013).

2.5.1 Application of solar PV systems in residential areas

The solar PV system has been implemented in many remote locations across the globe. In rural areas, ground-mounted PV systems are more common. For instance, South Africa established the Lucingweni mini-grid hybrid project in the Eastern Cape Province (Department of Minerals and Energy, 2007; Scholle and Afrane-Okese, 2007). The system was equipped with a battery backup system to compensate for potentially unreliable sunshine, especially in winter and seasons when wind speed is low.

The PV system is also applicable in remote areas such as mountains, islands and other places where the power grid is unavailable; in this application solar PV is used as the sole source of electricity, usually by charging a storage battery. Some countries have not yet explored the use of the off-grid hybrid system. In Algeria diesel generators or small hydroelectric plants (Saheb-Koussa *et al.,* 2009) usually power remote villages that are far from the grid. Since the cost of production of solar PV has reduced in recent years in response to technological advances, economies of scale and other factors, PV systems have become more viable and their potential for application in rural communities even greater.

2.5.2 Application of solar PV systems in buildings (building-integrated PV systems)

In urban and suburban areas, especially in developed countries, solar PV arrays are commonly used on rooftops to facilitate power generation. The building often has a pre-existing connection to the power grid, in which case the energy produced by the PV arrays will be sold back to the utility through metering agreements between the customer and the utility (Tiwari *et al.,* 2011). This happens mainly in countries where there is a FIT mechanism and the tariff for PV is set in such a way that it becomes beneficial for a household to invest in the technology. The rapid expansion in installed PV capacity is largely due to the increase in grid-connected PV systems mounted on buildings. Thus, the solar PV modules are readily integrated with the physical building or with the building's grid connection. The building-integrated system incorporates PV properties into building materials such as roofing, walls and glass. For that reason, it offers advantages in cost and appearance, as these PV substitutes replace the conventional materials in newly constructed buildings (Parida *et al.,* 2011).

Solar PV modules are composed of several solar cells. They can be installed on the roof (or wall) of a house with any orientation and can be part of the building. The output power of a PV module is mainly based on two factors, which are the cell temperature and the solar radiation incident on it.

2.5.3 Solar PV application in stand-alone devices

Solar PV systems have been widely used for many years to power calculators and novelty devices. Solar-powered remote fixed devices have seen increasing use recently. The PV system in stand-alone devices is also used in parking shades, streetlights, emergency telephones, temporary traffic signs and traffic lights.

2.5.4 Solar PV application in agricultural sector

Agricultural activities often require water for various purposes; it may be for animals to drink or watering plants or crops. A solar PV system can be used to operate a drip irrigation system for growing orchards in arid regions, considering different design parameters such as pump size, water requirements, diurnal variation in the pressure of the pump due to change in irradiance and pressure compensation in the drippers (Parida *et al.,* 2011).

2.6 Methodology for the determination of solar PV potential and output

2.6.1 The modelling method

Various tools and techniques are used for taking an informed decision in any investment; they differ depending on the scale, magnitude and type of such investment. Multi-Criteria Decision making (MCDM) with cross-matrix technique is one of the tools used to make decisions. It contains the options (design) on one axis and parameters (attributes) on the other axis. The implementation of solar PV energy (grid-connected and off-grid) and hybrid energy systems requires consideration of various factors. The methods for modelling in the MCDM are as follows:

2.6.1.1 Methods for modelling

- ***Technique for Order Preference by Similarity to Ideal Solution***

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a useful technique that deals with multi-attributes or multi-criteria decision-making challenges (Shih *et al.,* 2007). It is based on the concept that the chosen alternatives should have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution (Sen and Yang, 2012). It is a method of compensatory aggregation that compares a set of alternatives by identifying weights for each criterion, normalising scores for each criterion and calculating the geometric distance between each alternative and the ideal alternative, which is the best score in each criterion. It is in fact a utility based method that is able to compare each option/design directly depending on data in the evaluation matrices and weights (Shih *et al.,* 2007).

It is a multiple criteria method to identify solutions from a finite set of alternatives (Jahanshahloo *et al.,* 2006). TOPSIS has the ability to obtain a preferred solution by assuming the best possible options (design) and the worst possible option (design). It has become a favourite technique for solving multiple-criteria decision-making (MCDM) problems through modelling mainly because the concept is reasonable, easy to understand and needs less computational effort (Abdullah and Adawiyah, 2014).

The decision matrix contains competitive alternatives row-wise with attributes and weighting (Sen and Yang, 2012; Jahanshahloo *et al.,* 2006 and Shih *et al.,* 2007). This technique allows the decision makers to adjust weight in accordance with decision makers' confidence in the preference and evaluation of information. The attributes and design column will have figures/values corresponding to each attribute and design in the decision matrix. It is a simple and easy to use technique (Table 2.5).

TOPSIS has been deemed as one of the major decision making tools in the Asian Pacific areas, it has been successfully applied in taking decisions in a number and variety of subjects such as human resources, manufacturing, water management and quality control (Shih *et al.,* 2007). The TOPSIS technique has been used widely by different organisations in decision making and researched and proved to be effective and efficient.

Table 2. 5: Merits and demerits of TOPSIS technique (Source: Shih *et al.,* 2007; Sen and Yang, 2012; Velasquez and Hester, 2013)

TOPSIS	
Merits	**Demerits**
It is simple and fairly easy to follow and understand, and is more transparent, compared to other methods.	Direct and unlimited compensation among all attributes is assumed in the definition of distance; hence some attributes may not be allowed to compensate for each other in such a simple way
It has been used widely in many areas such as water management, human resources, quality management, engineering, electricity etc in Asian Pacifica areas. It is efficient and robust method	The definition of the separation between each alternative and the ideal point or the negative ideal point is sensitive to weights; hence these weights may only be subjectively evaluated and therefore are often inaccurate
It has sound logic that represents the rationale for human choice	
It is simple computation process that can be easily programmed into spreadsheet	
It is a scalar value that accounts for both the best and worst alternative simultaneously	
The steps to follow remain the same despite the number of attribute and options	

The decision making regarding the provinces with good solar PV potential would fall with the ambit of TOPSIS. Deciding which provinces are ideal for the setting up of solar PV and hybrid energy projects require the attributes such as population, land space, radiation, wind speed and options as provinces, hence this would be easily doable using the TOPSIS technique as this data is well-known and independent.

- ***Concordance and Discordance Analysis by Similarity to Ideal Design***

The Concordance and Discordance Analysis by Similarity to Ideal Design (CODASID) is based on an extended concordance analysis and a modified discordance analysis using raw data represented by the decision matrix, relative weights and veto threshold values on attributes (Sen and Yang, 2012). The concordance and discordance analyses are used to generate three new indices, which are a preference concordance index, an evaluation concordance index and a discordance index. These three indices provide independent measures for evaluation of each alternative design and span new space for ultimate ranking of alternative designs (Sen and Yang, 2012).

The CODASID is characterised by the ability to handle the limited compensation, allow full utilization of raw data, and provide a systematic computational procedure (Yang *et al.,* 1996). It is a computerised system that provides a systematic computational procedure for information processing and ranking of alternatives (Table 2.6). It is a method that formulates a Model design selection problem in terms of a decision matrix and generates a Normalised decision matrix. It ranks the alternative designs using the TOPSIS method. Just like TOPSIS, the CODASID technique allows the decision makers to adjust weight in accordance with decision makers' confidence in the preference and evaluation of information (Stoyell, 2004).

Table 2.6: Merits and demerits of CODASID technique (Source: Stoyell, 2004; Sen and Yang, 2012)

TOPSIS	
Merits	**Demerits**
It provides systematic approach to option evaluation and all options are compared on equal terms	It is not widely known and used, hence is complex and complicated
It responds more sensitively to changes in the weight vector	It could be risky technique of making decision due to absence of information on its success stories
It allows the decision makers to adjust weight in accordance with the purpose and objectives of the project	
It uses veto threshold values to eliminate inconsistency and use large amount of data	

2.6.2 The 'optioneering' method

The term *'optioneering'* was derived from the words '*option' + 'eering*' (from engineering), it is a choice to consider, in depth, various options and then to advise on the best possible option. Therefore, it is a process of selecting the most appropriate course of action whenever there are many competing options and there is no single objective to be satisfied (WPD, 2013).

When the consequences of the decision are serious, *optioneering* is the process that enables clear and structured decisions to be reached. The following elements are essential to the success of *optioneering:*

- Identification of the options and criteria for the option evaluation;
- Providing impartial scoring for the options and applying weighting criteria; and
- Viewing and analysing the results including, sensitivity and robustness analyses.

Two examples of the application of the *optioneering* process are given:

2.6.2.1 Western Power Distribution

A case where *optioneering* was used in the renewable electricity is by the Western Power Distribution (WPD). This is the electricity distribution network operator for the Midlands, South West and Wales in the UK and delivers electricity to over 7.7 million customers over a 55300 km^2 service area. The WPD sought options to connect proposed wind farms to its existing electricity distribution network and to identify the preferred option to be taken forward.

In order to come up with the best possible option for the connection point of the new wind farms, an *optioneering process* was conducted. The WPD (2013) reviewed the location and capacity of existing WPD assets in proximity to the proposed wind farm substations and an initial assessment of the likely connection options was made, which would be capable of providing the capacity required. This was necessary for strategic-level decisions to be made with a high degree of confidence.

The first step was to identify connection options and six options were subsequently identified. Each connection option was evaluated based on four identified parameters/attributes (Table 2.7). The points in each option and parameters/attributes were allocated and calculated accordingly. In conducting this evaluation, the following parameters/attributes were considered:

- Capital cost (132 kV circuit);
- Compliance and deliverability;
- The environment (ecology and biodiversity, cultural heritage, landscape and settlement); and
- Detailed electrical analyses (load variation, voltage and fault level analysis)

Table 2.7 demonstrate how the Western Power Board applied *optioneering* in decision making on the connection point for the electricity network. The values were added in the cells and analysis was performed.

Table 2. 7: The *optioneering* process with parameters and options (Source: WPD, 2013)

Option number	**Options**	**Attributes/parameters**			
		Capital cost	Compliance and deliverability	Environment	Electrical analysis
1	132 kV connection to Blaengwen substation, which serves the Alltwalis Wind Farm				
2	132 kV connection to Rhos or Lampeter substations				
3	132 kV connection to Carmarthen substation				
4	Connection to Swansea North GSP/Ammanford 132 kV				
5	132 kV Ccnnection to EE Route at Llandyfaelog				
6	Connection to Swansea North GSP substation via a new direct 132 kV circuit				

An evaluation was performed and each option was assessed against each parameter/attributes. A strength, weakness, opportunities, threat (SWOT) analysis was conducted.

Following the evaluation and SWOT analysis, the WPD (2013) concluded that:

- Options 1, 2, 3, were not compliant, were unlikely to be deliverable and were therefore ruled out as options.
- Option 4 might be compliant and deliverable; however, it carried increased system risk and was ruled out as an option.
- Options 5 and 6 were both compliant and deliverable;
- Option 5 used existing WPD assets as far as possible and required roughly 30 km of overhead line to be built.
- Option 6 required approximately 50 km of new 132 kV overhead line to be built and could thus have a greater environmental impact than option 5.
- Of the compliant options, option 5 had the lowest financial cost.

- Underground cable is significantly more expensive than new overhead lines constructed on wooden poles. New underground cable in this area cost approximately £986000 per kilometre.
- Underground cable could be used along sections of the overhead line route where circumstances justified its use in sensitive locations. The laying of underground cables was more invasive and could have a greater scale of effect on sites important for the ecology or cultural heritage.
- The report concluded that option 5 best met WPD's technical, financial and environmental obligations and should be taken forward for further investigation, taking WPD's statutory obligations and its licence standards into account.

2.6.2.2 National Grid Electricity Transmission plc

In 2009, National Grid Electricity Transmission plc applied the *optioneering* method to develop new electricity transmission infrastructure, which was intended to facilitate the connection of new generators. The parameter/attributes followed were:

- Economy (cost);
- Efficiency - system compliance; and
- Efficiency – deliverability.

The options that were available included the following: do nothing (no change in transmission lines), system enhancement, generator action, subsea cable or overhead lines (National Electricity Transmission plc, 2009). An evaluation and SWOT analysis were performed. It was decided to construct the new 400 kV overhead line electricity transmission connection between the proposed Hinkley Point C nuclear power station and Seabank substation near Avonmouth.

2.7 Energy and environment

Every electricity generation, transmission and distribution mechanism affects the environment in one way or another. Electricity generation from fossil fuels damages air, the climate, water, land and wildlife, biodiversity and the landscape (Tsoutsos *et al.,* 2005). Any energy production method, whether conventional or renewable, has a minor, moderate or adverse impact on the environment during all project phases, whether these are construction, installation, operation and/or decommissioning (Kaldellis *et al.,* 2013).

Energy sources such as nuclear materials produce hazardous substances as waste that are dangerous to human health. Conventional electricity generating technologies such as coal, gas and oil are responsible for a considerable amount of GHG emissions that affect air quality, cause environmental degradation and damage ecosystems. So renewable energy sources are vital in view of their potential to perform the dual roles of mitigating global warming and ensuring medium and long term energy security (Yue and Huang, 2011).

Global warming is an increase in the earth's surface temperature as a result of GHGs such as CO_2 caused by burning fossil fuels or deforestation that traps heat that would otherwise escape from the earth. The effects of global warming mainly lead to observed changes in many climatic and environmental aspects of the earth's system. An exceptional number of extreme heat waves, droughts and floods occurred around the world, with consequent severe, irreversible impacts, in the previous decade (World Bank Group, 2012). Moreover, the effects of climate change have increased the frequency and intensity of heat waves and are highly likely to worsen societal impacts.

The World Bank Group (2012) reported that the extreme Russian heat wave in 2010 had very significant adverse and severe consequences. The preliminary estimates indicated the death toll at 55000, annual crop failure at about 25%, burned areas at more than 1 million hectares and economic losses at about $15 billion (1% GDP). The effects of climate change can therefore be dire and destructive, with irreversible consequences.

2.7.1 Environmental impact of solar PV systems

Solar PV systems are known as a caring environmental impact technology that does not generate pollution such as noise or chemical pollutants during operation (Pavlovic´ *et al.,* 2013). However, negative environmental effects result from the manufacturing of solar PV electricity, which affect the climate and biodiversity. During the manufacturing of solar PV systems, there is a considerable carbon footprint, about

1200 kg of CO_2/kW of generating capacity (Ashby, 2015). Negative environmental impacts are also witnessed in some cases during the construction of a solar PV plant. These sometimes depend on the size of the plant, which could pose threats to ecosystems and valued biodiversity (Kaldellis *et al.,* 2013).

There are negative environmental impacts during the manufacturing phase of solar PV systems (Tiwari *et al.,* 2009). Furthermore, unfavourable environmental effects of solar PV systems during their operation are usually minor and can be minimised even more by adopting the appropriate mitigation measures (Kaldellis *et al.,* 2013). The toxic nature of thin-film manufacturing ingredients (cadmium) and the environmental consequences of deploying large solar systems based on toxic materials have caused serious concern, which is perpetually examined, even though the trace amounts of this material in thin-film PV modules do not approach toxic limits (Makrides *et al.,* 2010).

One way of preventing negative environmental impacts is for the PV system to be decommissioned at the end of its useful life, recycled and disposed of safely to minimise environmental harm, alleviate the raw materials shortage of PV devices to a certain extent and avoid waste of resources (Tyagi *et al.,* 2013).

Tsoutsos *et al.* (2005) described the environmental advantages of solar PV generation as follows:

- ***Land use***

The impact of land use on the natural ecosystem depends on many factors and characteristics, such as the topography of the landscape, the area of land covered by the PV system, the type of land, the distance from areas of natural beauty or sensitive ecosystems and the type and variety of biodiversity. Some aspects associated with solar PV systems, such as disturbance of wildlife and its impact on fauna and flora, are less severe when compared to other anthropogenic activities (Kaldellis *et al.,* 2013).

Solar PV plant can be implemented in areas or on land that has been abandoned or is no longer productive for agriculturally related activities. For that reason, a solar PV plant has the environmental advantage of being able to use such abandoned land.

- ***Environmental incidents (discharges of pollutants and spillages of hazardous chemicals)***

When the solar PV system is operating, there are no gaseous or liquid pollutants and spillages of hazardous chemicals such as oil or petrol, or harmful electromagnetic radiation, which can have negative impacts on the environment (Pavlovic´ *et al.,* 2013). However, some PV modules contain a small quantity of toxic substances that could pose a slight risk of fire in an array causing small amounts of these chemicals to be released into the environment. Consequently, there is a very small risk of accidental discharge of pollutants from solar PV projects compared to other energy technologies.

- ***Visual impacts***

The visual interference on solar PV plant depends on the type of the system and the surroundings. For example, if a solar PV system is constructed in an area of natural beauty such as nature reserve, the visual impact can be high for certain type of modules. Some people find thin-film modules less attractive and spoiling beautiful scene in the nature reserve.

Similarly, rooftop mono-crystalline solar PV modules have an aesthetic impact on the modern buildings. For that reason, the impact of visual intrusion depends upon specific parameters such as the topography of the landscape, the type and the area of land covered by the solar PV system and the distance from places of natural beauty or sensitive ecosystems (Kaldellis *et al.,* 2013). However, people have different opinions and some regard this as a nuisance and disturbing sight, whilst others are happy with the installation. Sensitivity to the views of the local population is important setting up solar PV systems.

- ***Air pollution***

As for the life cycle assessment, the environmental performance of the system depends heavily on the energy efficiency of the system manufacturing and especially electricity production. The emissions associated with transportation of the modules are insignificant in comparison with those associated with manufacture. The transport emissions are still below 0.1-1% of manufacturing-related emissions, while for polycrystalline and mono-crystalline modules emission is estimated at 1200 kg CO_2/kW, 5.049 – 5.524 kg SO_2/kW and 4.507 – 5.237 kg NO_x/kW (Tsoutsos *et al.,* 2005; Ashby, 2015). For example, South African electricity grid connected kg CO_2/kWh ranged between 0.30 to 0.37 kg CO_2/MWh between 2011 and 2017 (Eskom, 2017).

- ***Noise pollution***

PV solar plants operate noiselessly. Little noise is expected during the construction phase of PV system plants (Pavlovic´ *et al.,* 2013). Unlike in other energy plant construction where noise becomes severe, PV system plant construction causes a low level of irritating noise.

The solar PV and hybrid energy systems have very little negative impact on the environment and where a negative impact does occur; it can normally be prevented through precautionary measures.

2.7.2 Solar PV and GHG emissions

The energy sector has a negative impact on the environment in many ways, including combustion of fossil fuels that result in climate change and global warming. Furthermore, the extraction and transportation of fossil fuels pollute the environment (Hofman and Li, 2009). Therefore, clean energy technologies are required to offset the GHG emissions.

2.7.2.1 World GHG emissions trend

The total electricity output grew by 56% between 1990 and 2008 worldwide (Tanaka, 2011). Electricity production is responsible for 32% of the total global fossil fuel use and 41% of energy-related CO_2 emissions (Tanaka, 2008). In 1990 the CO_2 emission from coal burning for electricity generation was just below 5000 Mt; however, 15 years later (in 2005) the CO_2 emissions grew to over 8000 Mt.

Global emissions rose by 4.6% in 2010, after having declined in 2009 owing to the impact of the financial crisis. This represents an increase of CO_2 emissions of 1.3 $GtCO_2$ between 2009 and 2010 (International Energy Agency, 2014). North America, Europe and China accounted for 60.5% of the global power output in 2008, resulting in 61.6% of the electricity-related CO_2 emission in the same year (Tanaka, 2011).

Emissions from the combustion of fossil fuels such as coal and natural gas accounted for more than three-quarters of the GHG emissions in Canada in 2007 (Hofman and Li, 2008). However, the main GHG emission was CO_2, which accounted for over 80% of the Canadian total GHGs; the remaining less than 20% comprised CH_4, N_2O and SF_6. The energy sector has the potential to play a critical role in combating the effects of climate change.

2.7.2.2 North America and Europe GHG emissions trend

In North America, electricity output grew at an average of 1.5% per annum between 1998 and 2008. Similarly, electricity-related CO_2 emissions grew by 0.5% annually in the same period. North American CO_2 emissions account for 23% of global emissions (Tanaka, 2011). In 2008, coal contributed the largest share of electricity generation of 43%. In the same year, coal contributed 2000 Mt of CO_2 (Figure 2.23). Other energy sources such as gas, oil and renewables contributed the remaining 57%.

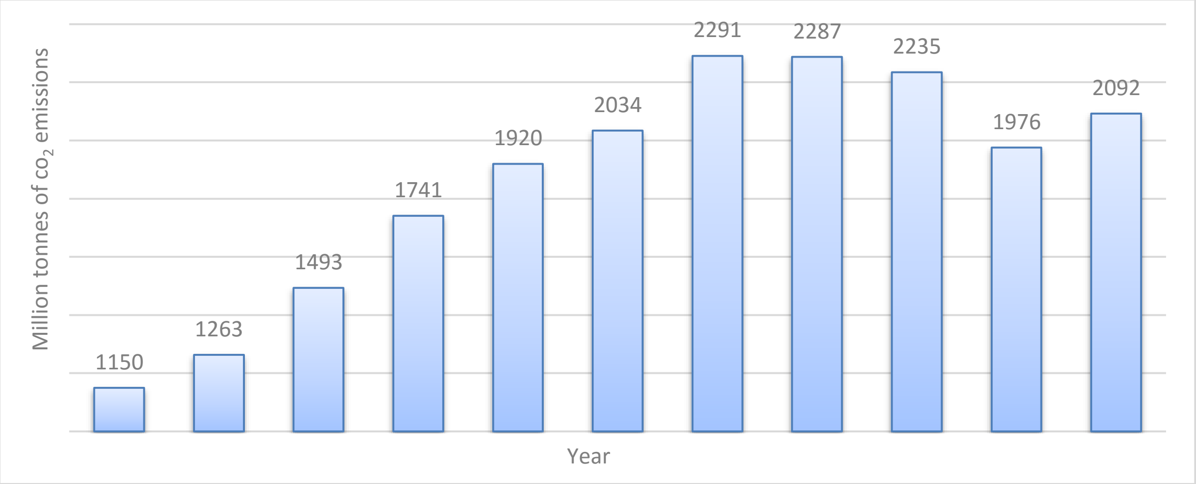


Figure 2.23: North American CO_2 emissions from coal burning for electricity generation (Source: Tanaka, 2011)

Coal was the largest source of emissions, contributing 78.1% in 2008. The annual emission growth rate was 3.1% between 1990 and 1998 and 0.2% between 1998 and 2008 (Tanaka, 2011).

In Europe, the largest source of emission was coal, which accounted for 68.2% in 2008, slightly less than the 78.1% of North America. The rate of coal consumption was lower, as the annual growth rate of emissions was 0.7% between 1998 and 2008 and -0.6% between 1990 and 1998 (Tanaka, 2011). In England, coal consumption decreased between 1990 and 2008 to less than 1000 Mt CO_2. The decrease is associated with the shift from conventional to clean energy technology, as well as the price volatility of the conventional energy sources.

The total European electricity output increased at an annual rate of 1.7% between 1998 and 2008. Nonetheless, CO_2 emissions remained relatively stable. The largest source of CO_2 emissions is coal-fired power plants. Germany, the UK, Poland and Italy account for 54% of the total European emissions from electricity generation (Tanaka, 2011). Over 90% of Polish electricity comes from coal, while approximately 45% of Germany's electricity comes from coal (Jain, 2010). This means that Germany and Poland are among the highest polluters in Europe.

2.7.2.3 African GHG emissions trend

The total electricity output (TWh) increased by over 50% between 1998 and 2008, resulting in an increase in emissions of 35% over the same period (Tanaka, 2011). In 2012 Africa produced 1052 CO_2 emissions (Mt) and these are likely to increase to 1 260 by 2020 (Birol, 2014). Just as in the North American and European countries, the largest source of emission was coal, which contributed 60.5% of the total emissions produced. The annual emission growth rate was 3.8% between 1990 and 1998

By comparison with the North American and European countries, Africa produced the lowest CO_2 emissions of 220 Mt in 2008. The decline in CO_2 emissions from 340 in 2008 to 320 is largely due to the global financial crisis, which resulted in less burning of coal (Figure 2.24). North America contributed over 2000 Mt CO_2 and European countries contributed just over 1000 Mt CO_2 during the same period.

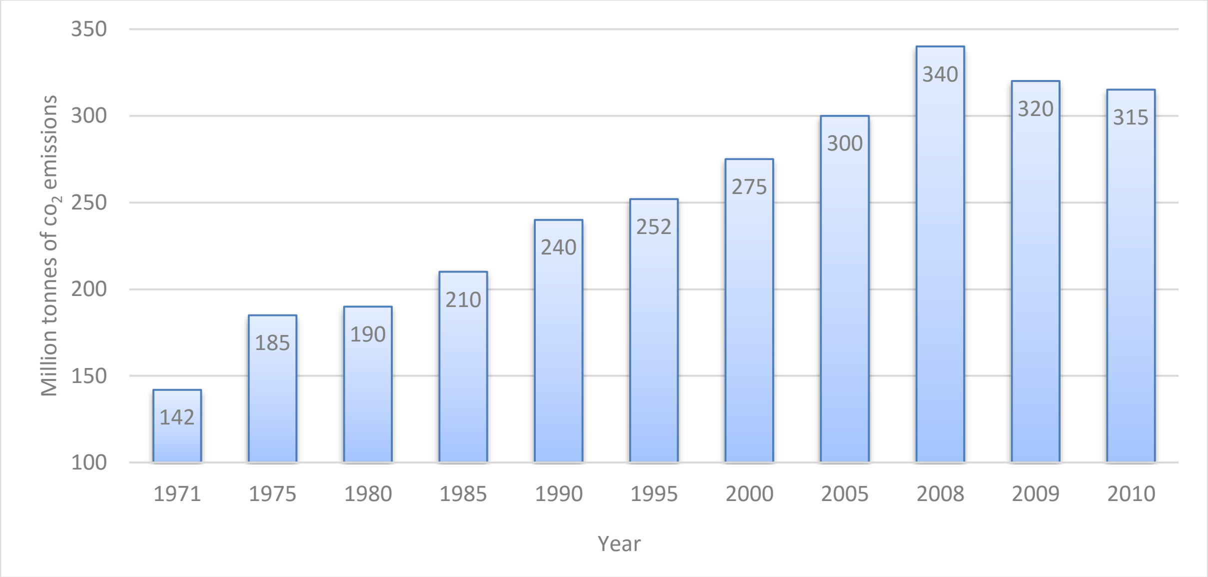


Figure 2.24: African CO_2 emissions from coal burning for electricity generation (Source: Tanaka, 2011)

The total continental CO_2 emissions in the electricity sector are dominated by a few main emitting countries such as South Africa, Egypt, Libya and Algeria, contributing up to 80% of the total emissions in 2008. CO_2 emissions in developing countries continue to increase at a fast rate owing to growing fossil fuel consumption (International Energy Agency, 2014).

2.7.2.4 South African GHG emissions trend

South Africa currently relies heavily on fossil fuels as a primary source of energy, around 87% in 2010, with coal providing 74% (Department of Minerals and Energy, 2006). The overall CO_2 emission from various sources of fossil fuel from 1971 to 2008 showed a steady increase (Figure 2.25). This is the case because energy utilisation in South Africa is characterised by high dependence on abundantly available coal. Furthermore, South Africa imports a large amount of crude oil. A limited quantity of natural gas is also available (Department of Minerals and Energy, 2006). The South African average emission is relatively higher because it generates approximately 40% of the continent power production (Birol, 2014). The GHG emission in South Africa almost as high as in developed countries. CO_2 emission is the largest proportion of the total GHG emissions in South Africa, namely about 80%, and is mainly generated by electricity production because of heavy reliance on fossil fuels (Pegels, 2010).

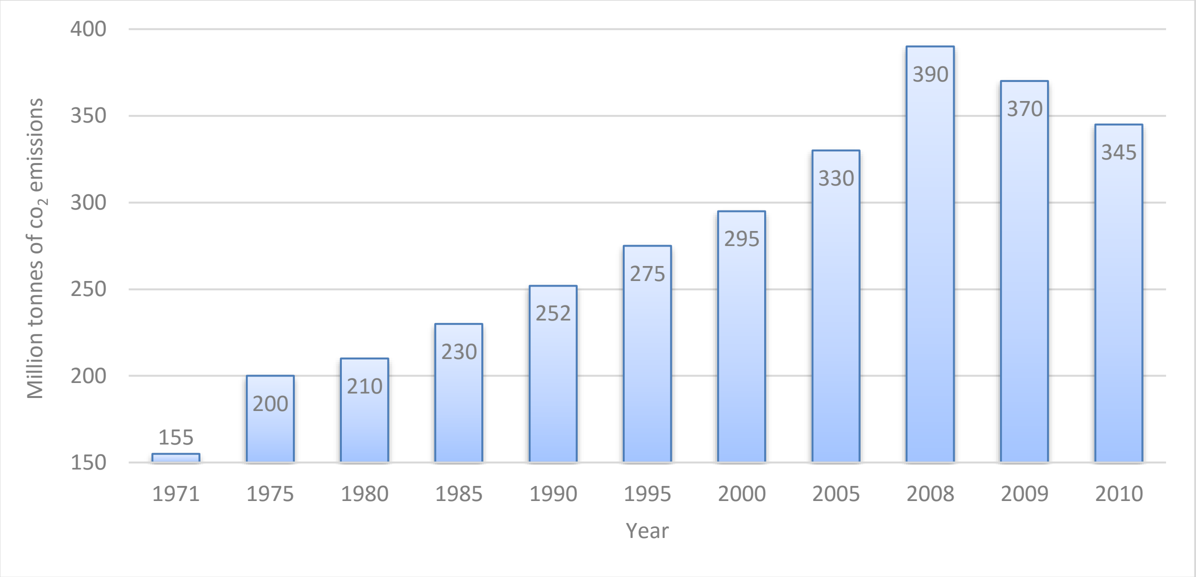


Figure 2.25: South African CO_2 emission from fossil fuels (Source: Tanaka, 2011)

The decrease in emission in 2009 and 2010 was caused by the global financial crisis. South Africa accounted for 37% of the CO_2 emission from fuel combustion in Africa by 2010; however, this represents only 1% of the global total (International Energy Agency, 2014).

The deployment of solar PV systems is anticipated to contribute significantly to a reduction in carbon emission from electricity generation. It is expected that solar PV systems will generate 4500 TWh by 2050 and thus save up to 2500 Mt/year of CO_2 emission worldwide. With the rapid expansion of solar PV deployment, as well as the continued lower prices of PV modules, solar PV technology is expected to grow towards 4500 TWh in the medium to long term. Coal-fired electricity generation contributes a substantial share of global CO_2 emission. It is responsible for 73% of the CO_2 from global power generation and 30% of the total CO_2 emission from energy (International Energy Agency, 2011).

2.7.3 Energy security

Affordable, secure and reliable energy supplies are fundamental to economic stability, growth and development (Tanaka, 2008). Energy security refers to the uninterrupted physical availability of energy products on the market, at a price that is affordable to all consumers. Moreover, energy security involves the provision of sufficient and reliable energy supplies to satisfy demand at all times while avoiding environmental impacts (OECD, 2012). The major parameters of energy security are availability, affordability and sustainability of energy supply, which are normally interlinked facets in the overall energy security.

As explained in section 2.2.1, coal remains central to the global energy system. It dominates the global energy mix largely because of its abundance and reliability. It is widely distributed across the globe and affordable to many nations (Clerici, 2013). However, it is a matter of time before such fossil fuels will be depleted.

Clerici (2013) estimates that there are 869 billion tonnes of coal reserves, which based on current production rates should last for around 115 years, significantly longer than conventional oil and gas reserves. The most coal reserves being in Asia, North America and Europe (Dudley, 2016) The natural gas reserve is estimated to last for the next 55 years (Dudley, 2014). In contrast, energy received from the sun in one single day if it is entirely captured and stored would represent more than 6000 years of total energy consumption (Van der Hoeven, 2011). Thus, the amount of energy received from the sun far surpasses the total estimated fossil fuel resources.

Fossil fuels are finite and it is difficult to predict their scarcity and the implications. Scarcity risk related to fossil fuels offers significant motive to increase the share of renewable and sustainable energy sources in the total energy mix (Van der Hoeven, 2011). Fossil fuel prices have risen considerably; moreover, the prices are projected to increase further with time (Tanaka, 2008). Over the past 20 years, the energy security concerns are compounded by the increasingly urgent need to mitigate GHG emissions, climate change and possible global warming effects. Solar PV energy is available and can play crucial role in reducing the dependency on fossil fuels for electricity generation and long term energy security.

Increasing the role of renewable energy technologies improves the availability of energy by providing improved diversity and a more distributed and modular energy supply that is less prone to interruption (OECD, 2012). However, renewable energy technologies may also have some elements associated with security issues, which may be due to resource fluctuations, such as seasonal variations in wind and solar energy resources. Nevertheless, renewable energy offers better energy security, as they are infinite and have the ability to provide sustainable energy solution.

2.8 Potential of solar PV energy

Solar energy has the potential to supply an ever-increasing proportion of the world’s energy needs. It is an energy source that has the potential to supply additional energy that the world needs over the next decades in a manner and way in which it is sustainable and protects the environment (Kelly and Gibson, 2011). Furthermore, solar energy is growing rapidly worldwide. It has been the fastest growing energy sector in the past few years (Van der Hoeven, 2011).

More often than not, the potential of renewable energy is assessed based on the projection of the energy demand, strongly influenced by population growth, economic development and Gross Domestic Product (GDP) development. Incoming solar radiation is determined by the state and nature of the atmosphere. However, the dynamics of the atmosphere are difficult to predict. When solar radiation reaches the earth’s surface, part of it is reflected and part is absorbed. The same occurs with long-wave radiation that each body emits as a function of its temperature (Meza and Varas, 2000).

According to Clerici (2013), the sun emits energy at a steady rate of certain kW capacity. Out of the total kW capacity emitted, a small fraction is intercepted by the earth, which is located about 150 million km from the sun. About 60% of the emitted kW capacity reaches the earth's surface. The rest is reflected back into space and absorbed by the atmosphere. Even if only 0.1% of this energy should be converted at an efficiency of only 10%, it would be four times the world's total generating capacity of about 3000 GW (Clerici, 2013).

The solar irradiance or amount of power that the sun deposits per unit area that is directly exposed to sunlight and perpendicular to it is 1368 W/m^2. The surface area of the globe is four times the surface area of the same diameter disk. Thus the incoming energy received from the sun, averaged over the year and over the surface area of the globe, is 342 W/m^2 (Van der Hoeven, 2011).

Out of the 342 W/m^{2,} roughly 77 W/m^2 is reflected back to space by clouds and aerosols. Out of the 342 W/m^2, 67 W/m^2 is absorbed by the atmosphere, hence the remaining 198 W/m^2 hits the earth's surface (Van der Hoeven, 2011). Another analysis suggests that out of 100% incoming solar energy, 6% is reflected by the atmosphere, 20% reflected by clouds, 4% reflected by earth's surface, therefore approximately half of the energy reaches the earth's surface while the other half gets reflected to outer space by the atmosphere (Camacho and Berenguel, 2012). Regardless of the analysis, a significant amount of solar radiation is available for energy generation.

Consequently, solar energy is the most abundant energy resource on earth; a substantial amount of power, about 885 million TWh, reaches the surface of the planet annually (Van der Hoeven, 2014). The most abundant, sustainable source of energy is the sun, which provides power to the earth (Camacho and Berenguel, 2012). The contribution of renewable energy to electricity generation is extremely diverse. Krewitt *et al.* (2008) defined and categorised renewable energy potential as follows:

- ***Theoretical potential***

Theoretical potential is derived from the climatic parameter, which is the total solar irradiance on the earth's surface. The theoretical potential of solar energy is substantial compared to global energy demand. However, there are various constraints in exploiting the theoretical potential. The theoretical potential describes the amount of resource available without considering other factors such as conversion efficiencies and losses. It is the maximum amount of energy that is physically available from a particular source, such as solar energy. For example, in the case of solar energy, this would be equal to the total solar radiation impinging on the evaluated surface (Hermann *et al.,* 2014 and Ölz and Beerepoot, 2010).

- ***Technical potential***

Technical potential takes into account geographical restrictions such as land use cover and structural constraints. This is the geographic or theoretical potential minus the losses from conversion or efficiency, space factors, available area and other constraining requirements that relate to installation, such as (grid) transportation or transmission losses (Hermann *et al.,* 2014). It is derived on the basis of technical boundary conditions such as efficiencies of the technology and overall technical limitations such as available land for the installation of solar PV systems (Ölz and Beerepoot, 2010).

The technical potential for the country or provinces can be calculated as follows:

Technical potential (kWh/year) = solar radiation (kWh/m^2/year) x PV module efficiency (%) x available area (m^2) / spacing factor

$$\boldsymbol{TP = \frac{SRxPVME}{SF} x\, AA}$$

The spacing factor or ground cover ratio depends on the type and characteristics of the PV plant, but an average factor for large PV installation is in the order of 5, which means that the ground area needed is five times more than the actual area that *"collects"* solar radiation. For PV generation the main factors that lead to additional space requirements are collector spacing areas and electrical equipment, especially for large-scale applications (Hermann *et al.,* 2014).

- ***Economic potential***

Economic potential is the technical potential that can be exploited at a competitive cost. Technical potential can be used with an economic model and taking into account costs and other socio-economic factors such as fuel and electricity prices, other opportunity costs and land prices (Hermann *et al.,* 2014). The break-even point between renewable energy technologies and conventional technologies changes over time owing to, among others, the rise in fossil fuel prices and reduction in renewable energy generation costs.

Thus, the economic potential is highly dependent on the framing conditions. It is defined as the potential that can be exploited without a need for additional support (Ölz and Beerepoot, 2010).

2.8.1 Global perspective

Global irradiance on a horizontal surface is the measure of the density of the available solar resource per surface area. The yearly profile of mean daily solar radiation for Northern Europe shows that the May, June, July and August months have the highest irradiance, which reaches a maximum of 5.9 kWh/m^2/day (Figure 2.26). The average energy received from the sun in Europe is about 1200 kWh/m^2 per year. However, it has been found that Africa and Asia have better solar resources than Europe (Van der Hoeven, 2011). There is much better solar PV potential in Africa and Asia, yet much of the PV growth is in Europe.

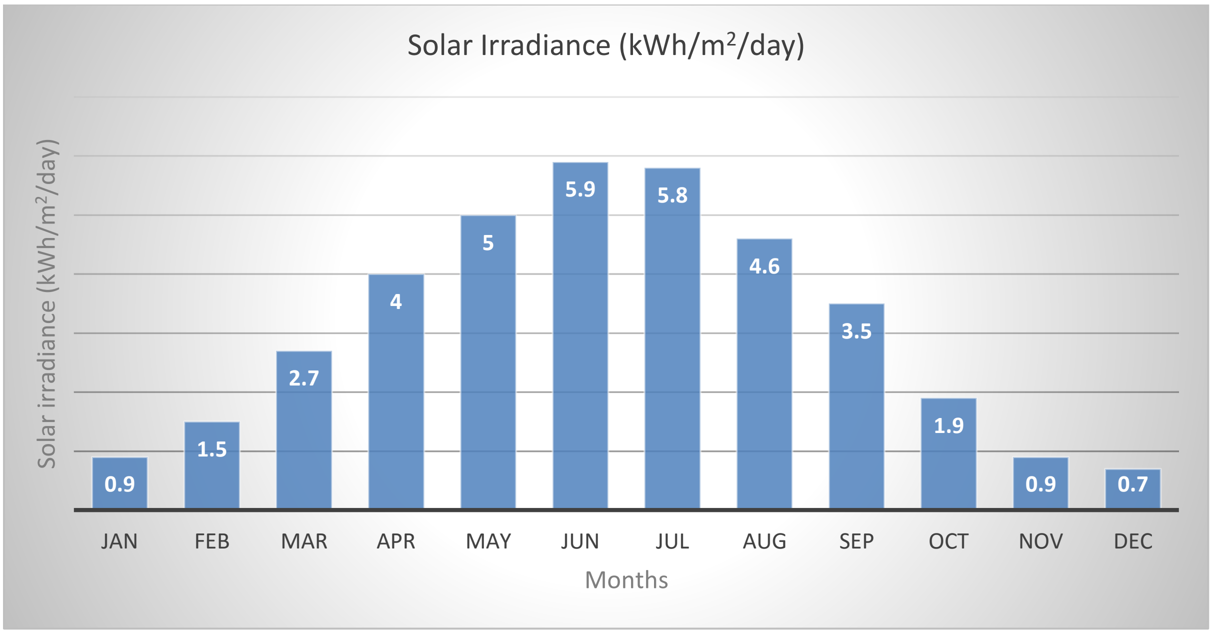


Figure 2.26: The annual profile of mean daily solar radiation for the Northern Europe (Source: Van der Hoeven, 2011)

The solar irradiance goes below 1 kWh/m^2/day in November, December and January in Europe. Much of the solar PV power is therefore likely to be generated mid-year in Northern Europe. Southern Europe has higher solar radiation than Northern Europe. In Southern Europe, the highest irradiance is 7.5 kWh/m^2/day in June and July (Figure 2.27). Moreover, the lowest solar potential is above 2 kWh/m^2/day during the months of November, December and January, which is winter (Van der Hoeven, 2011).

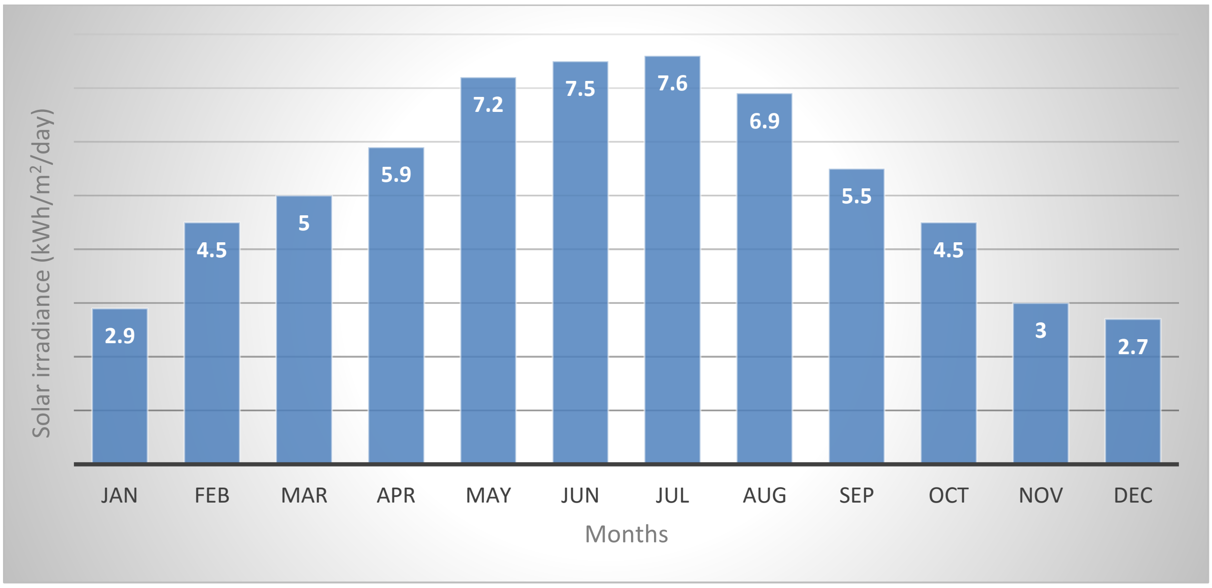


Figure 2.27: The annual profile of mean daily solar radiation for the Southern Europe (Source: Van der Hoeven, 2011)

On average the European energy received measured in global horizontal irradiance is approximately 1200 kWh/m^2/year (Van der Hoeven, 2014). In Asia, Mondal and Islam (2011) conducted a study on the potential and viability of a grid-connected solar PV system in Bangladesh. They used the Geospatial toolkit to obtain solar radiation map of Bangladesh and it was found that solar radiation was in the range of 4 to 5 kWh/m^2/day on about 94% of the total area. Bangladesh has a theoretical potential of approximately 70 TWh of solar energy per year, which is more than 3000 times higher than the current electricity generation. The Bangladeshi potential is similar to the Southern European one; however, solar PV development is still lower than in Europe.

2.8.2 African solar PV potential

Africa has two deserts where weather conditions are arid. One of them is the Kalahari Desert, which is situated in the middle part of Namibia and parts of Botswana, both countries share border with South Africa. The Northern Cape Province shares a border with both Namibia and Botswana. The Northern Cape has high solar irradiance, which is, in part, the cause of the arid weather conditions. Building solar power plant in a desert area, such as in the Kalahari, could supply many communities with energy (Bollen and Hassan, 2011).

The Sahara Desert is located in the northern part of Africa and covers over 3.5 million square miles (9 million km^2) or roughly 10% of the continent. It is bounded in the east by the Red Sea and stretches west to the Atlantic Ocean. To the north, the Sahara Desert's boundary is the Mediterranean Sea, while in the south it ends at the Sahel, an area where the desert landscape transforms into a semi-arid tropical savannah. The deserts are dry and barely suitable for significant land use. Hence, they provide good potential sites for solar PV plants.

The Sahara covers parts of several African countries, including Algeria, Chad, Egypt, Libya, Mali, Mauritania, Morocco, Niger, Sudan and Tunisia. Most of the Sahara Desert is undeveloped and features a varied topography. The solar irradiance in the Sahara Desert reaches maximum theoretical potential of 8 kWh/m^2/day (Figure 2.28), which is higher by far than in Northern and Southern Europe (Van der Hoeven, 2011). The seasonal pattern in the northern part of Africa follows that of Europe because of its position north of the equator; summer in mid-year and winter towards the end of the year and early in the New Year.

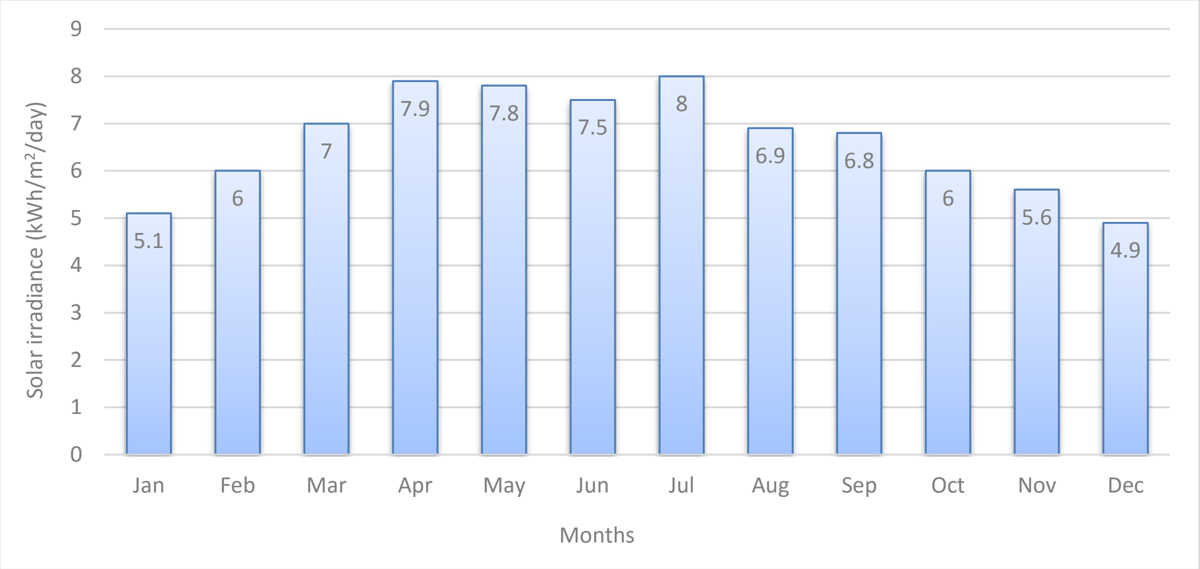


Figure 2.28: Annual profile of mean daily solar radiation for the Sahara Desert-Northern part of Africa (Source: Van der Hoeven, 2011)

Rural electrification is expected to represent the bulk of installed capacity in many developing countries. This is the case because most of the electrified areas in many developing nations are the towns and cities, with limited smaller locations and villages electrified. At the end of 2009 in West, East and Southern Africa, off-grid capacity was estimated at 7 MW for Ethiopia, Kenya and Nigeria and 5 MW for Senegal (Van der Hoeven, 2011).

The West African region is strongly, if not completely, dependent on fossil fuels, even though it has massive solar energy potential ranging from 4 to 6 kWh/m^2/day, which has been poorly exploited thus far. The main challenges have been the capital cost of projects and skills (Yamegueu *et al.,* 2011). It is necessary to exploit this constantly available local resource in order to enhance energy availability and security.

2.8.3 South African solar PV potential

South Africa is located on the southern tip of Africa and comprises nine provinces, with 2798 kilometres (1739 miles) of the coastline on the Atlantic and Indian oceans. The Solar and Wind Energy Resource Assessment (SWERA) [2008], in conjunction with the National Renewable Energy Laboratory, established that South Africa has solar potential of 4204499 GWh/year, therefore it is ranked 23rd worldwide.

During December and January South Africa receives average daily solar radiation of approximately 7.6 kWh/m^2/day theoretical potential. The lowest average of below 6 kWh/m^2/day occurs from March to June, which is the winter season (Figure 2.29). On average South Africa receives annual solar radiation of 7 kWh/m^2/day of theoretical potential (SWERA, 2008; Van der Hoeven, 2011), which is above that of Northern and Southern Europe.

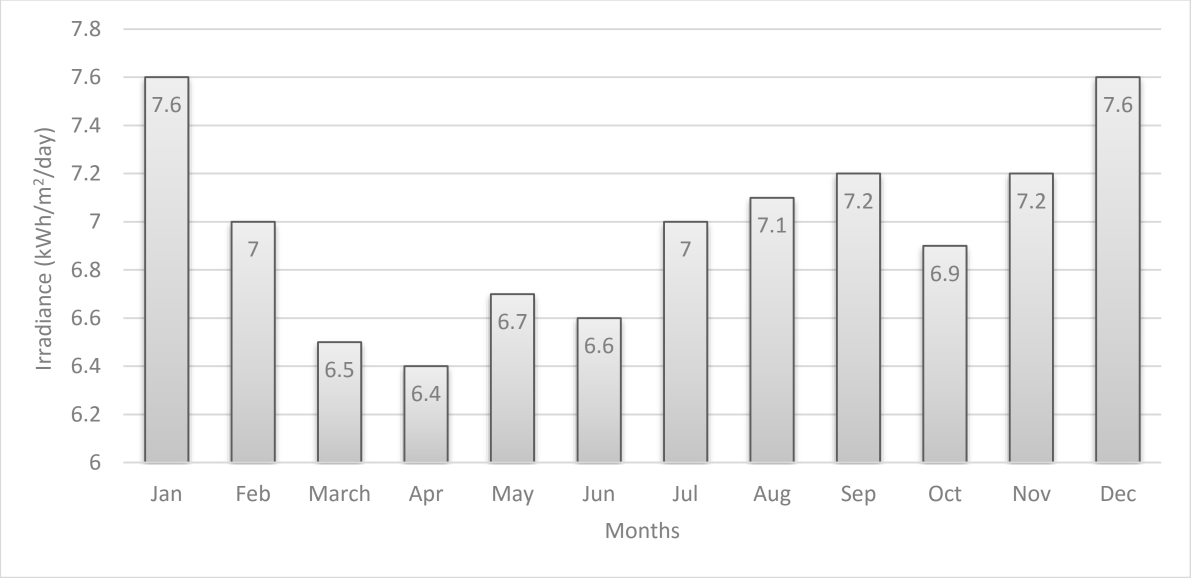
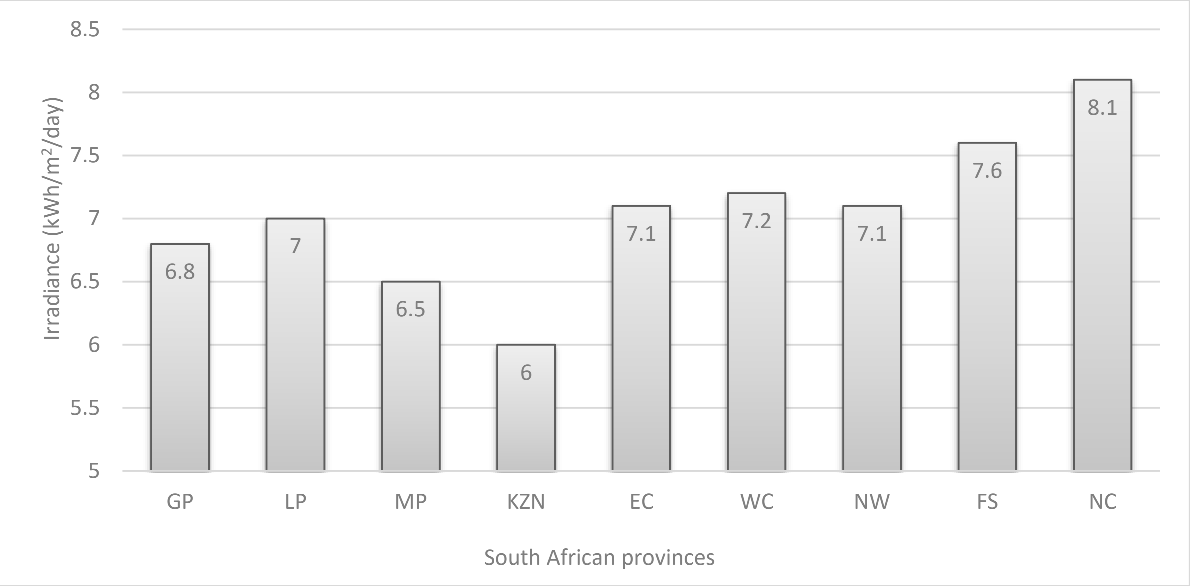


Figure 2.29: The annual profile of average daily solar radiation in South Africa (Source: SWERA, 2008)

According to the SWERA (2008), the Northern Cape Province has the highest annual average direct normal irradiance (DNI) of just over 8 kWh/m^2/day, which at times reaches 10 kWh/m^2/day in the hottest months (December and January). The Free State, Western Cape, Eastern Cape and Limpopo Provinces follow the Northern Cape, with just below 8 kWh/m^2/day (Figure 2.30). However, the Free State and Eastern

Cape reach 9 kWh/m^2/day in November, December and January (SWERA, 2008; Van der Hoeven, 2011).

The Northern Cape and Free State Provinces have hotter summer and much colder winter pattern than other provinces. However, other provinces, such KZN, Limpopo and Mpumalanga have fairly warm winter and hot summer. The Free State, Mpumalanga and KZN show small margin of solar potential during winter and summer.



[2]

Figure 2.30: South African annual average DNI (kWh/m$_2$/day) per province (Source: SWERA, 2008)

Thus South Africa is one of the top countries for solar PV theoretical potential, but the solar PV contribution in the total energy mix is still low, at approximately 961 MW connected in 2015 (DOE, 2015). Various studies have been conducted on solar PV potential and the findings differ from one study to another, depending on methodologies, parameters and the primary purpose of the research. The following renewable/solar energy potential was found in South Africa:

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[2] GP-Gauteng, LP-Limpopo, MP-Mpumalanga, KZN-Kwazulu Natal, EC-Eastern Cape, WC-Western Cape, NW-North West, FS-Free State, NC-Northern Cape

- ***CSP energy potential determined by Fluri (2009)***

Fluri (2009) investigated CSP potential and found that the Northern Cape has the best CSP potential over a total area of 14288 km^2, which assumes the land area of 28 km^2/GW translating to power generation capacity of 510.3 GW. He concluded that South Africa has total CSP power generation capacity of 547.6 GW. However, the external factors that partly determine potential include solar resource, proximity to transmission lines, the land use profile and slope.

- ***Potential contribution of renewable energy in South Africa according to Banks and Schaffler (2006)***

Banks and Schaffler (2006) argued that solar PV would not reach more than 10% of the South African power capacity because it would need power storage. However, the modelling conducted indicated that renewable energy technologies are likely to contribute up to 13% by 2020; the installed PV capacity could be 199 MW in 2015, 737 MW in 2020 and 1834 MW in 2025. This prediction was incorrect because in 2015 there was more 961 MW solar PV that is online (DOE, 2015).

The main limitation for the growth of PV is likely to be the ability of the global industry to supply the materials and components required to manufacture the cells on the scale (and price) that would take PV to greater heights. Some PV module types rely on small amounts of potentially scarce materials (indium and tellurium), but the main ingredient required is silicon, which is the second most common element in the earth's crust. This argument is equally wrong because there are two solar PV manufacturing companies that began operation in 2015 (REN21, 2016).

- ***Redrawing the solar map of South Africa for photovoltaic applications, according to Munzhedzi and Sebitosi (2009)***

Munzhedzi and Sebitosi (2009) studied solar PV potential in South Africa using the Meteonorm and PVDesignPro software packages to redraw the solar map. They found that areas around the North West, Northern Cape, Limpopo and Western Cape

Provinces are yellow zones, which means that there is a solar irradiance of 4.3 – 4.5 kWh/m^2/day. Other areas, such as Mpumalanga, Gauteng, the Free State and part of the Western Cape Provinces, are green zones, which are equivalent to a solar irradiance of 3.1 -3.9 kWh/m^2/day, and KZN and part of the Eastern Cape Provinces are light blue, which means that their solar irradiance is 3.6 – 3.7 kWh/m^2/day.

- ***Economic analysis of PV/diesel hybrid power systems in different climatic zones of South Africa by Dekker et al. (2012)***

Dekker *et al.* (2012) measured the economic viability of a hybrid energy system in six cities in South Africa, namely Bloemfontein, Nelspruit, East London, Pretoria, Cape Town and Upington, using the Hybrid Optimization Model for Electric Renewables (HOMER) GIS software in various sensitivity cases. The software takes into consideration solar radiation, load profile and other system technical equipment such as batteries and inverters. They found that Upington and Bloemfontein have the maximum power sizing of PV modules (5 kW capacity) in all sensitivity cases. Upington has the larger battery bank of 30 batteries, whereas Bloemfontein has 24 batteries for both sensitivity cases. Moreover, the generator and converter sizes are 5.5 kW and 6 kW respectively for each of the lowest net present value designs.

The highest renewable fraction found in both sensitivity cases was 0.751 for Upington, in the arid interior climatic zone, with Bloemfontein in the second position. The lowest renewable fraction of 0.207 occurred in East London in the sub-tropical coastal climatic zone of the Indian Ocean coast. Therefore, Upington (Northern Cape Province) and Bloemfontein (Free State Province) were found to have good hybrid energy potential.

2.8.4 South African household access to electricity

Inadequate access to modern energy services is a serious hindrance to social and economic development. South Africa has the highest electrification rate on the continent (Birol, 2014). In 2012, approximately 85.3% of South African households were connected to main electricity grid line; moreover, 3.6% of households were using electricity but were not connected to the main grid (StatsSA, 2012a). Other African countries have a relatively low electrification rate; for example, electricity access in

Tanzania was 24% in 2012. To address this requires a reduction in connection fees, which is regarded as an important contributory factor, as some poor rural communities were unable to afford it (Birol, 2014). Approximately 11% of South African households did not have access to electricity in 2012 (Figure 2.31). The off-grid solar PV and hybrid energy system has potential to cover the remaining households that do not have access to electricity. China is a case in point; it achieved 100% electrification in 2015 with off-grid having played a crucial role.

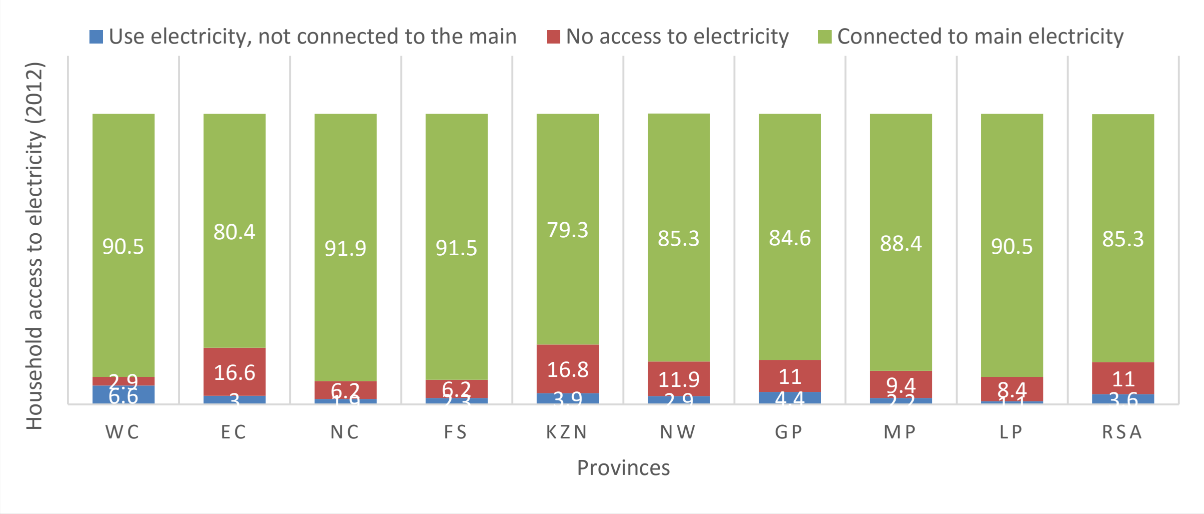

Figure 2.31: Households' access to electricity by province in 2012 (Source: StatsSA, 2012a)

The highest percentage of households connected to the main grid is in the Northern Cape, with 91.9%, followed by the Free State with 91.5%. The lowest percentage connected to the main grid is in KZN, with 79.3%, followed by the Eastern Cape with 80.4%. KZN and the Eastern Cape are also the provinces with the highest percentage of households not connected to electricity, at 16.8% and 16.6% respectively. Off-grid solar and hybrid energy systems have the potential to provide a sustainable energy solution for these provinces. The Western Cape, Northern Cape and Free State are the provinces with the lowest percentages of households with no access to electricity at 2.9%, 6.2% and 6.2% respectively.

2.9 Solar PV policy trends and regulations

Governments in different countries have continued to revise policy design, objectives, targets and implementation in response to advancement in renewable energy technologies, which mainly resulted in decreasing cost and changing priorities (REN21, 2012). Policymakers, especially in developing countries, are increasingly aware of renewable energy's wide range of benefits. These include ensuring energy security, reduced dependence on imports, reduction of GHG emissions and meeting international obligations on combating climate change.

The development and implementation of policies and strategies in many countries is influenced by, among others, previous experience of others, especially those with dire consequences such as nuclear accidents. The year 2016 marks the 5th anniversary of the Fukushima disaster and the 30th anniversary of the Chernobyl disaster, the 2 most catastrophic nuclear accidents in history. It is known that the Fukushima nuclear catastrophe in Japan had severe, irreversible impacts. There are health risks associated with the ongoing radiation contamination and clean up in the Fukushima region, and as to how long this will continue to make impacts is not yet known. Two of the most important public health issues related to both the Chernobyl and the Fukushima disasters are thyroid cancers and Posttraumatic Stress Disorder (PTSD) [Marks, 2016]. Furthermore, the announcement made by the UN Secretary-General about the objective to double the share of renewables in the energy mix by 2030 stimulated many nations to focus on clean and sustainable energy technologies.

Broad ranges of policies are needed to unlock the considerable potential of solar energy. These policies include the following:

- Establishment of incentives for early deployment;
- Removal of non-economic and market barriers;
- Developing effective, efficient and sustainable public-private partnerships (PPP); and
- Subsidising research and development and developing effective encouragement and support innovation (Van der Hoeven, 2011).

Support incentives indicate the willingness of an ever greater number of governments and policy-makers to broaden the range of energy technology options with clean and renewable energy sources (Van der Hoeven, 2011). The countries whose governments have established firm goals and targets for the penetration of renewable energy into primary energy and electricity generation and adopted specific policy mechanisms are achieving great success with an increased renewable energy contribution in the total energy mix.

The policies implemented thus far in many parts of the world are aimed at supporting the development and deployment of solar energy, among other renewable energy sources (Clerici, 2013; Van der Hoeven, 2011). A few examples are the successful REFIT act, which was adopted in several European and some Asian countries. Similarly, the Renewables Portfolio Standard (RPS) was adopted by the majority of American states, which ensures that the minimum amount of renewable energy is included in the portfolio of electricity production (Clerici, 2013).

The success of policies and strategies depend on predictable, transparent, stable framework conditions, and on an appropriate design and desired goals. Although many policy developments have helped to expand renewable energy markets, encourage investment and stimulate industry developments, not all policies have been equally effective or efficient at achieving these goals. Targets for renewable energy now exist in at least 118 countries, more than half of which are developing countries.

2.9.1 The global perspective on renewable energy support policy and incentives

Various policies, such as FIT, RPS, investment tax credits, pricing laws, production incentives, and quota requirements and trading systems, have been developed and implemented to promote and advance the use of renewable energy across the world (Moosavian, 2013). The FIT is the most widely used policy type in the electricity sector, having been adopted by at least 65 countries and 27 states/provinces as of early 2012 (REN21, 2013). However, the policy measures and mechanisms vary according to the financial support they provide (Table 2.8). Most incentives to support the deployment of solar energy technologies have taken the form of FIT and RPS (Van der Hoeven, 2011; Moosavian, 2013). The FIT guarantees special rates for renewable electricity provided to the grid.

Table 2.8: Renewable energy financial support policies and mechanisms (Source: REN21, 2014)

Regulatory policies	Fiscal incentives	Public financing
Feed-in tariff (including premium payment)	Capital subsidy, grant, or rebate	Public investments, loans or grants
Electric utility quota obligation/RPS	Investment or production tax credits	Public competitive bidding
Net metering	Reductions in sales, energy, CO_2, VAT, or other taxes	
Tradable REC	Energy production payment	

Different countries on different income levels across the globe have implemented different policies, regulatory frameworks and mechanisms to support renewable energy projects (high income countries, upper middle income countries, lower middle income countries and lower income countries). The regulatory framework and implementation of policies differ from one country to another.

According to REN21 (2011), more than 90% of the high income countries have the following financial support and mechanisms in place:

- FIT and biofuels obligation/mandate as regulatory policies;
- Capital subsidy, grant or rebate as a fiscal incentive; and
- Public investments, loan or grants as a public financing mechanism.

These high income countries include Canada, Australia, Finland, Germany and the USA. The upper middle income countries such as South Africa, Tunisia, Russia, Brazil, Jordan, and Jamaica do not have FIT in place, rather public financing such as public competitive bidding is more common (REN21, 2012). An example is South Africa's current competitive bidding programme to support renewable energy technologies.

2.9.1.1 The Feed-In-Tariff (FIT)

A FIT guarantees the generator of renewable electricity a certain price per kWh at which electricity is bought (OECD, 2012; Cherrington *et al.,* 2013). It is a scheme where the owner of electricity generated from a renewable energy source is paid for any amount of electricity generated (kWh) at a set rate (tariff) for each kWh generated and/or fed into the grid for a certain period (Muhammad-Sukki *et al.,* 2011; Muhammad-Sukki *et al.,* 2013). The FIT is a price-driven policy that has been designed to support renewable energy, therefore electricity generated from renewable energy sources is paid a premium price for delivery to the grid (Ölz and Beerepoot, 2010).

In the FIT, the government usually sets the price per kWh and the utilities are obliged to purchase a given amount of this energy at a premium price, which is passed on to the consumers. A FIT is expected to accelerate cost reduction of renewable energy technologies and speed up cost competition with conventional technology. The grid-connected solar PV market has an average annual growth of 81%; however, the main driver for such high percentages in almost all countries is the FIT scheme (REN21, 2011). A FIT is becoming more widely known and is the most effective mechanism for promoting renewable energy development (Ölz and Beerepoot, 2010). However, the design of the FIT needs to be adjusted to local circumstances in view of the vulnerability of electricity consumers, especially in developing countries where most of the consumers are poor.

Some case studies where the FIT was successfully implemented and hence increased the uptake of renewable energy technologies in Europe and Asia, solar PV energy in particular, are the following:

- ***Impact of FIT in German solar PV energy***

Germany introduced the FIT in 1991 under the Electricity Feed Law; however, the revised FIT scheme under the Renewable Energy Law in 2000 transformed the solar industry in Germany (Zhai *et al.,* 2010).

Germany has therefore become the world leader in solar PV installation even with low average solar radiation. With such a massive increase in solar PV energy in Germany, it has been established that from 2000 until the end of 2009, FIT policies led to the deployment of more than 15000 MW of solar PV power across Europe (Muhammad-Sukki *et al.,* 2013). By the end of 2011, Germany added solar PV capacity very rapidly; about 40% of the new PV capacity was introduced from December because of the problem with weather conditions and slow FIT during the early months of the year. However, the German solar industry has set a target of increasing the share of solar PV energy by 10% in 2020 and by 20% in 2030 (Sahu, 2015).

- ***Impact of FIT in UK solar PV energy***

Like Germany, the UK introduced the FIT scheme in April 2010. The introduction of the FIT scheme meant a major change in the policies that support low carbon electricity generation technologies and in the operation of the UK electricity market (DECC, 2010). The scheme was introduced to support new anaerobic digestion, hydro, solar PV and wind projects up to a 5 MW limit, with differing generation tariffs proposed for different scales of each of those technologies (DECC, 2010).

It was implemented in such a way that for any house owner who registered in this scheme there would be three separate meters installed in the house, one for measuring the generated electricity, the second one for measuring the exported electricity and the last one for quantifying the amount imported from the grid (Muhammed-Sukki *et al.,* 2011). According to the DECC (2010), every individual who installed a solar panel in the UK would benefit from the FIT in mainly three ways:

- All the electricity generated would gain a generation tariff per kWh;

- Any electricity exported into the grid would be awarded an export tariff per kWh; and
- The electricity generated could be used by the participants, which reduced the amount of electricity required by the household.

The FIT has grown the UK renewable energy market. Moreover, the FIT is a crucial financial scheme that increases penetration and grows the market for solar PV technology. The PV deployment reached 8.1GW installed capacity at the end of March 2015 (KPMG, 2015). The installations continued and by July 2016 it was 10.7 GW (https://www.gov.uk/government/statistics/solar-photovoltaics-deployment)

The UK solar PV market has, within a space of one year (July 2015 to July 2016), grown from 8300 to 10700 MW with over 4 MW from the REFIT (Figure 2.32). The 10700 MW is an increase of 29% (2423 MW) compared to July 2015. To date, 50% (5403 MW) of total installed solar PV capacity comes from large scale installations greater than 5 MW (https://www.gov.uk/government/statistics/solar-photovoltaics-deployment)

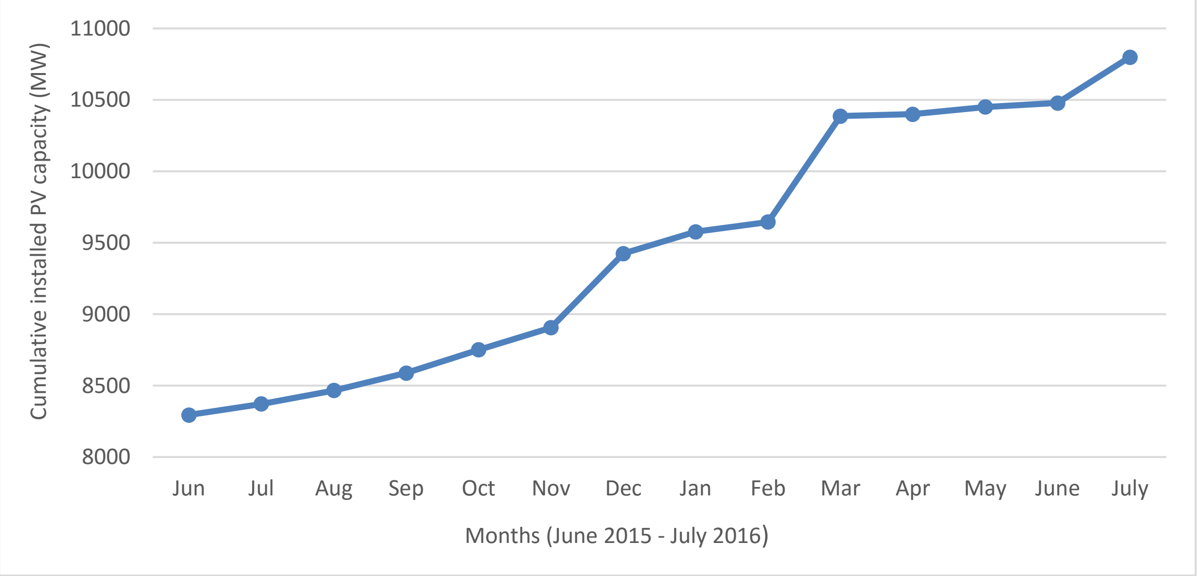

Figure 2.32: UK solar PV cumulative capacity from June 2015 to July 2016 (Source: http://www.gov.uk/government/statistics/solar-photovoltaics-deployment)

- ***Impact of FIT in Japanese solar PV energy***

Following the Tsunami that caused widespread damage to Japan and crippled the 4700 MW Fukushima-Daichi nuclear power plant, the Japanese government responded to the crisis by introducing a new FIT scheme to accelerate the penetration of solar PV on 01 July 2012 (Moosavian *et al.,* 2013; Muhammad-Sukki *et al.,* 2014). The scheme targeted the non-residential segments, such as large-scale PV projects, in the commercial and industrial sectors.

It was expected that there would be a reasonably high uptake of solar PV in the FIT scheme mainly because of the lucrative incentive given by the Japanese government. This scheme sought to obtain between 20% and 35% of energy from renewables by 2030. This target is achievable, taking into account solar irradiance and the FIT scheme that makes the renewable energy market favourable to IPPs and households. (Sahu, 2015). Solar PV energy is expected to increase the installed capacity to 28 GW by 2020 and 50 GW by the end of 2030. (Sahu, 2015).

This scheme was financed by the public through an increase in the electricity tariff (Muhammad-Sukki *et al.,* 2014). At the end of 2012, it was recorded that 1.7 GW of solar PV capacity had been installed in Japan, of which solar PV energy contributed 1.5 GW, then solar PV technology proved to have significant potential for electricity generation, compared to other renewable energy sources in Japan (Muhammad-Sukki *et al.,* 2014; Sahu, 2015). The side effect of FIT is that it is mainly financed by the public, meaning increasing electricity tariffs and that consumers could pay a significantly higher price per kWh unit of electricity. This may have an adverse impact on developing nations where the citizens are relatively poor.

- ***Impact of FIT in Malaysian solar PV energy***

The Malaysians introduced the FIT in 2011 after a long process of getting the legislation passed by the cabinet. The eligible technologies were biogas, landfill, small hydro and solar PV energy. As in many other countries, consumers through an increase in electricity tariffs (Muhammad-Sukki et al., 2011) finance the FIT scheme. In 2013, the installed solar PV capacity was approximately 20 MW. It is believed that it has the potential to reach more than 6500 MW by 2030 (Wong *et al.,* 2014). Since the introduction of the FIT, renewable energy technologies have produced 142441 MWh in 2012, 360320 MWh in 2013 and 212971 MWh in 2014 (http://seda.gov.my). To date, the renewable energy capacity (MW) under the FIT scheme from the commencement is 191.80 MW (Table 2.9). Solar PV generation has been the highest contributing renewable energy technology that contributed 116 MW from 2012 to 2014.

Table 2. 9: Installed capacity of renewable energy technologies under FIT in Malaysia (Source: http://seda.gov.my)

RE technology	**Year**			
	2012	**2013**	**2014**	**Total**
Biogas (MW)	2	3.38	0	5.38
Landfill (MW)	3.16	3.20	0	6.36
Biomass (MW)	43.40	0	0	43.40
Solid waste (MW)	8.90	0	0	8.90
Small hydro (MW)	11.70	0	0	11.70
Solar PV (MW)	31.57	83.11	1.38	116.06
Total (MW)	100.73	89.69	1.38	191.80

Prior to the introduction of the FIT, Malaysia’s electricity capacity through renewable energy was 50 MW and is expected to reach about 2000 MW by 2020 (Chua and Oh, 2012). For that reason, the FIT has been proven the right mechanism to uplift the contribution of renewable energy technologies in both developed and developing countries. Just two years after its introduction in Malaysia, it had made a contribution of just below 200 MW.

- **Impact of FIT in South Africa**

The FIT policy was investigated in South Africa and tariffs were suggested for different renewable energy technologies. The policy was ultimately not implemented, instead the country chose competitive bidding. The prices that the IPPs bid were much less than what the FIT was suggesting. Therefore, FIT requires prices to be carefully set, overgenerous tariffs become beneficial to the generators and results in the public paying for such high cost, which could have been less if the implemented policy was different.

2.9.1.2 Competitive bidding

Competitive bidding is a transparent procurement method in which bids from competing contractors, suppliers, vendors, and bidders are invited by openly advertising the scope, specifications, and terms of reference of the proposed contract, as well as the criteria by which the bids are evaluated. Competitive bidding aims at obtaining goods and services at the lowest prices by stimulating competition among bidders.

In open competitive bidding (also called open bidding), the sealed bids are opened in full view of all who may wish to witness the bid opening and in closed competitive bidding (also called closed bidding), the sealed bids are opened in the presence of only the authorised personnel.

Most developing countries are implementing competitive bidding that is funded by the state. South Africa is a case in point; the IPP Procurement Programme was established in 2011. By the end of 2015 there was approximately 6 GW registered from different renewable energy technologies (DOE, 2015).

2.9.1.3 Tax incentives/credits

A tax incentive is often made available to increase the competitiveness of renewable energy technologies. This incentive includes tax credits, a tax reduction or tax exemption. In Eastern Asia, in the Philippines, generating electricity from renewable energy is exempted from income tax for the first seven years of operation. After that the power plant pays a reduced tax rate of 10% annually (Ölz and Beerepoot, 2010). It is not clear whether the tax credit and tax reduction are applicable to any renewable energy technology of any size, or whether it is for certain technology with a particular minimum capacity.

Furthermore, companies that build renewable energy power plants pay no custom duty on materials imported into the country for the power plant construction, and no value added tax is paid either on the green electricity that these power plants sell (Ölz and Beerepoot 2010).

2.9.1.4 Capital cost/direct cash grants/rebates

This scheme is intended to reduce investment costs. It is a common means of overcoming high initial capital costs in many renewable energy technologies. The capital cost grant is heavily reliant on the state budget and this can affect the stability and sustainability of the scheme negatively. Limited financial means, especially in developing countries, can result in limited possibilities for the introduction of the capital cost grant.

In Asia, Thailand has introduced a financial incentive scheme with some elements of a capital cost grant. The programme is funded by a fossil fuel tax and has provided financial assistance and incentives to renewable energy as well as research and development programmes (Ölz and Beerepoot, 2010).

2.9.2 South African renewable energy policies and regulations

South Africa has a high level of renewable energy potential, solar power in particular. Moreover, the Minister of Energy has made a determination of 3725 MW to be generated from renewable energy sources through the IPP programme. This 3725 MW is required to ensure the continued uninterrupted supply of electricity (Table 2.10). The determination is broadly in accordance with the capacity allocated to renewable energy generation in the IRP 2010-2030.

Table 2.10: The allocation of MW per renewable energy technology

RE technology	Allocated MW
Onshore wind	1 850
Concentrated solar power	200
Solar PV	1 450
Biomass solid	12.5
Biogas	12.5
Landfill gas	25
Small hydro	175
Total	3 725

2.9.2.1 The Integrated Resource Plan

The IRP is a mechanism by which key electricity system, sustainability and government policy requirements are met. It answers questions such as what the electrical energy requirements in South Africa are, by when the capacity will be needed to provide the energy requirements and what is the appropriate mix of technologies is to meet these needs?

The IRP 2010-2030 was promulgated in March 2011 as a "*living document",* to be revised every two years. The electricity demand in 2030 is projected to be in the range of 345-416 TWh (IRP, 2013). The update of the IRP considers the aspirational economic growth suggested by the National Development Plan in order to reduce unemployment and alleviate poverty in South Africa.

Solar PV generation was allocated 2700 MW capacity over a period of eight years between 2012 and 2020, with wind energy allocated 2800 MW over a six-year period (Table 2.11). The IPP procurement programme ensures that developers are competing within the space of 2700 MW over an eight-year period for solar PV energy. Given the energy demand, electrification backlog, availability of land, solar radiation, population growth and economic development in South Africa, 2700 MW could have been allocated for two years instead of eight years. Moreover, the annual 300 MW for eight years is far too low, given the solar PV potential in South Africa. It should be that in the next two-year review of the IRP the allocation of solar PV generation should be increased to at least 1000 MW per year. This will stimulate economic development and increase solar energy growth in South Africa.

Table 2.11: The proposed solar PV, CSP, wind and coal MW allocation between 2013 and 2020 (Source: IRP 2010-2030, 2013)

Year	Energy technologies and new capacity allocation (MW)			
	Wind	CSP	Solar PV	Coal
2012	0	0	300	303
2013	0	0	300	823
2014	400	0	300	722
2015	400	0	300	1444
2016	400	100	300	722
2017	400	100	300	2168
2018	400	100	300	723
2019	400	100	300	1446
2020	400	100	300	723
Total	2 800	500	2 700	9 074

Coal has the highest allocation of 9074 MW between 2012 and 2020. This is over and above the current two coal-fired power plants that are under construction.

2.9.2.2 The independent power producer procurement programme

The South African government (Department of Energy - DoE) released the first round of renewable energy bids for the IPPs in 2011. By December of the same year, the 28 preferred bidders in the state's IPP procurement programme were announced. The second round of bidding closed in March 2012. The first 1451 MW allocated were divided across wind, solar PV and CSP systems. By 19 June 2012 the first-round bidders were expected to complete financial closure on their projects and begin construction in order to be operational by 2013 (DOE, 2015).

The competitive bidding was done in four different windows. For bid window 1, there were 28 bidders, which entered into agreements on 5 November 2012, with a total of 627 MW capacity for solar PV technology. For bid window 2, nine preferred bidders for solar PV power contributed to 417 MW (Figure 2.33). In competitive bidding window 3, a total of 93 bids were received on 19 August 2013. A total of 435 MW was allocated to solar PV projects (Table 2.12). On 16 April 2014, the DOE announced bid window 4, with 26 successful bidders that will make up to 813 MW (Figure 2.33)

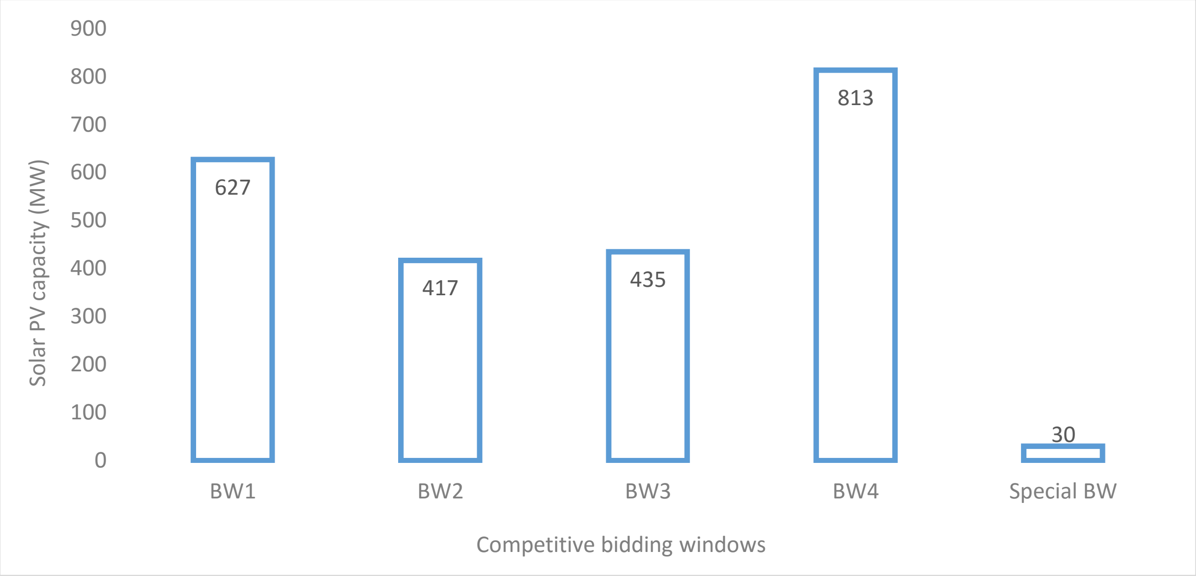

Figure 2.33: South African solar PV energy capacity procured (Source: DOE, 2015)

2.9.2.3 The Renewable Energy White Paper Policy

As part of promoting renewable energy technologies and increasing the share of renewables into the total energy mix, the DOE established the White Paper on Renewable Energy Policy in November 2003. The long-term goal for the government of South Africa is to establish a renewable energy industry that produces modern and sustainable energy sources for the future. These industries should be fully non-subsidised alternatives to fossil fuels (Department of Minerals and Energy, 2003a).

The White Paper Policy aimed to set out government objectives and targets for renewable energy technologies. This was triggered by the South African energy profile, which is highly dependent on fossil fuels. The 10000 GWh renewable energy contribution to final energy consumption by 2013, would be produced mainly from biomass, wind, solar and small-scale hydro. The renewable energy is to be utilised for power generation and non-electric technologies such as SWH and bio-fuels" (Department of Minerals and Energy, 2003a). However, the policy did not break down the renewable energy technologies to achieve the target.

2.10 Challenges and barriers in solar PV energy development

The renewable energy sector has not developed and grown at the pace and magnitude it should have over the past years, because of a number of impediments and barriers. The challenges and barriers differ from technology to technology and from country to country, depending on infrastructure development, policies and regulatory frameworks, financial support mechanisms and other factors. The challenges are as follows:

2.10.1 Economic barriers

The cost of many renewable energy technologies has been a major barrier to their widespread market introduction and penetration. This is mainly because they have not been economically competitive with energy sources based on fossil fuels. Policy and regulatory measures are crucial to bridging the economic gap (OECD, 2012). They provide for financial and infrastructure support. As long as the cost of a solar PV technology is above the cost of competing alternatives, the economic barrier will persist. In many parts of the world, the economic barrier is one of the major hurdles to the growth and development of solar PV energy.

2.10.2 Administrative and regulatory barriers

The lack of strong and dedicated institutions for the authorisation and permitting processes contributes to the slow pace of solar PV energy penetration and development. Various permits related to electricity generation, transmission and distribution licenses, water use licenses, waste licenses, environmental authorisations and atmospheric emission licenses, depending on the legislation of the country, are needed for the development and implementation of solar PV technologies.

The major barrier affecting renewable energy projects is the uncertain regulatory regime governing the energy sector. The key obstacles are the large number of organisations involved in permitting procedures and lack of coordination among the authorities involved, as well as the absence of a comprehensive and strategic renewable energy development plan (Ölz and Beerepoot, 2010).

Therefore, the factors that contribute to administrative and regulatory barriers are summarised as follows:

- Lack of a legal/regulatory framework for renewable energy sources;
- High number of authorities involved;
- Lack of coordination between different stakeholders;
- Renewable energy projects insufficiently taken into account in spatial and energy planning;
- Regulatory restriction for development of new energy technologies;
- Complexity and/or duration of obtaining permits and legal appeal procedures; and
- Complexity and/or duration of grid connection authorisation.

2.10.3 Financial barriers

The upfront capital costs for the establishment of a renewable energy project such as a solar PV plant are very high, hence lack of upfront financial support is one of the key barriers, especially for small suppliers. Adequate funding support mechanisms and financing products for renewable energy technologies are needed for the successful introduction and penetration of renewable energy technologies into the market.

A lack of adequate financing options for renewable energy projects persists, especially in developing countries. The biggest challenge for Africa to gain access to modern energy sources is lack of such financial mechanisms. A wide range of public financing instruments will need to be employed, including specialised funds to provide equity and debt for private sector ventures, and consumer subsidy schemes (Brew-Hammond, 2010).

The financial barriers are summarised as follows:

- Lack of experience and trust among financiers or investors;
- High capital costs;
- Lack of access to capital, especially in developing countries;
- Lack of access to consumer credit; and
- Absence of appropriate financing options, mechanisms and platforms.

2.10.4 Technical and infrastructure barriers

The electricity sector requires adequate infrastructure in place for it to be successfully implemented and sufficiently maintained. The generation, transmission and distribution of electricity requires sufficient network infrastructure, such as power grid lines, sub-stations or mini-substations to take power generated from a plant (solar PV energy), and switch to high voltage using step-down and step-up transformers for long distance transmission. Infrastructure barriers pose a challenge, especially in remote and small-scale grid-connected renewable energy installations such as solar PV projects (Ölz and Beerepoot, 2010).

The technical and infrastructure barriers are summarised as follows:

- Insufficient available grid capacity;
- System constraints such as weak transmission and distribution networks;
- Grid access that is not guaranteed and unclear grid connection rules;
- High grid connection costs and unclear pricing mechanisms;
- Remoteness from grid and limited opportunities to connect new and small-scale solar PV plants; and
- Electricity market structure, such as dominance of monopoly state-owned utilities.

2.10.5 Lack of public awareness and skilled personnel

Insufficient knowledge about the availability and performance of renewable energy technologies contributes to the slow pace and uptake of solar PV technology. Moreover, there is a lack of skilled personnel in the design, planning and construction of renewable energy projects, taking into consideration the availability of such renewable energy sources and their site-specific nature.

The lack of public awareness and skilled personnel barrier is summarised as follows:

- Land tenure issues such as land ownership and permitting procedures;
- High risk perception related to renewable energy technologies;
- Perception of unrealistically high costs for renewable energy technologies;
- Lack of awareness of social environmental impacts on non-renewable energy sources (fossil fuels); and
- Lack of skills and adequate training for renewable energy technology installation.

2.10.6 Research and development

Innovation, research and development are key parameters for the advancement of all renewable energy technologies, solar PV energy in particular. The slow pace of research to improve the performance and efficiency of solar PV energy hampers the application of the technology. The innovation value chain is summarised in Table 2.12. Academia, research and development as well as business are key sectors in transforming the solar PV market, through quality research until commercialisation. Consumers, the energy sector, government and exporters are the demand sectors after research and development. The rate of degradation also creates negative perceptions of renewable energy technologies. Research and development should unlock ways and means to reduce the rate of degradation and increase the efficiency of solar PV modules.

Table 2.12: Research and development value chain

Supply	**Innovation chain (phases)**					**Demand**
Academia	Basic research	Research and development	Demonstration	Deployment	Commercialisation (diffusion)	Consumers
Research centres						Energy sectors
Business						Government
						Exports

Investment in research and development is changing over time in the government and private sectors. While installed capacity in wind and solar technology has grown by 20% to 30% a year, private sector spending on wind energy has declined over the years. However, nearly USD 1 billion was poured into alternative energy research and development ventures in California in 2007 (Tanaka, 2008).

2.10.7 Market barriers

The fluctuations and inconsistence in pricing of solar PV modules and structures disadvantage their uptake and penetration of the industry. The PV price has declined recently, but high subsidies for fossil fuels create an unfair scenario in which renewable energy technologies have to compete.

The market barriers are summarised as follows:
- Lack of market competition;
- Asymmetrical availability of market information;
- Restricted access to technology;
- High transaction costs;
- Missing market infrastructure;
- Subsidies to conventional energy; and
- Taxes on renewable energy technologies.

2.11 Conclusion

There is a substantial potential of solar PV in South Africa. However, it remains unexploited. The competitive bidding that was introduced in 2011 is a good step to the right direction. The major side effect is that it focuses mainly on commercial large scale PV rollout, and exclude other sectors such as residential. The most active policy that would have been ideal for all sectors (residential, commercial, agriculture and mining) is REFIT. This policy would create an enabling environment whereby the rooftop solar PV could have been installed in many middle and high income residential class. The REFIT is an instrument that create market for renewable energy technologies (Pegels, 2010). Nonetheless, the competitive bidding has thus far added over 6000 MW capacity of renewable energy in the country.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

Research is a systematic, objective and thorough search for new information in a particular area such as solar PV energy. It is an investigation in order to obtain solutions to socio-economic, environmental or scientific challenges through objective analysis, which mainly refers to a search for knowledge and discovery of unknown or hidden solutions, truths, ideas or ways of doing things in order to advance and improve knowledge (Creswell, 2013). The data are collected from different sources in different ways and through different methods and techniques, which ultimately result in new contributions to the existing body of knowledge.

The methods, process, procedures and statistical approaches used to collect and analyse data, find solutions to research problems and fulfil the research objectives are called the research methodology (Kothari, 2004). It is the procedure used to describe, explain and predict the phenomena that occur broken down into the steps taken to ensure that good quality data are collected, which ultimately leads to production of new knowledge. The process includes a theoretical analysis of the body of methods and principles associated with a branch of knowledge in order to select those appropriate to the work to be undertaken. The research methodology adopted in this research collects data and uses it to produce quantitative and qualitative decision-making tools for the selection of appropriate places and sites where solar PV and hybrid energy projects can be established.

The study area for this research is South Africa. Hence, data collection was carried out in nine provinces of South Africa, namely Limpopo, Gauteng, Mpumalanga, KZN[3], the Eastern Cape, Western Cape, Northern Cape, North West and Free State (Figure 3.1). South Africa had a population of 51.8 million by 2011 (StatsSA, 2012a). The province with the largest population was Gauteng with 23.7% and the Northern Cape had the smallest population with 2.3%. Furthermore, Gauteng and KZN registered the

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[3] Kwazulu Natal

highest electricity consumption in the country, with approximately 39% of combined electricity consumption (Table 3.1). The volume of electricity available for distribution in March 2015 was 19627 GWh (StatsSA, 2015; Eskom, 2016). The generation capacity comprised a total of 42746 MW with 37780 MW from coal-fired power stations, 1940 MW from nuclear power stations and the remainder from hydro-electricity, solar, wind and gas turbines.

Table 3.1: Population and access to electricity per province in 2012 (Source: StatsSA, 2012a; StatsSA, 2015a)

Province	Population (%)	Access to electricity (%)	*Electricity (GWh) consumed in March 2015
Limpopo	10.4	90.5	960
Mpumalanga	7.8	88.4	2867
Gauteng	23.7	84.6	4868
Free State	5.3	91.5	685
North West	6.8	85.3	2055
KwaZulu-Natal	19.8	79.3	3529
Eastern Cape	12.7	80.4	721
Western Cape	11.2	90.5	1930
Northern Cape	2.3	91.9	415
Total	100		

Population growth and patterns influence electricity consumption. In March 2015, much of the electricity was distributed to Gauteng Province, due its high population and economic activities (Table 3.1). The province where least electricity was distributed in March 2015 was the Northern Cape, namely 415 GWh (Table 3.1), which has the lowest population. The total electricity consumed in March 2015 across the country was 18030 GWh with 27% going to Gauteng and 2.3% going to Northern Cape, there is a direct relationship between population and electricity distribution across the country. The Northern Cape and Eastern Cape Provinces are the largest provinces in size and Gauteng the smallest (Figure 3.1). Therefore, the land area of the province is clearly not a good guide to electricity consumption.

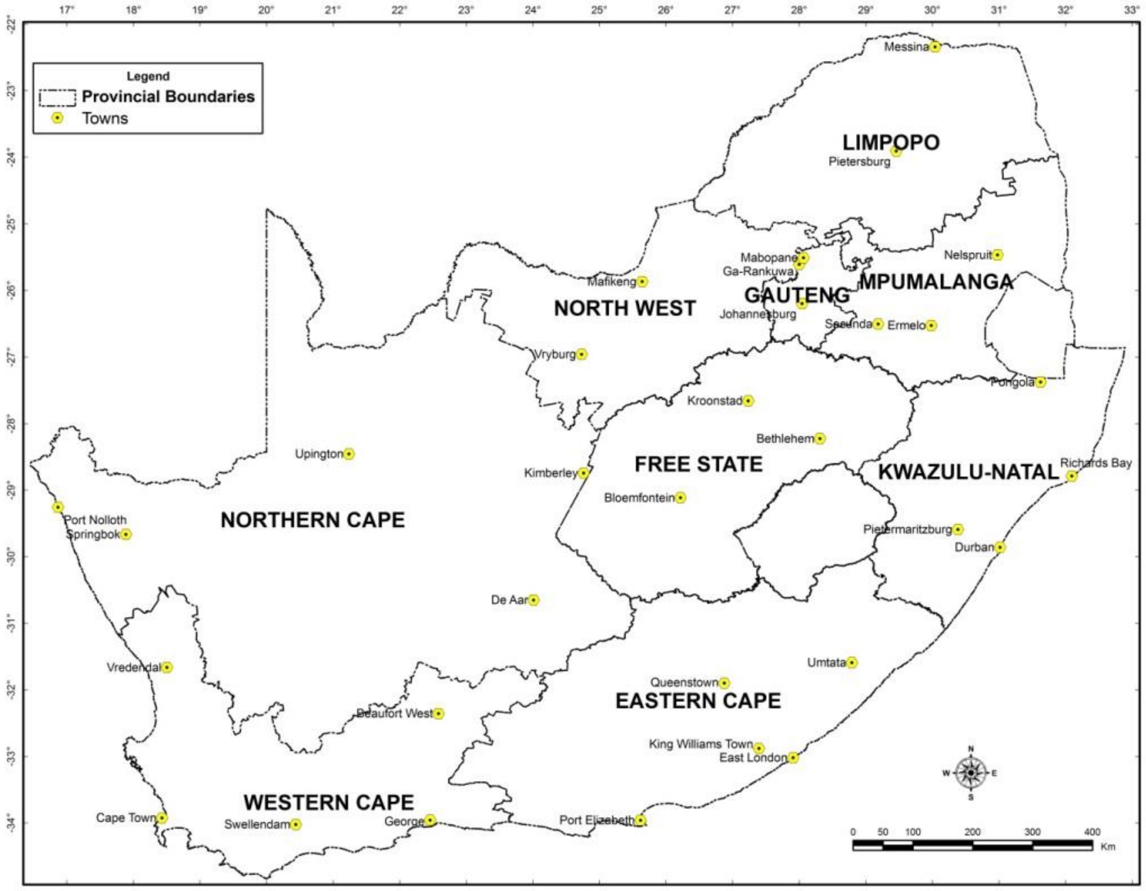

Figure 3.1: South African map depicting nine provinces

3.2 Research method

The mixed research method (qualitative and quantitative) was used in this study. It is an approach that deploys strategies of inquiry involving collecting data either simultaneously or sequentially to best understand the research problems (Creswell, 2013). It combines quantitative (for example, a survey or census for running the models) and qualitative (for example, interview or questionnaire) research methods (Kerlinger, 1979). Moreover, in this study a mixed research method produced a combination of statistical and interview data, which are referred to primary and secondary data (Figure 3.2). The primary data were collected through interviews and questionnaires. The interviews were conducted with different stakeholders, such as inhabitants of a residential settlement in two district areas of each province (Figure 3.3). The qualitative data were collected from four distinct stakeholders, namely government, generators, solar PV installers and residential households. Eight steps of data collection, analysis and presentation are summarised in figure 3.4

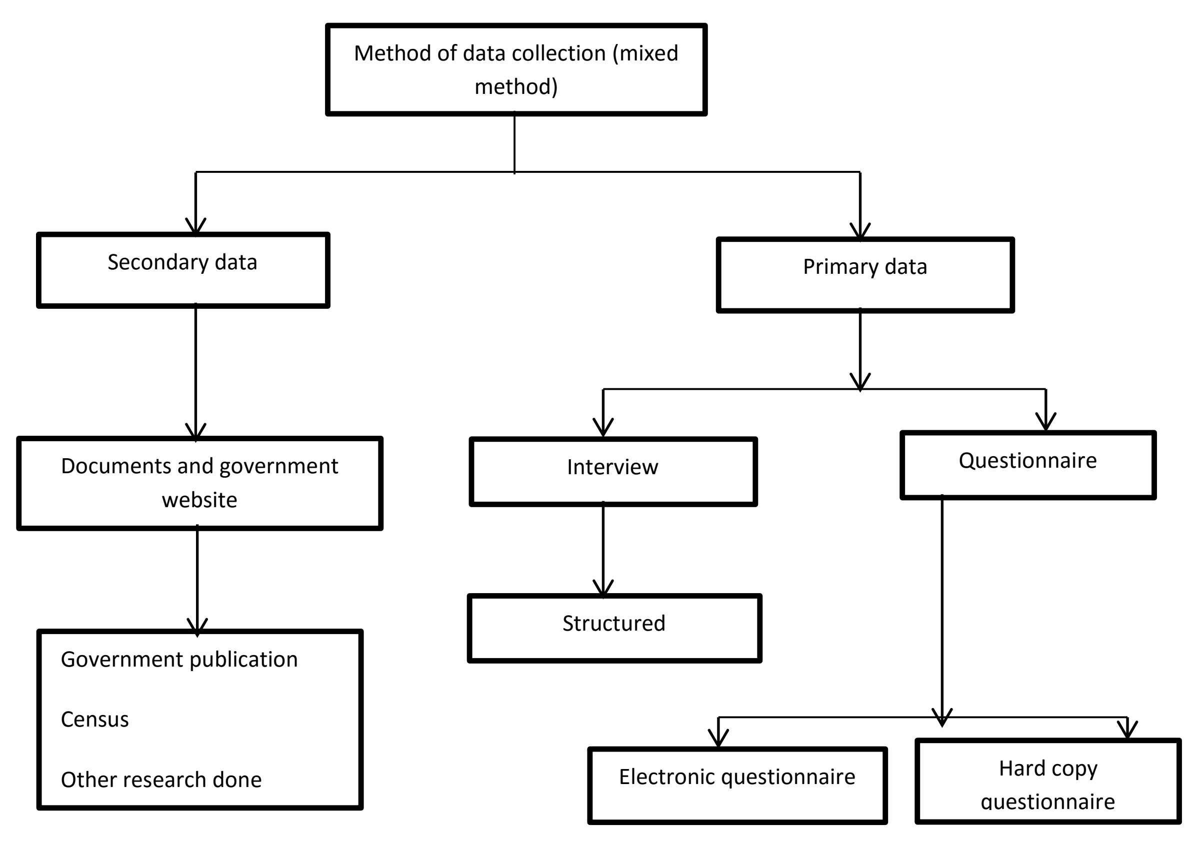

Figure 3.2: The structure of mixed method data collection

3.3 Data collection method and sampling design

To conduct a study in a huge area such as an entire country, sampling is required. This is a technique of selecting a representative part of a population for the purpose of determining parameters or characteristics of the whole population (Creswell, 2013). In this study the samples were selected because the population (country) is too large to study in its entirety. A sample is a subset of a population. Therefore, the samples were representative of the general population.

The probability sampling methodology that is known as random sampling was employed in this study. This is the sampling design giving every individual in the population an equal chance of inclusion in the sample (Kothari, 2004). It is a method of sample selection that gives each possible sample combination an equal probability of being picked up, and each item in the entire population an equal chance of being included in the sample. This sample design type ensures the law of s*tatistical regularity*, which states that if an average of the sample chosen is a random one, the sample will have the same composition and characteristics as the general population.

Primary (interview and questionnaire) and secondary (for modelling) data were collected and analysed in this study.

3.3.1 Primary data collection

The type and structure of primary data collected from the stakeholders are depicted in the questionnaires and the questions asked during the interviews (Appendices, A, B, C and D). The specifics on the data collected and analysis are presented in the methods and material section of each chapter from 4 to 7. Additional data (for appendices A, B and D) was collected to ensure that the research objectives are satisfactorily fulfilled and research questions are adequately answered. The questions for additional data are depicted in the appendices.

3.3.1.1 Residential households

The data from the residential households were collected in nine provinces across South Africa. Two random sampling methods were used for the residential settlement/electricity consumers (data sources):

- ***Stratified random sampling***

Stratified random sampling was used to select the sample in order to give every individual (residential households) in the population (country) an equal chance of inclusion in the sample. It is a sample method that involves the division of a population (country) into smaller groups known as strata. For this study, the strata are referred to as provinces. Consequently, the population (country) was broken down into nine (strata) provinces (Figure 3.3).

- ***Systematic random sampling***

Systematic random sampling was used to complement the stratified random sampling in this study. It is a sample method that yields a more representative sample than a simple random one, especially when the sample size is small (provinces), and needs to be broken down into district areas within the provinces (Figure 3.3). It seeks to eliminate sources of bias. Systematic sampling is a sampling method in which sample members from a larger population are selected according to a random starting point and at a fixed periodic interval.

The systematic random sampling yields more accurate results than simple random sampling. This interval depends on the number of population, for instance, in the provinces with 5 districts, the interval could be 2, meaning that after every second district the third one is chosen. In this research, the district municipal areas were listed and every third district municipal area in each province was selected. Then two districts in each province were included in the sample, for example in Limpopo Province, the Capricorn and Vhembe districts were selected for data collection in this study (Figure 3.3).

A team was established in each province for data collection. The team was comprised of students chosen from the nearest University or College, mainly in the Faculty/Department of Natural Sciences, Environmental Sciences or Electrical Engineering as the understanding on the subject is anticipated to be better than students from other Faculties. Each team was comprised of four students. Therefore, a total of 36 students participated in the residential household data collection in nine provinces across the country. This is believed to have benefited students as they learnt skills on the field data collection and it was one way of preparing them towards their postgraduate studies.

The students were given training by the researcher. The training took place prior to field data collection. The training included the following aspects:

- Community members general behaviour during data collection;
- Understanding of solar PV;

- Electrical appliances;
- How to fill in questionnaire;
- How to handle difficult community member; and
- Suppliers of electricity in South Africa (which is Eskom and some Municipalities).

The decision to get students in the nearest University was for two reasons; namely: 1) the students are able to communicate with the residents using the local language, hence the communication becomes better and easier for the residents to understand the questionnaire during data collection; and 2) local students are familiar with the villages/locations around, hence it would be easier to approach community members. In the field data collection, there is an element of errors and biasness in the first few days of data collection. However, as data collection continues the experience and confidence of field workers grow up and errors and biasness may reduce or stop, if ever they were there in the first place. In order to check, verify and validate the data; the first 50 questionnaires were compared to the last 50 questionnaires to check the variation and consistency. This helped to ensure that there are no mistakes, errors or biasness from students.

In rural areas, the Headmen were approached by the researcher and the data collection team requesting permission to collect data in their villages. A letter from Newcastle University and researcher's university student card were presented to the Headmen for credentials and legitimacy of the project (Appendix F). There are some villages where the data was collected on Sundays. This was because the Headmen would have called for the meeting with all residents in the village to communicate matters concerning the village, thus the data collection team waited until the meeting came to an end, then collected data from members of the community. Some residents, especially senior citizens or pensioners were unable to write; in this case, the data collection team members were asking questions and filling in the questionnaire on their behalf.

Apart from team of students that collected data from the residence using hardcopy questionnaire, there was an electronic questionnaire that were sent to the residents through e-mail using the '*SurveyMonkey*' website (www.surveymonkey.co.uk). The questionnaires were sent to the members of community in the same district municipalities across the country. The e-mail addresses were collected from the provincial government departments, municipalities and private organisations that are based in the district areas selected (Table 3.2). The communication divisions were approached and a request for e-mail database was made. The letter from Newcastle University (Appendix F) and a student card were produced for verification by the organisations before the release of e-mail database.

The e-mail addresses were collected and a database was established where a link on the '*SurveyMonkey*' data collection website was sent through to the respondents. The response turnover was not great at first, reminder e-mails were sent four times and in the end, approximately 70% responded though. The breakdown of responses per reminder was that approximately 20% responded after the initial e-mail with *'SurveyMonkey'* link for questionnaire. The first reminder e-mail was sent and 40% responded, 20% responded after the second reminder e-mail, 15% responded after the third reminder e-mail and 5% responded after the fourth reminder e-mail.

The main challenges experienced during data collection on a house to house and *'SurveyMonkey'* were as follows:

- Respondents took too long to complete questionnaire, reminder e-mails were sent four times, and approximately 70% of the respondents completed the questionnaire;
- Respondents did not like questions in which they are supposed to explain, rather prefer questions that they would put tick in a box;
- Some respondents were not willing to complete the questionnaire;
- Some respondents asked for money in exchange for completing questionnaire;
- In some houses there were dogs which threatened to bite the data collection team members;
- Some respondents said the questionnaire is too long;
- Some respondents did not know their electricity supplier because they are not the ones that pay the bill;
- Some respondents did not know what solar PV is all about; and

- Many respondents did not like the household income category (low, medium to upper) question, they deemed it too personal and private. Therefore, it was subsequently removed from the questionnaire.

The questionnaire used for data collection at the residential households is appended in Appendix A.

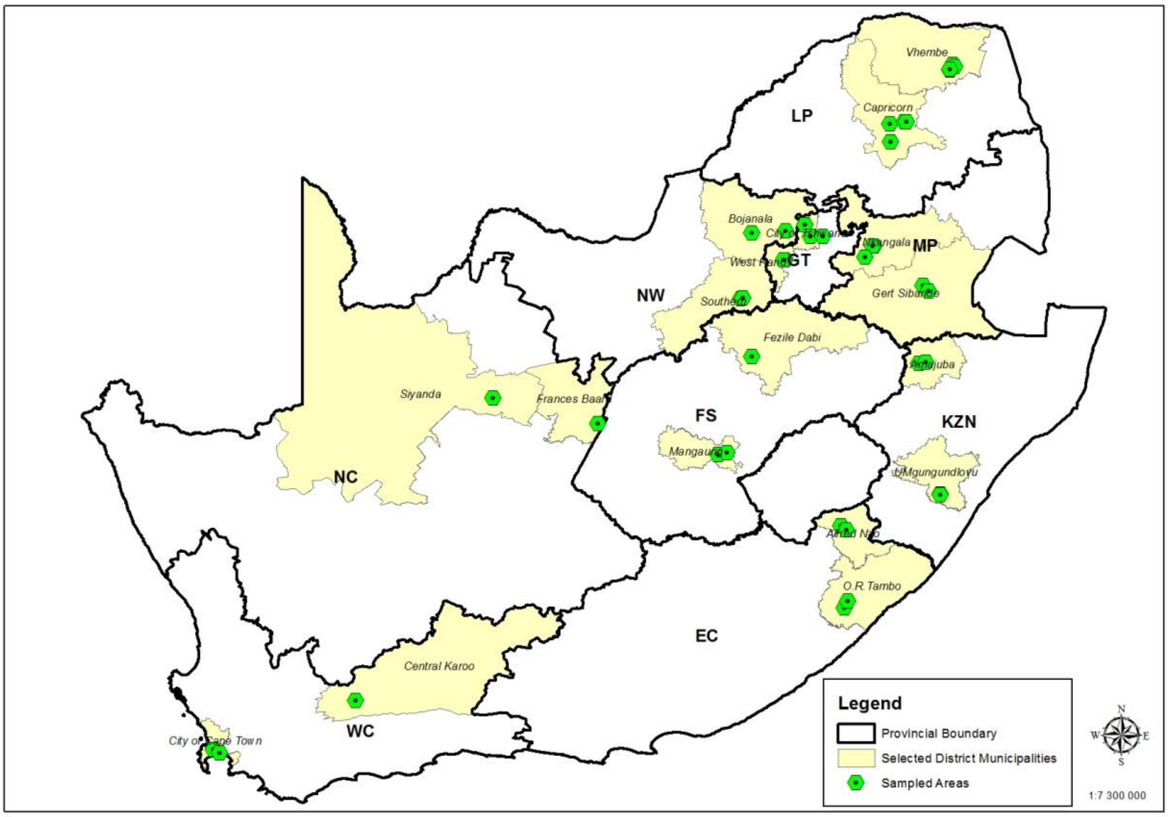

Figure 3.3: Villages and towns that data was collected in two districts from each province

Thirteen thousand (13000) questionnaires were completed across the country in two district municipalities in each province. There were 60% questionnaires for the villages and informal settlements, which totalled 8800 from 18 district municipal areas, where data was collected though hardcopy questionnaires. On average each student collected approximately 250 data questionnaires.

The remaining 40% was collected from the cities and suburbs, which is 4200 (this is 70% of the questionnaires sent through in e-mails). The questionnaire was sent to a total of 6000 e-mail addresses, and 4200 responses were received, with 1 800 responses that were not received, despite all the reminders. More information on the province, municipal areas and number of questionnaires completed in each municipality is detailed in table 3.2. On average a total of 720 questionnaires were completed for each municipal area (Table 3.2).

The establishment and training of data collection teams in each province took place from January – March 2014. The data collection started in April 2014, preliminary data was analysed in June 2014 in preparation of the first year viva examination. The data collection and capturing continued from September 2014 to March 2015. This was because in other provinces such as Northern Cape and Kwazulu Natal the responses were low, and from mid-October to early December the students were writing their examinations.

Table 3.2: Locations where data was collected and number of questionnaires collected

Province	**Municipality**	**Villages/Towns where data was collected**	**University/College that students are based (for hardcopy questionnaires)**	**Number of questionnaires completed**
Limpopo	Vhembe	Thohoyandou Shayandima Tshino Vyeboom	University of Venda	1200
	Polokwane	Polokwane Chuenespoort Ga-Mothiba	University of the North	850

Province	**Municipality**	**Villages/Towns where data was collected**	**University/College that students are based (for hardcopy questionnaires)**	**Number of questionnaires completed**
	Mogale	Kagiso Krugersdorp	West Rand College	626
Mpumalanga	Nkangala	eMalahleni Ogies Masakhane	Tshwane University of Technology-Nelspruit Branch	580
	Gert Sibande	Ermelo Camden	Gert Sibande FET College	450
Kwazulu Natal	Amajuba	Newcastle Ngagane	Majuba FET College	835
	Umgungundlovu	Richmond Ndaleni	Umgungundlovu FET College	480
Eastern Cape	OR Tambo	Mthatha Nyandeni	Walter Sisulu University	756
	Alfred Nzo	Mbizana Dumasi	Walter Sisulu University	790
Western Cape	Cape Town	Khayelitsha Gugulethu	Cape Peninsula University of Technology	855
	Central Karoo	Laingsburg	South Cape College	480
Northern Cape	Francis Baard	Kimberly	Northern Cape Urban College	890
	Siyanda	Postmanburg	Northern Cape Urban College	587
North West	Bojanala	Rustenburg Brits	Springfield College	789
	Dr Kenneth Kaunda	Ikageng Potchefstroom	West Rand College	613
Free State	Mangaung	Thabanchu Botshabelo	Central University of Technology	713
	Fezile Dabi	Kroonstad	West Rand College	633
Total questionnaires				**13007**

3.3.1.2 Solar PV companies

The South African Photovoltaic Industry Association (SAPVIA) is an organisation whose members are active in the solar PV technology sector. The SAPVIA is a non-profit association representing members largely made up of developers, manufacturers/installers and service providers operating within the PV industry. The association is devoted to promoting the growth of South Africa’s solar PV electricity market and representing the industry to provincial and national Government.

A list of solar PV companies was obtained from SAPVIA. The systematic sampling was used to select the companies for data collection through interviews. The list comprised 28 companies. The data to be collected for this research involve various sectors such as residential, generators, government and solar PV companies for the primary data. Moreover, there was also a secondary data to be collected for the modelling. Therefore, the researcher decided to cover at least 20% of the solar PV companies received from SAPVIA instead of interviewing all 28 companies due to volume of data collection for all sectors. The interval was three, meaning that every third company in the list was chosen (Appendix B). Then out of 25 companies, 9 were chosen and interviewed. The 9 companies represented more than 20% of the total sample size. This method yielded a more representative sample than the random sample.

All nine companies were interviewed. Seven companies are based in Gauteng Province with satellite offices in other provinces where they have solar PV projects. The researcher went to their offices where the interview meetings took place. The other two companies are based in Durban. Telephonic interviews were conducted and 5 companies requested the results of the study when the report is completed. The company representatives that were interviewed were the Business Development Managers in seven of the companies, whilst in the other two they were technical personnel that are involved in projects on the site. Not all the companies were comfortable with the questions around the cost of their PVs and proportion of their customer base (residential, commercial, mining etc.). The reason cited was confidentiality, fear that their competitors might unfairly, and unlawfully use the information to attract customers, even though the researcher explained that data given is confidential and will neither be divulged to other parties nor used for other things except for research work. The prices given on the questions asked was therefore a general price, but not company specific prices.

The challenges experienced were to secure the appointment for interviews. Most of the Business Development Managers seemed to be extremely busy with meetings after meetings day in day out. The researcher made several follow-ups until the meeting took place for data collection. Similarly, for the two companies in Durban it was difficult for the company representatives to be available for telephonic interviews.

3.3.1.3 Government

The government departments that deal with energy matters were identified. Four departments were approached by the researcher and interviews were arranged. The researcher presented the letter (Appendix F) and student card to confirm the credentials and legitimacy of the project. The departmental spokesperson identified the relevant Senior Manager for the interview. Then the researcher arranged a meeting directly with the representative of the department.

The interviews took place and representatives in all departments were helpful and answered all the questions (Appendix C). The departments that were interviewed are:

- Department of Energy (Energy policies, strategies and legislation);
- Department of Science and Technology (Energy research, development, and technology innovation);
- Department of Trade and Industry (Import and export of energy resources and equipment); and
- National Energy Regulator of South Africa (Energy tariffs determination and approval).

There were no challenges encountered with the government sector regarding data collection. The departments gave their best cooperation and there was an interest regarding the research findings.

3.3.1.4 Generators

The South African electricity sector comprises the national utility (Eskom Holdings) that generates over 90% of the total electricity production in the country. The remaining less than 10% comes from the municipalities and private generators. Therefore, data was collected from Eskom Holdings and other smaller generators (Table 3.3).

Table 3.3: Electricity generators from different energy sources

Generator	**Capacity (MW)**	**Power source**
Eskom	42 000	Coal, Gas, Oil, Nuclear, Hydro, Wind
City of Tshwane	480	Coal
Bethlehem Hydro	7	Hydro
Kelvin power station	420	Coal
Darling wind farm	5	Wind

The data from Eskom Holdings was collected in April 2014, and for the other generators was collected in October and November 2014. The data for Eskom was collected in two separate meetings in a form of discussion and completing questionnaire, the reason for two meetings was that in the first meeting the Eskom representative did not have all the facts and figures as the company is big with over 40000 MW power generation. A questionnaire (Appendix D) was sent to the other three generators for completion.

There were no challenges experienced in data collection from the generator except that the researcher had to make follow up for the questionnaire to be completed by the three generators (except Eskom Holdings).

3.3.2 Secondary data collection

The secondary data were for statistical purposes to enable modelling to be performed. These were the data for solar irradiance, wind speed, population, land space, electricity tariffs, electrification backlog, and electricity consumption. These data were collected from published documents supplemented by the respective organisations' websites from 01 September to 30 November 2014, (StatsSA, 2012a; StatsSA, 2012; StatsSA, 2013; StatsSA, 2015; Department of Minerals and Energy, 2006; Department of Energy, 2009; City of Cape Town, 2014; Ethekwini Municipality, 2014). These included data on the census (population of South Africa) and households' energy survey. The data on solar and wind energy were collected from the SWERA website (http://en.openei.org/apps/SWERA/) and NASA, cited in Boxwell (2014) and Mortensen *et al.,* (2014).

3.4 Modelling

The implementation of solar PV energy (grid-connected and off-grid) and hybrid energy systems requires consideration of a number of factors. Options, evaluation and requirements need to be framed within an overall decision-making process. This approach seeks to identify potential areas and sites for the setting up of solar PV grid-connected, off-grid and hybrid energy systems, and to enable the authorities to take well-informed decisions on the country's future energy policies, strategies and legislation.

The option evaluation approach refers to *optioneering*. It is a structured evaluation of options in support of decision-making. Such an evaluation takes the form of an option study that collates information on options and the different attributes that influence the decision to be made and also consider how the decision is influenced by different value judgments (Authority, 2010). *Optioneering* is often used to select the most appropriate course of action whenever there are many competing options and there is no single objective to be satisfied. The objective is to investigate and identify opportunities for siting solar PV systems optimally.

- **Method used for running the models**

There are various methods for running the models and techniques for weighting attributes in each model. Emanating from section 2.6.1 (Modelling) in Chapter 2, TOPSIS was used to run the models in this research. It is simple and fairly easy to follow and understand, and is more transparent, compared to other methods. This method is one of the major decision making tools in the Asian Pacific areas, it has been successfully applied in taking decisions in a number and variety of subjects such as human resources, manufacturing, water management and quality control (Shih et al., 2007). By comparison with other method as discussed in section 2.6.1 of chapter 2, this method is more suitable for this research.

- **Software used for modelling**
  - **Design Matrix Methods Application version 1.0 © 2009 by John Dalton**

The software used for running the model was the Design Matrix Methods Application (DMMA) version 1.0 © 2009 by John Dalton (John.Dalton@ncl.ac.uk)[4]. It contains various methods for running the model and techniques for weighting attributes.

The cross-scoring matrix was used to analyse the potential of solar PV in different provinces using different parameters (Tables 3.4 and 3.6). The attributes were converted into percentages (%) in order to enable the software to analyse the data. The conversion of units into percentage for each provinces was done through multiplying the solar radiation (kWh/m^2) by 100 and dividing by the total solar radiation (kWh/m^2) for all provinces

Example of solar radiation conversion into percentage:

$$\boldsymbol{Solar\ radiation}\ (\%) = \frac{\boldsymbol{kWh/square\ meter\ x\ 100}}{\boldsymbol{Total\ kWh/square\ meter\ for\ all\ \ provinces}}$$

The parameters/requirements that were used in the modelling are:

- Solar radiation (kWh/m^2);
- Electricity tariff (c/kWh);
- Wind (m/s) [for hybrid model only];
- Available land space (km^2);

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[4] John Dalton, Director: Engineering Design Centre,
School of Chemical Engineering and Advanced Materials, Merz Court,
University of Newcastle upon Tyne, NE1 7RU United Kingdom, Telephone: +44(0)191 208 8556

- Electricity consumption (GWh);
- Electrification backlog (%); and
- Population (million).

The ‘*optioneering’* approach was taken within the modelling parameters and requirements, and hence enabled the options, clearly indicating various choices that could be taken in setting up solar PV plants.

The following modelling processes were performed:

3.4.1 The potential of solar PV application in different provinces

The potential of solar PV application depends on a number of factors and requirements. Various characteristics determine the potential, suitability and effectiveness of solar PV application. The cross-scoring matrix was used to determine potential solar PV application across the country (Table 3.4).

In order to analyse and understand solar PV potential when different parameters are incorporated in the modelling, it is important for the model to be conducted in different scenarios. This helps to understand which scenario is suitable for which province and based on which parameters. Hence, it helps the authorities to take an informed decision. For instance, scenario 1 may come out with good solar PV potential in province x due to the weighting in different parameters, and scenario 2 may come out with equally good potential in province y because of certain parameters that are ideal in a specific province based on several factors around the province including the available space, electrification backlog etc.

There were 3 scenarios that were conducted in this research. The scenarios are differentiated by weightings, which the template is depicted in table 3.4. The data is presented in chapter 4 and 5. That is each parameter has its own weight for modelling. This is to identify avenues for the solar PV potential because provinces have different characteristics such as different land sizes, population density and magnitude of solar radiation. Therefore, 3 scenarios are reasonably sufficient to give an indication of different types of solar PV potential across different provinces.

Table 3.4: Cross-scoring matrix for solar PV and hybrid energy systems application in different provinces

		Options									
Requirements/attributes (%)	**Weight (%)**	**LP**	**GP**	**NW**	**KZN**	**MP**	**EC**	**WC**	**NC**	**FS**	**Total**
Solar radiation											
Electricity tariff											
Land space											
Population											
Electrification backlog											
Electricity consumption - 2013											
Total points											

Where LP: Limpopo Province, MP: Mpumalanga Province, GP: Gauteng Province, KZN: KwaZulu-Natal Province, EC: Eastern Cape Province, WC: Western Cape Province, NC: Northern Cape Province, FS: Free State Province, NW: North West Province

The parameters have different weights because their roles in solar PV differ according to their significance in determining potential. The weights for 3 scenarios obtained from different sectors, scenario 1 weight was obtained from government departments; scenario 2 weight was obtained from the Universities; and scenario 3 weights was obtained from the solar PV industry.

- **Scenario 1**

The government departments (Appendix C) were requested to allocate weight for different parameters in accordance with their experience and expertise in so far as solar PV is concerned. The average weights were determined by summing all four departments' scores and then divide by 4. The template used for the averaging the departments' score is depicted in table 3.5.

Table 3.5: Weight per attribute to be determined by the government departments

Requirements (%)	**Government department 1**	**Government department 2**	**Government department 3**	**Government department 4**	**Total**	**Average**
Solar radiation						
Electricity tariff						
Land space						
Population						
Electrification backlog						
Electricity consumption						
Total points						

- **Scenario 2**

The academic sector (South African Universities) was requested to allocate weight for different parameters in accordance with their experience and expertise in so far as solar PV is concerned (Appendix G). The Head of Environmental Sciences or Science related departments and Professors responsible for Energy were identified and requested to nominate the suitable staff member to allocate weight for different parameters. The average weights were determined by summing all Universities' scores and then divide by the number of Universities that have responded. The template used for the averaging the departments' score is depicted in table 3.5.

- **Scenario 3**

Just like scenario 2, the solar PV sector (Annexure B) was requested to allocate weight for different parameters in accordance with their experience and expertise in so far as solar PV is concerned. The average weight was determined by summing solar PV industry's scores and then divide by the number of the solar PV companies that have responded. The template used for the averaging the departments' score is depicted in table 3.5.

3.4.2 The potential of hybrid energy systems in the coastal provinces

The model for a hybrid system was similar to the one for solar PV potential; the difference was that wind energy was added in the matrix, the template used is depicted in table 3.6. The weight for scenarios is similar to section 3.4.1, the difference is that for scenario 3 the weight included wind energy in the modelling.

The three coastal provinces (Eastern Cape, Western Cape and Kwazulu Natal) were chosen because they are located in windy coastal part of South Africa. They are the only three provinces that are situated in the coastal area, with an exception of Northern Cape, which part of it has coast. Moreover, provinces such as Eastern Cape and Kwazulu Natal have relatively higher electrification backlog yet with good solar radiation and wind energy.

Table 3.6: Cross-scoring matrix for solar PV and hybrid energy systems application in different provinces

		Options									
Requirements/attributes (%)	**Weight (%)**	**LP**	**GP**	**NW**	**KZN**	**MP**	**EC**	**WC**	**NC**	**FS**	**Total**
Solar radiation											
Wind Energy											
Electricity tariff											
Land availability											
Population											
Electrification backlog											
Electricity consumption -2013											
Total points											

3.5 Software for data analysis

The data was collected in both numeric and text format. Microsoft Word, Excel and ArcGIS software was used in this study. The software was used as follows:

3.5.1 Text data

The Microsoft office package was used to analyse the text data. This includes Microsoft Excel, Microsoft Word and ArcGIS software. The data were captured and stored in Microsoft Excel and analysis was performed. The results are presented in tables, graphs and pie charts.

The ArcGIS software was used to draw a map showing the districts where the data had been collected. The solar radiation data were analysed and maps were produced using this software. Some of the analysed data from Microsoft Excel were presented in map format drawn from the ArcGIS software.

3.5.2 Numeric data

Microsoft Excel was used to store and analyse the numeric data specifically for the models. The data were collected from different sources and captured in the model. Analysis was performed through this software.

3.6 Overview of the research undertaken

The research involved various steps from data collection (chapter 3) to the presentation of the results (chapter 4, 5, 6 and 7) [Figure 3.4].

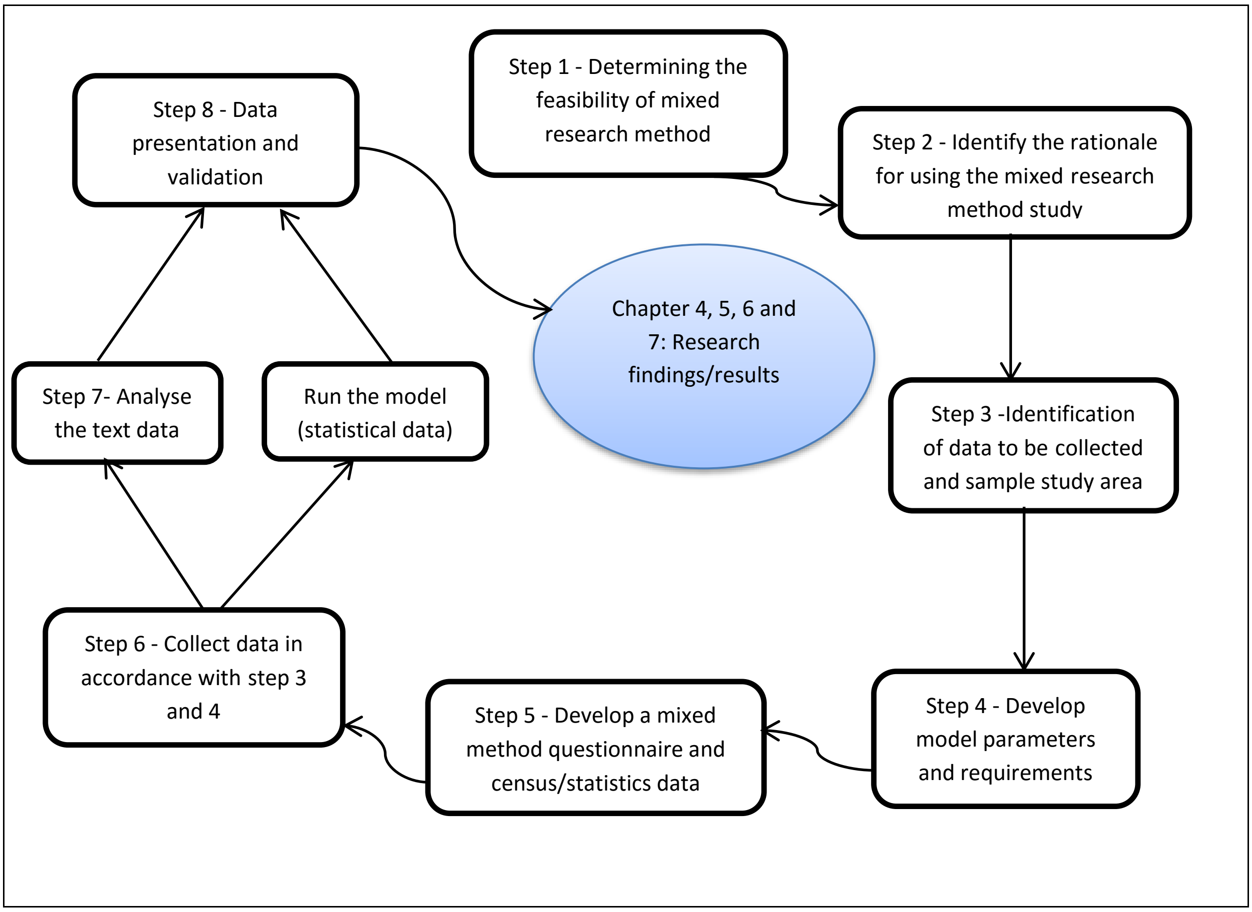

Figure 3.4: Steps followed for the mixed research method

CHAPTER 4: POTENTIAL OF SOLAR PV SYSTEM APPLICATION IN DIFFERENT PROVINCES

4.1 Introduction

Energy is the crux of any development worldwide; it is an essential requirement for socio-economic activities, production of goods and the provision of services in all spheres of life (Ma *et al.,* 2014). The solar PV system has substantial potential to supply in the ever-increasing energy demand. The need for additional power to meet the growing demand, specifically clean energy in an effort to reduce emissions and minimise reliance on fossil fuels, has led to South Africa establishing the Renewable Energy Independent Power Producers (REIPP) procurement programme for the installation of renewable energy technologies. South Africa has different climatic conditions with different levels of solar PV output and potential compared to other countries that have installed significant solar PV systems. This chapter investigates and assesses the solar PV potential in different provinces in South Africa using the *'optioneering'* process where various parameters and attributes are data inputs to calculate the PV potential.

The contribution of renewable energy technology, solar PV in particular, to electricity generation is significant, taking into consideration the fact that solar energy is freely and available. This chapter describes solar PV potential from Krewitt *et al.* (2008) perspective, where the types of renewable energy potential are explained, this includes theoretical, technical, economic, deployment, demand, market and realisable potential.

Solar irradiance is the power density incident on an object due to illumination from the sun (Syafawati *et al.,* 2012). Incoming solar radiation at ground level is determined by the state and nature of the atmosphere. However, the dynamics of the atmosphere are difficult to predict. When solar radiation reaches the earth's surface, part of it is reflected and part is absorbed. The same occurs with long-wave radiation that each body emits as a function of its temperature (Meza and Varas, 2000). The assessment of potential then relies on measurements of solar irradiance at ground level in different places. This data is obtainable from NASA cited in Boxwell (2014).

4.2 Methods and materials

4.2.1 Solar PV potential

The identification and assessment of the potential of solar PV requires a rigorous process and modelling of critical parameters such as solar radiation, land space and population, among others. In this chapter, modelling was conducted through '*optioneering*'. This approach sought to identify potential locations (provinces) for the setting up of solar PV plant. It is a structured evaluation of options in support of decision-making. This evaluation took the form of an option study that collates information on the options and the different attributes that influence decision-making.

The method used for the modelling process was the TOPSIS, as explained in detail in section 2.6.1 (Modelling) of chapter 2 and further confirmed in section 3.4 (Modelling) of chapter 3. The software used for running the model was the DMMA version 1.0 © 2009 by John Dalton.

The data for modelling in the *'optioneering'* approach were obtained from different sources. For example, data on the electrification backlog and population were obtained from Statistics South Africa (South African government department responsible for statistics), data for electricity tariffs were obtained from Eskom (South African electricity generation and supply utility) and municipalities. The data came in different units (for example, tariff data were in c/kWh, solar radiation was in kWh/m^2, land availability was in km^2, population was in percentages). The units were converted into percentages (%) to enable the model to run in a comparable manner (Table 4.1).

Table 4.1: The raw data for the parameter used in the modelling process

Parameter/attributes (%)	**Options (designs)**								
	LP	GP	NW	KZN	MP	EC	WC	NC	FS
Solar radiation	11	10.7	11.1	9.4	10.2	11.1	11.3	12.7	11.9
Electricity tariff	10.2	11.9	9.9	11.4	9.9	10.7	13.2	12	10.4
Land	10.3	1.3	8.7	7.7	6.2	13.8	10.6	30.5	10.6
Population	10.4	23.7	6.8	19.7	7.8	12.7	11.2	2.2	5.3
Electrification backlog	9.5	15.4	14.8	20.7	11.6	19.6	9.5	8.1	8.5
Electricity consumption (2013)	5.3	27.3	11.4	18.9	15.9	4.4	10.5	2.5	3.6

The modelling process for the solar PV potential was run in three different scenarios as explained in Chapter 3 (section 3.4.1). Scenario 1 represented by government departments, Scenario 2 represented by the Academic sector (Universities) and scenario 3 represented by the Solar PV industry.

The scenario 1 weighting of attributes was averaged from different government departments (Table 4.2).

Table 4.2: The average weight for scenario 1 model from governments

Requirements (%)	**DOE**[5]	**DST**[6]	**DTI**[7]	**NERSA**[8]	**Total**	**Average**
Solar radiation	35	30	30	25	120	30
Electricity tariff	15	10	5	15	45	11
Land space	30	35	25	20	110	28
Population	5	5	0	15	25	6
Electrification backlog	5	5	25	20	55	14
Electricity consumption	10	15	15	5	45	11
Total points	100	100	100	100	500	100

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[5] Department of Energy
[6] Department of Science and Technology
[7] Department of Trade and Industry
[8] National Energy Regulator of South Africa

In scenario 2, the 23 South African Universities were asked to allocate weight for different attributes and 6 Universities responded (University of Venda, University of South Africa, University of Fort Hare, North West University, Stellenbosch University and University of Johannesburg). The weights were averaged and final weights for scenario 2 were generated (Table 4.3).

Table 4.3: The average weight for scenario 2 model from academic sector

Requirements (%)	**Univ.1**	**Univ.2**	**Univ 3**	**Univ. 4**	**Univ.5**	**Univ.6**	**Total**	**Average**
Solar radiation	40	45	36	40	30	35	226	38
Electricity tariff	0	5	0	10	5	10	30	5
Land space	15	35	26	33	41	20	170	28
Population	30	15	30	10	20	15	120	20
Electrification backlog	5	0	0	0	4	15	24	4
Electricity consumption	10	0	8	7	0	5	30	5
Total points	100	100	100	100	100	100	600	100

Eleven solar PV industry company of out 28 responded **(Appendix B).** The average was calculated (Table 4.4).

Table 4.4: The average weight for scenario 3 model from solar PV industry

Requirements (%)	**Total weight from companies**	**Average**
Solar radiation	500	45
Electricity tariff	0	0
Land space	196	18
Population	50	5
Electrification backlog	24	2
Electricity consumption	330	30
Total points	1100	100

4.2.2: Seasonal and monthly variations of solar PV output

Radiation at the earth's surface varies from one area to another; however, the solar radiation incident on the earth's atmosphere is relatively constant. Thus, the radiation varies owing to atmospheric effects, local variations in the atmosphere, latitude of the location, season of the year and time of day (Syafawati *et al.,* 2012).

Solar irradiance varies from one place to another and changes throughout the year in different seasons in South Africa. In order to calculate the seasonal variation of solar PV output in a given location, the monthly figures of solar irradiance are taken into account (Boxwell, 2014).

In this research the solar irradiance figures were obtained from the National Aeronautics and Space Administration (NASA), as cited in Boxwell (2014). NASA is the US government agency that is responsible for the civilian space programme as well as for aeronautics and aerospace research. It has a network of weather satellites that has monitored, among others, the solar irradiance across the surface of the earth for many decades. NASA's readings have been available every three hours for the past quarter of a decade.

4.2.3 Solar PV technical potential

The technical potential was calculated in similar fashion that was done by different researchers. According to Hermann *et al.* (2014), the technical potential (MWh/year) is calculated by multiplying radiation (kWh/m^2/year) with PV module efficiency (%), dividing by the spacing factor and multiplying by the available area (km^2):

$$\boldsymbol{TP} = \frac{\mathbf{SR\ x\ PVME}}{\mathbf{SF}}\ \boldsymbol{X\ AA}$$

Where TP is the theoretical potential, SR is the solar radiation, PVME is the photovoltaic module efficiency, SF is the spacing factor and AA is the available area.
The spacing factor or ground cover ratio depends on the type and characteristics of the PV plant, but an average factor for large PV installation is in the order of 5, which means that the ground area needed is five times higher than the actual area that *"collects"* solar radiation. For PV systems the main factors that lead to additional space requirements are collector spacing areas and electrical equipment, especially for large-scale applications (Hermann *et al.,* 2014).

4.3: Solar PV potential in different provinces

The ground-mounted surface and limited rooftops models dominate the installed solar PV energy in South Africa. Moreover, applications are widely distributed in large commercial, industrial, residential and agricultural sector. The absence of (Feed-In Tariff) FIT makes it difficult for rooftop PV to penetrate the market, especially in the residential sector as the residence are unable to sell the surplus power back to the grid like in many other countries.

4.3.1 Solar PV potential for scenario 1: Government sector

Of all nine provinces, the Northern Cape Province has the highest solar PV potential with 21.7%, followed by the Eastern Cape and KZN Provinces with 13.5% and 10.9% respectively. Mpumalanga province has the lowest potential of 7.2% (Figure 4.1). Gauteng Province, despite its relatively small land mass, has the same potential as for the Limpopo and North West Provinces with 9.1% and very close to KZN. This seems to have been influenced by a 14% weight allocation to the electrification backlog and 11% for electricity consumption parameters, in which Gauteng Province has the highest level.

The Northern Cape Province has the smallest population of 0.22%, highest land space of 30.5% and highest solar radiation of 12.7%, therefore it has the highest potential in scenario 1, mainly because of high weight allocated to solar radiation and land availability (Table 4.3). The Gauteng Province has the highest population of 23.7% (6% weighting) and highest electricity consumed in 2013 of 27.3% (11% weighting), which is opposite to the Northern Cape Province. It was the fourth province with good potential after KZN and Eastern Cape. Hence, solar radiation and land space are key parameters for the Northern Cape, Eastern Cape and KZN Provinces.

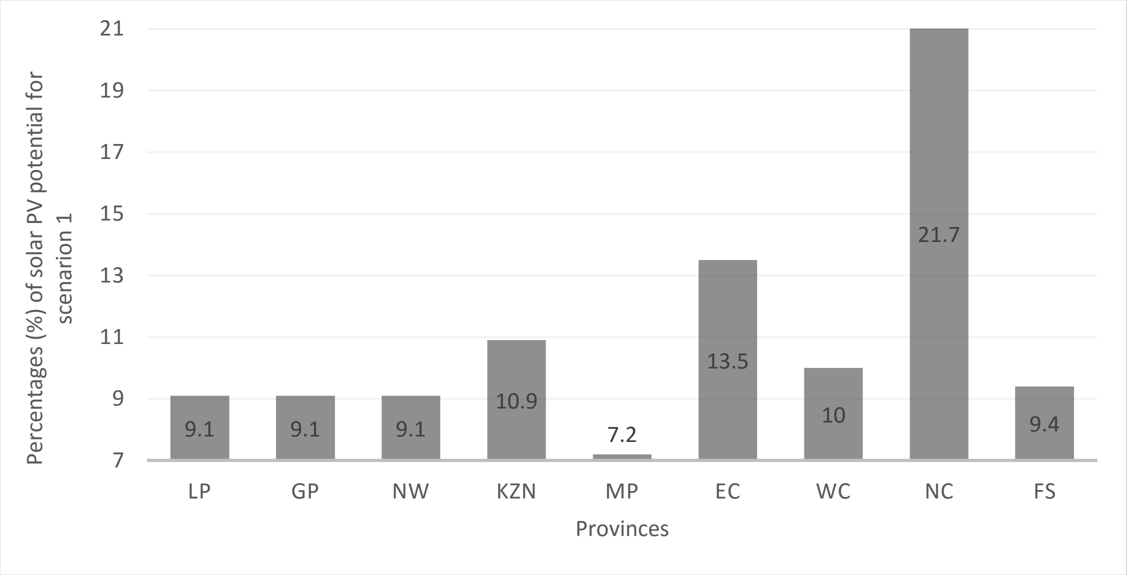


Figure 4.1: Solar PV potential for scenario 1

The government sector seems to suggest that Northern Cape, Eastern Cape and KZN Provinces are ideal for solar PV development.

By comparison, scenario 1 results are similar to those obtained in the study conducted in 2009 by Fluri (2009), who measured CSP potential using solar radiation. Fluri (2009) found that the Northern Cape Province had the highest CSP potential largely because of vast land available in the province. Though the parameters used for modelling are not exactly the same, the findings are similar in this study. Equally, Munzhedzi and Sebitosi (2009) found that Upington city in Northern Cape Province has exceptional solar PV potential, compared to other cities in other provinces.

There are several possible ways of explaining these results. The Northern Cape Province seems to be an attractive place for solar PV generation mainly because of two parameters, solar radiation level and land space.

4.3.2 Solar PV potential for scenario 2: Academic sector

The weight allocation for this scenario was 38% for solar radiation, 28% for land space, 20% for population, 5% for tariff and 4% for electrification backlog and 5% for electricity consumption (Table 4.3). A similar pattern to scenario 1 was observed in this scenario; the Northern Cape Province has even higher potential of 19.1% than in scenario 1, followed by the Eastern Cape and KZN Provinces with 13.6% and 12% respectively (Figure 4.2). The academic institution recognises the significance of solar radiation, land space and population parameters in setting up the solar PV plants.

The reason is the same as for scenario 1: more weight has been allocated to solar radiation and land space, which are highest in the Northern Cape Province. In addition, the weighting for solar radiation was 38%, even more than the 30% allocated in scenario 1, and that the land space was similar to that of scenario 1, which is 28%. Those are key parameters, which are critical in the implementation of large-scale commercial solar PV plants, mainly grid-connected. However, solar radiation alone is key for the residential, agricultural, mining and industrial sectors, as power is mostly generated for own use in these sectors.

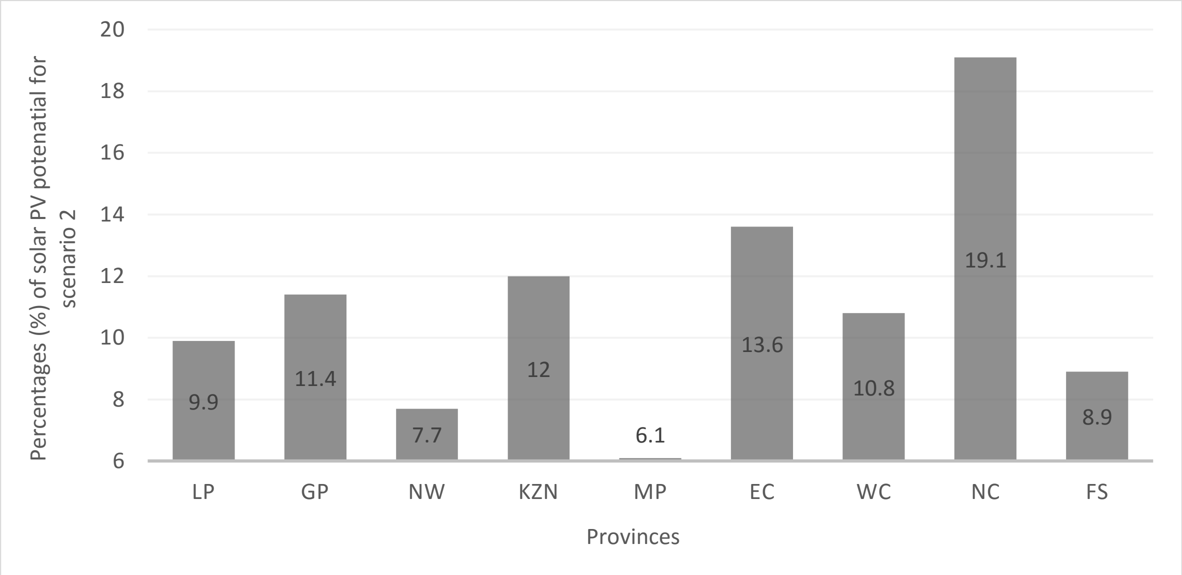


Figure 4.2: Solar PV potential for scenario 2

The North West and Mpumalanga Provinces have the lowest solar PV potential in scenario 2 (Figure 4.2). The reason for low potential is that Mpumalanga has the least land space and relatively smaller population; the weightings for these parameters were 48% combined. The key issues in determining and deciding which province should be ideal for a solar PV plant are parameters and weighting. Solar PV is applied in different sectors. For industrial, mining and agricultural purposes, land space may not be needed, since the power generated is for local use. However, for large-scale commercial use and a noticeable contribution to the country's total energy mix, land space is needed.

The Northern Cape, Eastern Cape and KZN were the top three provinces with good potential for scenario 1, hence the similar results in scenario 2, with Gauteng Province ranked the fourth. The Northern Cape Province has the potential to make a significant contribution to clean energy in South Africa. The crystalline PV module is the preferred economic choice for grid-connected applications because it has a good efficiency level of up to 20%. This is the highest efficiency among all other market technology based PV modules (Tyagi *et al.,* 2013). Therefore, the Northern Cape, Eastern Cape and KZN Provinces would make a significant large-scale solar PV contribution, and other provinces would be more viable for alternative solar PV application, such as residential use.

4.3.3 Solar PV potential for scenario 3: Solar PV industry

The solar PV industry preferred the solar radiation, electricity consumption and land space as the main core parameters for determining solar PV potential. The weight allocations were 45% for solar radiation, 30% for electricity consumption and 18% for land space. The population and electrification backlog were allocated 5% and 2% respectively, effectively meaning that they had no role to play in determining the potential for this scenario. This weighting allocation primarily sought to prioritise areas where there was high solar irradiance and electricity consumption. This scenario has the advantage of identifying areas where power supply is inadequate because of high demand, and reducing transmission loss by transmitting power over a short distance either through the main grid network or mini-grid network.

Interesting results were observed in this scenario. Gauteng Province emerged to have the highest potential for solar PV generation with 18%, followed by KZN with 15.3%. It is worth noting that the Northern Cape and Mpumalanga Provinces are third highest potential with 12.88% (Figure 4.3). Unlike scenarios 1 and 2, where the Northern Cape, Eastern Cape and KZN Provinces demonstrated good solar PV potential, scenario 3 presented different results altogether. The Eastern Cape was the third lowest province with 7.6% potential. The Northern Cape Province was third precisely because of 30%

weight allocated to electricity consumption, yet it was the province that had consumed the least electricity, 2.5%, in the entire country, largely because it has the smallest population of 2.2%.

There are two possible explanations for these results. In order to address the long-distance transmission lines that usually requires capital investment for construction and maintain, and often results in energy loss along the way, the solar PV power plant should be established as close as possible to the area where there is high energy demand and power consumption. In 2013, Gauteng Province consumed more than quarter of the total power produced in the country, and it receives good solar radiation. Equally, KZN Province scored second highest, having consumed 18.9% of the country's power produced in 2013. In this scenario, it was proven that for South Africa to save cost and power loss on transmission infrastructure, the solar PV plants could be built in Gauteng and KZN Provinces where there is high power consumption.

The Eastern Cape dropped significantly to less than 10% because it consumed less than 5% of the total electricity produced in South Africa in 2013, and 30% weight was allocated to electricity consumption. Similarly, Mpumalanga Province had slightly higher electricity consumption of 15.9%, which made it the fourth province in terms of solar PV potential. The mining activities in the province contribute to high electricity consumption in Mpumalanga.

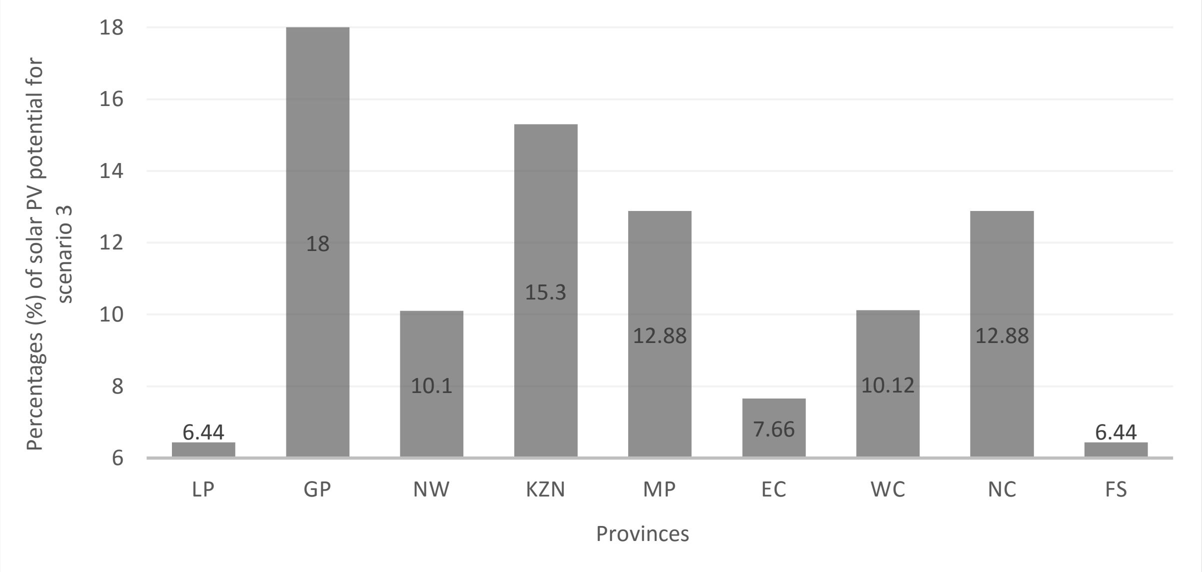


Figure 4.3: Solar PV potential for scenario 3

Gauteng Province has the highest ranking in scenario 3 and Limpopo and Free State Provinces the lowest ranking. One of the reasons being that Limpopo consumes less electricity, which effectively means that its demand is less. The allocation of weights for this scenario suggests that areas with high solar irradiance and high electricity consumption are Gauteng, KZN, the Northern Cape and Mpumalanga Provinces.

The overall result for the three scenarios is that the Northern Cape, Eastern Cape and KZN Provinces have shown to have significant potential in scenarios 1 and 2, whereas Gauteng, KZN and the Northern Cape were the top three provinces with the best solar PV potential in scenario 3 (Figure 4.4). On average, the top four provinces in terms of potential for solar PV use in South Africa are the Northern Cape, KZN, Eastern Cape and Gauteng (Figure 4.4). These are the provinces that this study recommends that solar PV should be established.

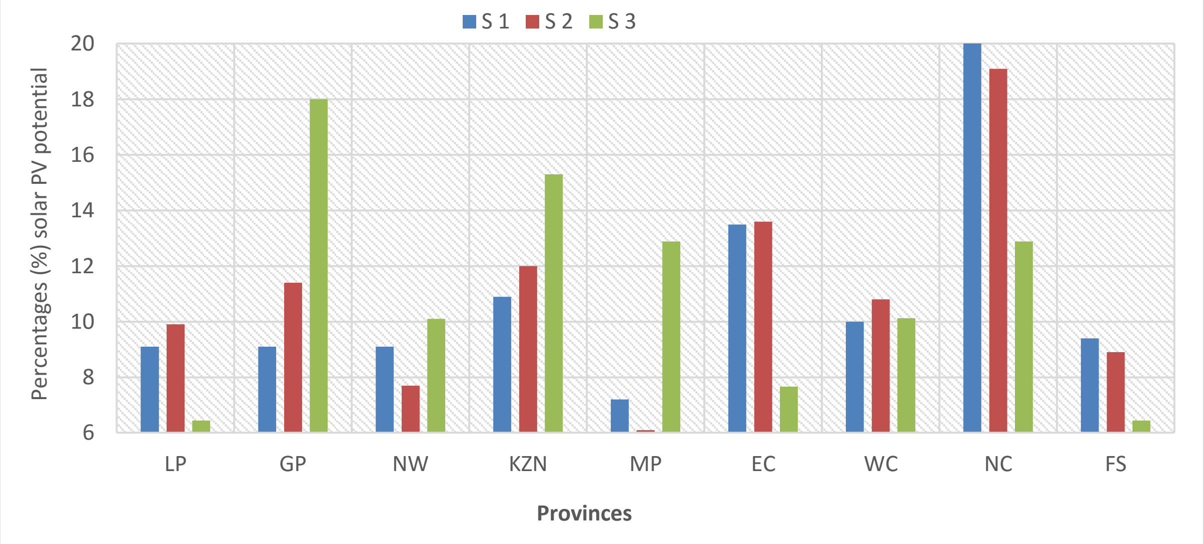


Figure 4.4: Solar PV potential for three scenarios

4.3.4 Sensitivity analysis

The solar irradiance, land space, population and electricity consumption are the main parameters that any change in their weightings affect the output in the modelling process. The Northern Cape Province has the highest potential in scenario 1 mainly because of the more weight on solar irradiance and land space, which this province has substantial solar irradiance and massive land space. Therefore, if the weight for these parameters are reduced by 10% and added population and electricity consumption, Gauteng and KZN Provinces would have high solar PV potential in scenario 1 (Figure 4.5). This would be because Gauteng and KZN have high electricity consumption and Gauteng with little land space, which would have had less weight in the sensitivity analysis.

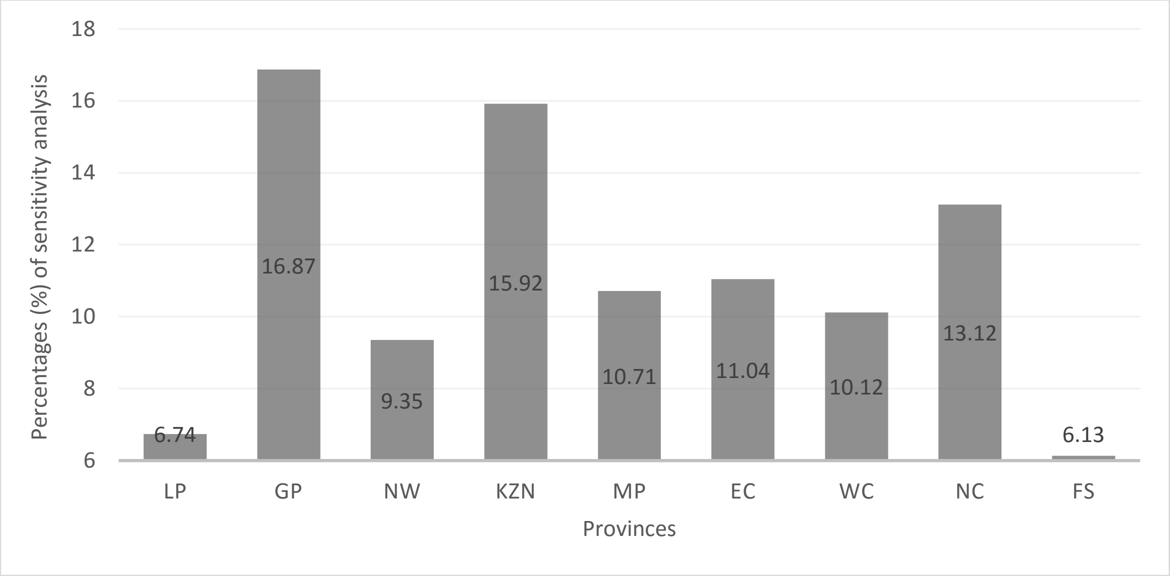


Figure 4.5: Sensitivity analysis for scenario 1

Similarly, in scenario 2, there is 66% weight allocated to solar irradiance and land space combined, if 10% of each is removed and added to electrification backlog and electricity consumption, Gauteng and KZN Province would have high solar PV potential than all other provinces (Figure 4.6). Scenario 3 is not adversely affected by a change of 10% weighting for any parameter.

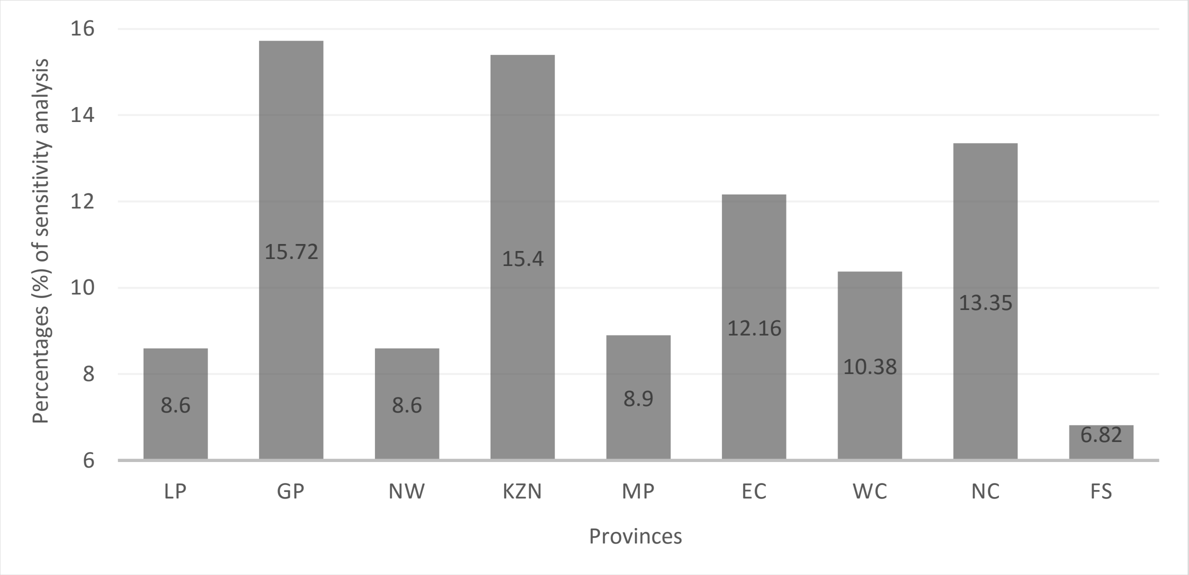


Figure 4.6: Sensitivity analysis for scenario 2

The sensitivity analysis shows that the change in any of the parameters, especially the solar irradiance and land space adversely affect the solar PV potential. The Northern Cape and Eastern Cape Provinces are highly sensitive in any change around land space and solar irradiance, mainly because they have massive land space, which gives them good potential if and when more weight is allocated to such parameter.

4.3.5 Monthly and seasonal variation impact of solar PV output

The energy output of solar PV primarily depends on the amount of solar radiation that arrives at the surface of the PV modules from time to time. For a given location, this depends on the inclination and azimuth of the modules, assuming modules mounted in a fixed position tilting (Monforti *et al.,* 2014). The winter and summer seasons have direct implications for solar radiation and consequently solar PV output.

In the northern hemisphere, the modules yield maximum efficiency and output when facing in a southern direction; in the southern hemisphere, the solar module yields maximum efficiency when facing in a northern direction. If a module in the northern hemisphere faces north, there could be high loss of around 40% in efficiency (Boxwell, 2014). In South Africa, the temperature drops significantly in the winter months (May, June and July) and the sunshine hours become shorter, while in the summer months (November, December and January) the temperature rises and the sunshine hours become longer. For that reason, seasonal variation is crucial in the modelling and planning of a solar PV plant.

The performance of solar PV modules is largely determined by the orientation and the tilt angle with the horizontal plane. These two parameters change the amount of solar energy received by the surface of the PV module (Pavlovic *et al.,* 2010). The tilt of a solar module has an impact on how much sunlight can be captured. If the solar module is mounted at an angle that is tilted towards the sun, it captures more sunlight and therefore generates more electricity (Boxwell, 2014). Consequently, the tilt angle, position and orientation are the main factors that should be optimised for each solar PV projection in accordance with the location (Miller and Lumby, 2012).

When the absorbing surface and the sunlight are perpendicular to each other, the power density on the surface is equal to that of the sunlight (that is, the power density will always be at its maximum when the PV module is perpendicular to the sun). However, as the angle between the sun and a fixed surface is continually changing, the power density on a fixed PV module is less than that of the incident sunlight (Boxwell, 2014).

There are various tilting positions and angles for solar PV modules:

- **Flat angle:** the solar PV module normally lies flat, horizontal to the surface and faces upwards to the solar radiation. This mounting system is simpler, cheaper and has lower maintenance requirements than other angles, such as the upright tilting position (Miller and Lumby, 2012). However, it needs more regular cleaning to prevent dust and soiling.
- **Upright angle:** The solar PV module is installed vertical to the surface.
- **Best year-round tilt:** This is an optimum tilt for a fixed solar module’s all year round power generation. It does not give maximum power output every month in a year; rather it gives the best compromise and generates electricity all year round with minimum fluctuation throughout different seasons of the year. The angle is between 56^0 and 64^0, depending on a specific area in South Africa.
- **Best winter tilt:** The performance of a solar PV system is normally low in winter; however, tilting the module in a particular direction and angle that capture as

much power as possible is crucial. The module can be tilted to between 41^0 and 48^0 to generate maximum power during winter (May-July).

- **Best summer tilt:** Solar PV modules perform well during summer; however, the performance can be maximised by tilting the modules to between 71 and 78 from November to January.

Solar irradiance varies significantly from one area to another and seasonal changes occur throughout the year. The monthly solar irradiance figures were obtained from NASA (2013) as cited in Boxwell (2014). To maximise efficiency in power generation from the PV modules, the tilting angles and positions should be studied carefully and the most efficient tilting angle should be chosen. However, the flat surface angle seems to be most effective in South Africa, since it captures maximum solar radiation in the summer months.

There is an interesting relationship and pattern in all the provinces; they have shown a similar and obvious pattern of higher power output in summer and less in winter. Almost all provinces receive approximately 5.5 to 8 kW/m^2/day in summer, and drop to less than 4 kW/m^2/day in winter (Figure 4.7). The Western Cape Province receives the highest solar irradiance in the summer months and drops to the lowest of all provinces during the winter months. The Northern Cape and Limpopo Provinces have well-balanced annual solar irradiation, with the least drop in winter and an average increase in summer. Thus, the tilting angle is crucial to capture maximum solar radiation in winter.

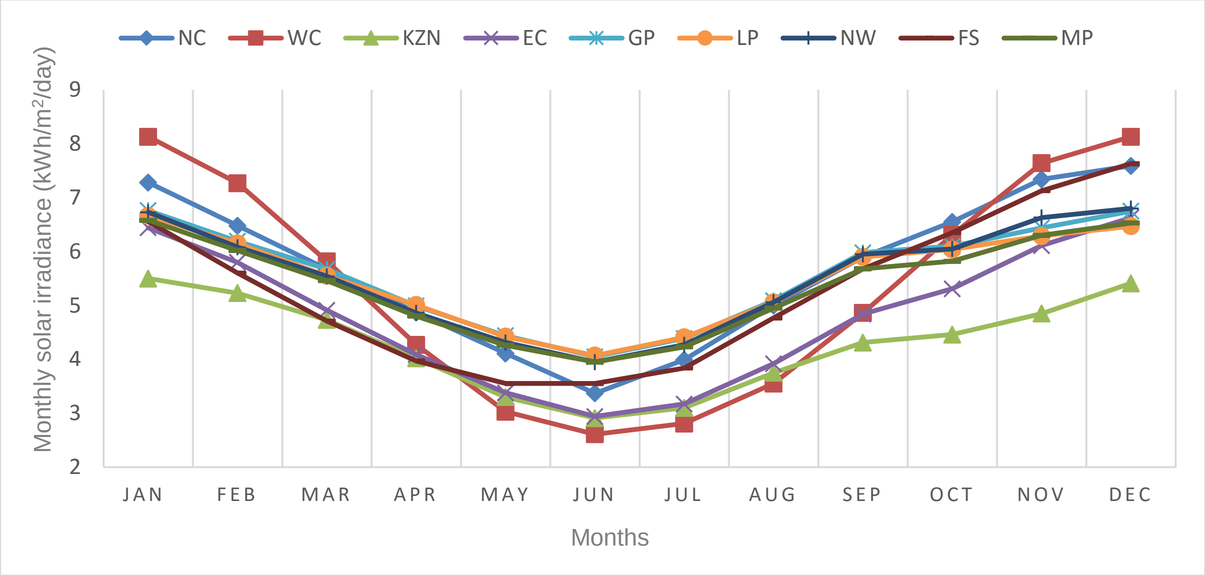


Figure 4.7: Monthly solar irradiance on flat surface module

The amount of solar radiation received differ from one place to another, the seasonal variation and cloud cover play critical role in electricity production from solar PV. However, the amount is highest in the desert arid environment; Africa has two deserts, the distant Sahara Desert and the Namib Desert in Namibia which is close to Northern Cape Province. Nevertheless, solar modules can be tilted toward the sun in different seasons to compensate for the curving of the earth to collect maximum solar irradiance (Bollen and Hassan, 2011). The highest tilting point during winter and summer in different provinces in South Africa should be identified and hence tilted every season to capture maximum solar radiation.

Pavlovic *et al.* (2010) conducted an experiment on solar radiation to ascertain tilting position and angle. It was done in such a way that the solar PV module faced different directions in Serbia (Northern hemisphere) and it was found that the solar module oriented towards the south gave the greatest values of electrical energy for all the chosen angles. Furthermore, if the solar PV module is oriented south, which is an optimal solution, it should ideally be installed at an angle of 30^0.

Other researchers observed that positioning the PV module is critical. It may result in gain or loss of power production. Therefore, the location, angle and tilting position should be carefully studied before the implementation of a solar PV project. Vermaak (2014) found that the electricity production from a 1 kWp PV system with a horizontal orientation for a period of one year was 1800 kWh/year; however, at a static angle of 29° the total electricity production in this scenario was 2030 kWh, which is 230 kWh or 12% more than the electricity produced with horizontally mounted PV modules in Bloemfontein, Free State Province. Then the angle at which the module is placed has serious implication for total electricity production in different months of the year.

A solar PV system with a capacity of 3.6 kW was installed in Malaysia in 2013 and was monitored for a period of nine months, with frequent data collection to check the daily, monthly and seasonal fluctuation. It was found that there were numerous fluctuations of the power output, which were largely caused by the high frequency of clouds passing over the PV system (Wong *et al.,* 2014). Furthermore, it was noticed that sometimes there was high power output suddenly rather than gradually. This was because many of the passing clouds were very thick, and hence usually caused a sudden change in total solar radiation (Wong *et al.,* 2014). Therefore, fluctuation is caused not only by seasonal variation; the daily temperature and cloud cover have implications for power output. It is recommended that other renewable energy technologies such as biogas be used to supplement the solar PV power generation, during winter in particular.

4.3.6 Hourly and daily energy consumption variation in South Africa

The winter and summer hourly load profile pattern is the same in South Africa, the difference is that demand in winter is relatively higher than in summer. The hourly load profile has peak hours from 5H00 to 11H00 in the morning and drops down in the afternoon in winter, whilst in summer it remains steady until it picks up from 18H00 in the evening and drops down just after 20H00 late evening (Figure 4.8). This would mean that solar PV is required to generate more power from 7H00 in the morning until 20H00 late evening in order to match the hourly load demand in South Africa.

- **Winter season (May-July)**

South African has fewer day hours in winter season than summer. The sun rises around 08H00 and set at 17H00. Then, the maximum power is likely to be generated for three hours only between 12H00-15H00, which would be insufficient to meet the hourly load profile demand. Consequently, the solar PV output does not match the hourly load profile in winter season. Hence, much power would need to come from other source(s) of electricity such as coal. This would mean that solar PV would have less power contribution in winter season.

- **Summer season (November-January)**

Summer has more day light than night in South Africa. The sun rise at 5H30 and set at 19H00. Therefore, summer has approximately 14 hours of day light. The solar PV is likely to start generating power from 9H00 in the morning and maximum power from 11H00 until 17H00, which the power demand is steady in these hours in summer. However, power demand goes up from 18H00 until 20H00, whilst solar power generation is declining. Just like winter, the solar PV does not match hourly load profile in summer season. Nonetheless, much power would have been generated during the 5 hours generation peak (11H00 – 17H00) and would have been stored for the peak hours demand.

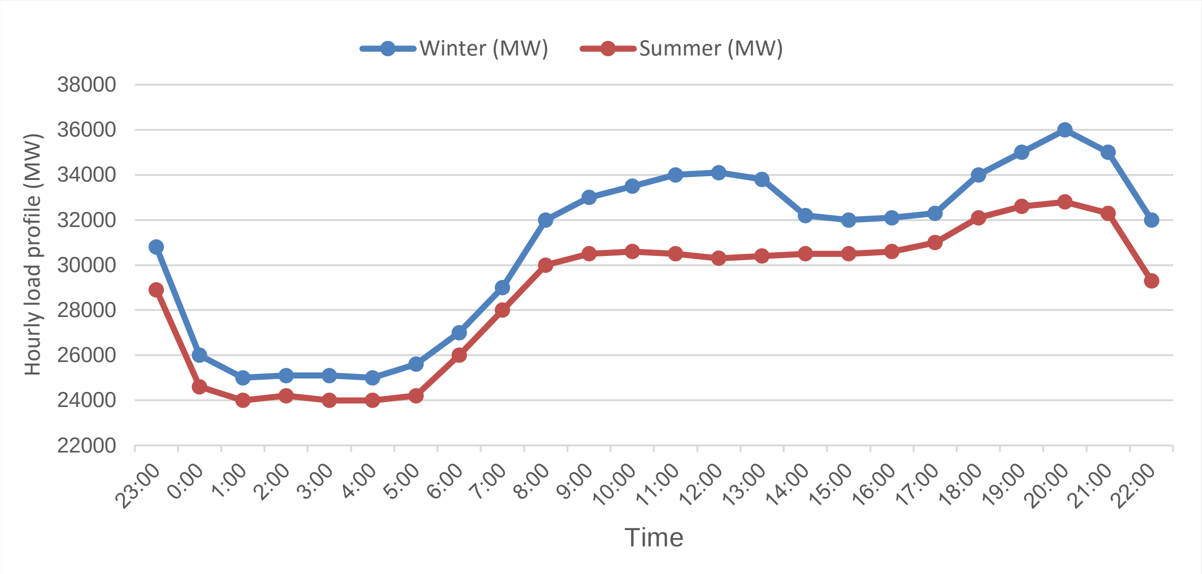


Figure 4.8: South African winter and summer load profile (Source: Eskom 2012)

In 2015, South Africa has generated 230122 GWh, which was distributed in different parts of the country for consumption (StatsSA, 2016a). Much of the power was consumed in June, July and August, which are winter months (Figure 4.9). The monthly solar irradiance shows decline in winter months and increase in summer months. There is a significant mismatch in so far as the monthly solar irradiance and electricity consumption is concerned. Figure 4.7 and 4.9 do not match; hence, the months with high power demand have less solar irradiance.

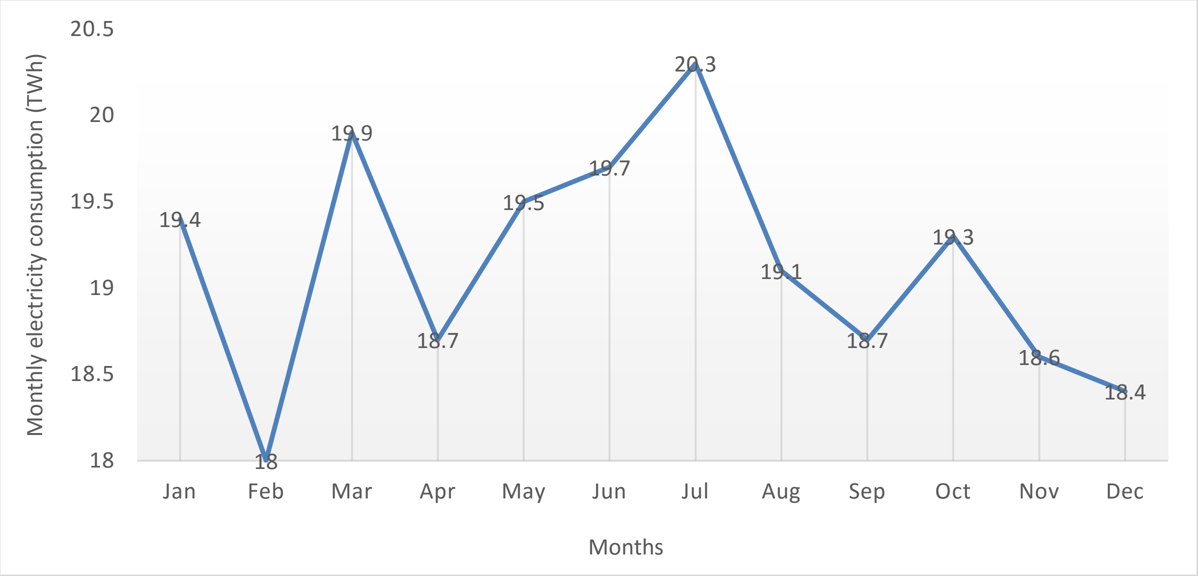


Figure 4.9: South African monthly electricity consumption in 2015 (Source: StatsSA, 2016a)

The solar irradiance does not match the daily and hourly load demand in South Africa. The hourly mismatch is bigger in summer than in winter season. Similarly, the season solar irradiance does not match the load demand as the irradiance declines in winter season, whilst power consumption increases in South Africa. Therefore, solar PV alone would not be able to provide sustainable and required amount of power in South Africa, rather it would supplement other sources of power generation.

4.4 Discussion

4.4.1 Validation of solar PV potential across the provinces

In order to test, validate and confirm the results of this chapter, the distribution of solar PV potential per province were compared to four fundamental aspects, namely:

- The current private solar PV capacity installed in different sectors;
- Solar PV theoretical potential;
- Solar PV Technical potential; and

- The South African REIPP procurement programme

Scenario 3 found that Gauteng and KZN have substantial solar PV potential. These provinces consumed 26.9% and 19.5% of total electricity production in March 2015, which translates to high electricity demand of almost 50% of the country's total power supply. The high electricity consumption in these provinces is influenced by the following factors:

- **Population**

The Gauteng Province is home to approximately 23.7% of the population of South Africa. Most of these people moved from different parts of the country to Gauteng for economic and business opportunities. Furthermore, the province experiences a high influx of immigrants from other African countries because of economic crises and political violence in their countries. This high volume population results in a high demand for electricity. The KZN Province is the province with the second largest population, with many manufacturing and agricultural enterprises, making it attractive to local citizens and immigrants seeking job opportunities.

- **Industrial provinces**

Industry consists of groups of initiatives and enterprises engaged in similar kinds of economic activity in a particular area. The Gauteng and KZN Provinces have high volumes of various industrial sectors, such as wood and wood products, pulp and paper, petroleum, chemical products, rubber and plastic products, electrical machinery, motor vehicles, parts and accessories and other transport equipment, furniture and other manufactured products. Then people move into these provinces seeking job opportunities in the industrial sectors. Ultimately, this industrial activity and large population have a direct influence on electricity consumption.

- **High economic zones**

The Gauteng and KZN are major economic zones, as is the Western Cape Province. These are the busiest provinces, with a variety of economic activities, encompassing all sectors of industry. They are an attraction to both national and international tourists, the business community and immigrants.

The above-mentioned factors result in high electricity demand and consumption, which is largely influenced by the population density that reduces land area/space in these provinces. Scenario 3 suggests that South Africa should consider establishing solar PV plants in these provinces, among others to reduce and balance consumption in the country, and to avoid power loss due to long transmission networks. This seems to be a cheaper viable option for South Africa. However, the main challenge would be the land needed for the establishment of the plant. It is understood that land space is limited and expensive in these provinces because of the conflict of interest among different land uses.

4.4.1.1 Solar PV technical potential

The technical potential takes into account parameters such as land space, solar irradiation of a particular area and PV module efficiencies. In other words, it is a theoretical potential minus the losses from conversion into secondary energies and constrained by the requirements related to installation such as (grid) transportation or transmission losses (Hermann *et al.,* 2014). However, the module efficiency and land determine the primary power output minus transmission losses.

Solar PV systems comprise crystalline and thin-film module types. The difference is efficiency level; crystalline modules range from approximately 18-20% efficient whereas the thin-film modules have lower efficiency percentages i.e. up to 12%. Therefore, the output differs, depending on the module type. The thin-film module’s output is approximately 40% less than that of the crystalline module. South Africa is likely to generate approximately 7815 TWh/year, mainly from crystalline PV modules. However, around 60% of this can be generated using a thin-film PV module, which yields around 5372 TWh/year (Table 4.4 and Figure 4.6). This potential is based on 11% efficiency for thin-film and 16% for crystalline module. The thin-film module potential is comparable to the SWERA (2008) that concluded that South Africa has 4204 TWh/year.

In 2016, South Africa generated 238 TWh, therefore, the technical potential is massive to an extent that solar PV technology could contribute significantly to the total power production in South Africa. Nevertheless, the technical potential does not take into account certain limitations such as regulations, which does not allow residential sector to sell the surplus power (generated from the roof-top for own use) back to the grid network.

The recommended PV modules are crystalline PV because they are the preferred economic and commercial choice for grid-connected applications and they have a good efficiency level of up to 20% (Makrides *et al.,* 2010; Pavlovic´ *et al.,* 2013). Table 4.5 presents the possible power output from the crystalline and thin-film modules. It is anticipated that the solar PV output will improve with time when modules that are more efficient have been developed through research and innovation.

Table 4.5: Technical solar PV potential per province

Provinces	**Solar radiation (kWh/m^2/year)**	**Spacing factor**	**Land (km^2)**	**Crystalline module (TWh/year)**	**Thin-film module (TWh/year)**
NC	2178	5	372 889	2598	1786
GP	2131	5	16 547	112	77
EC	1892	5	168 965	1022	703
KZN	1867	5	94 361	563	387
LP	1980	5	125 754	796	547
WC	1932	5	129 462	800	550
MP	1939	5	76 494	474	326
NW	1940	5	106 512	661	454
FS	1900	5	129 825	789	542
Total				**7815**	**5372**

The provincial technical potential has a similar pattern as for scenario 1. This is because technical potential takes into account land and solar irradiance for each province, among other parameters; scenario 1 allocated 70% weight for land and solar irradiance combined in the modelling input. The Northern Cape and Eastern Cape provinces have a much higher PV output of 2598 and 1022 TWh/year respectively for the crystalline module, while Limpopo, the Western Cape and Free State Provinces have almost equal solar PV technical potential of approximately 800 TWh/year (Figure 4.10). Gauteng Province has the lowest technical potential because of its limited land space. It is anticipated that with technological development and advancement there will be more efficient PV module, which will yield more potential.

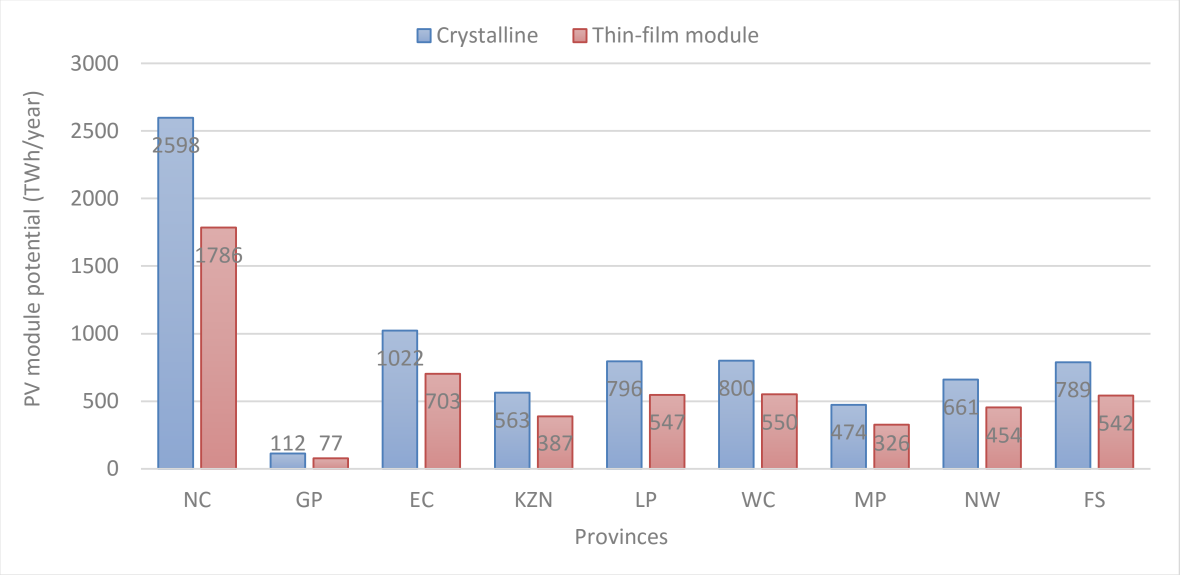


Figure 4.10: The provincial solar PV technical potential

Approximately 33% of the total South African solar PV power output is likely to be generated in the Northern Cape Province alone, mainly because of its vast land, which is suitable for large-scale commercial solar PV projects. This could be true particularly taking into consideration the current solar PV procured through the REIPP procurement programme, where more than 60% of PV projects are in Northern Cape Province (DOE, 2015). However, 10% is likely to be generated in each of the three provinces, Limpopo, Western Cape and North West, with 13% envisaged to be generated in the Eastern Cape Province (Figure 4.11).

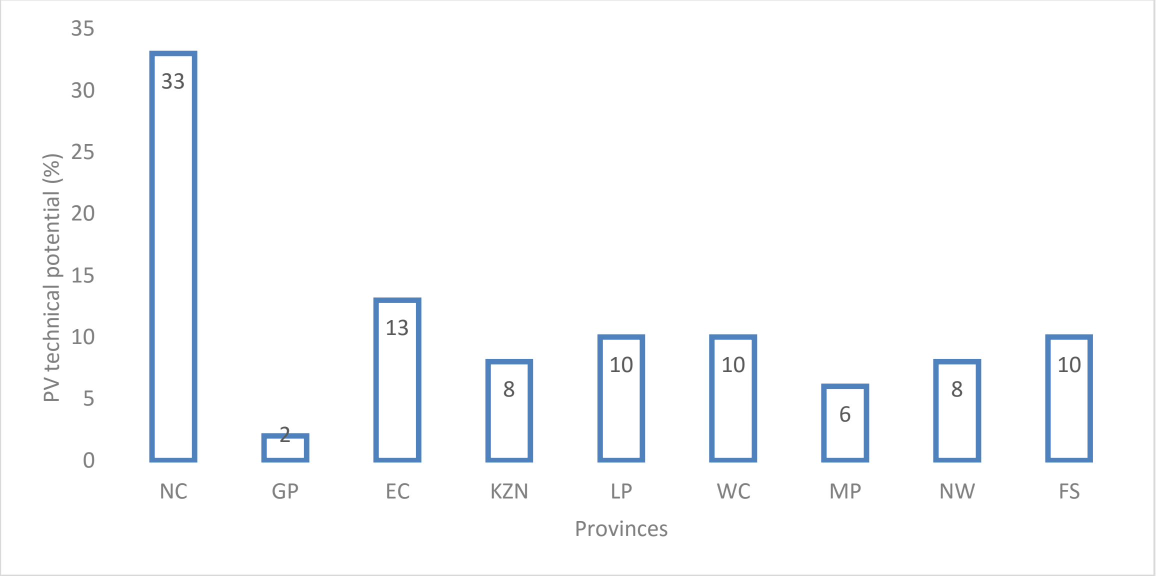


Figure 4.11: the provincial solar PV technical output percentages (Source: http://pqrs.co.za, 2016)

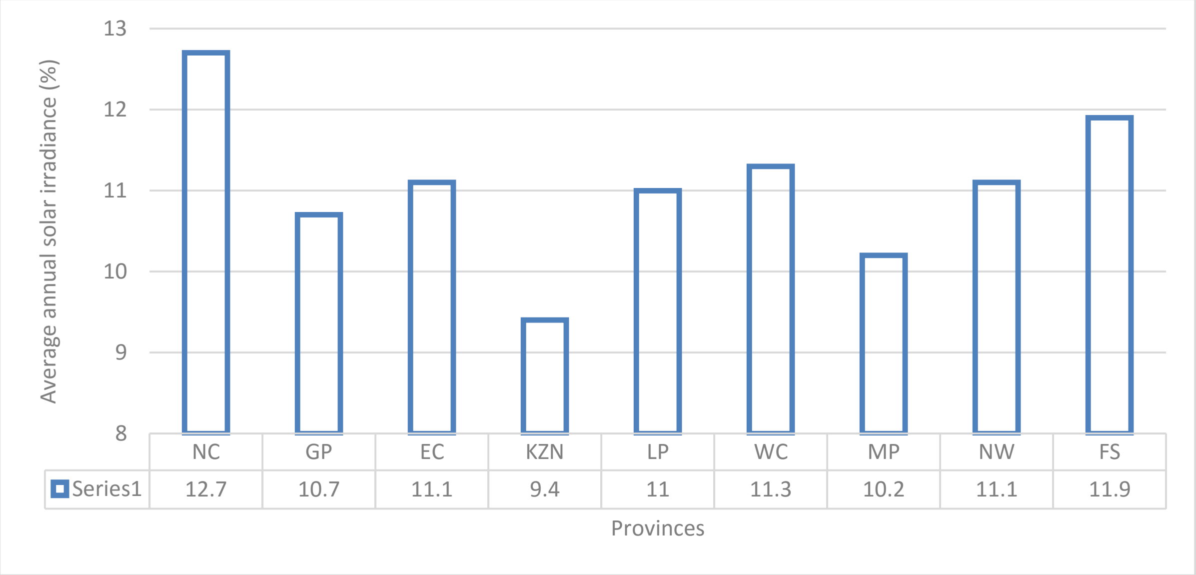
The technical potential data validate and confirm the findings of scenario 1, which concluded that Northern and Eastern Cape Provinces have good solar PV potential. It is mainly due to favourable solar radiance and vast land space, which is suitable for large scale solar PV projects.

4.4.1.2 Theoretical solar PV energy potential

Emanating from the modelled solar PV potential from section 4.3.1 to 4.3.3 above, this sub-section seeks to present the theoretical potential across the provinces. It is a useful potential for residential, agricultural and mining areas, as land space is not necessarily required, and in most cases, the project is implemented at a lower scale, such as stand-alone PV systems. The Northern Cape Province has an average solar PV output of 2052 kWh/m^2/year, which is an annual average of 12.7% (Figure 4.12). The Free State has the second highest score with solar irradiance of 11.9%; this is approximately 1980 kWh/m^2/year.

South Africa has good solar irradiance compared to the European and Asian countries, yet its solar PV projects' power output remains low. Solar irradiance in Cyprus is one of the highest in Europe, with annual irradiance of around 2000 kWh/m^2/year (Makrides *et al.,* 2010). In some geographical locations, it ranges from 1400 to 1900 kWh/m^2/year (Muhammad-Sukki *et al.,* 2012; Wong *et al.,* 2014; Alsharif *et al.,* 2015). Indeed, the Northern Cape Province is globally competitive with good potential compared to European and Asian countries such as Cyprus and Malaysia.

According to Pavlovic´ *et al.* (2013) the Serbian annual average solar radiation ranges from 1200 to 1550 kWh/m^2/year in the northwest to southeast, whereas in the central part it totals around 1400 kWh/m^2/year. Thus, Serbia has favourable conditions for the use of solar energy and its conversion into thermal and electrical energy, but less solar irradiance than African, Middle Eastern and Asian countries such as Cyprus, Malaysia and South Africa, specifically the Northern Cape.



	NC	GP	EC	KZN	LP	WC	MP	NW	FS
☐Series1	12.7	10.7	11.1	9.4	11	11.3	10.2	11.1	11.9

Figure 4.12: The provincial average annual solar irradiance per province

The theoretical solar PV potential confirms scenario 1 and 2 findings for on province in particular, the Northern Cape that was found to have over 18% of the total PV potential in the country. However, other provinces such as Free State and Western Cape have good solar irradiance.

4.4.1.3 Private solar PV systems installed in different sectors

The Power Quality & Renewable Services (PQRS) provides the latest information on solar PV technology for the Southern African Region specifically. The data is, however, unverified (solar PV industry database project, http://pqrs.co.za, 2016)[9]. The privately installed solar PV projects are not connected to the national grid line in South Africa, except the REIPP procurement programme. It is reported that the privately installed solar PV was 94 MW by March 2016. The installed capacity is spread across different provinces in various sectors.

Gauteng Province has the highest installation rate of 38%, followed by Western Cape and KZN with 30% and 7% respectively (Figure 4.13). The dominance of privately installed solar PV by Gauteng, Western Cape and KZN Provinces is associated with various factors. These include the fact that these provinces are the hubs of country’s economy. Moreover, other factors such as high electricity consumption and desire to make areas attractive to business and tourists through greening the environment and energy consumption are also important.

The private solar PV installation (up to March 2016) confirms and validates the scenario 3 findings, particularly Gauteng and KZN. The Northern Cape Province with big land space has 4% privately installed off-grid PV. This is because there is low population and electricity consumption. The majority of installed solar PV are large scale commercial for the REIPP procurement programme. Therefore, there is little private installed solar PV in the Northern Cape.

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[9] Unverified industry project database: http://pqrs.co.za/ as published 23-09-2016

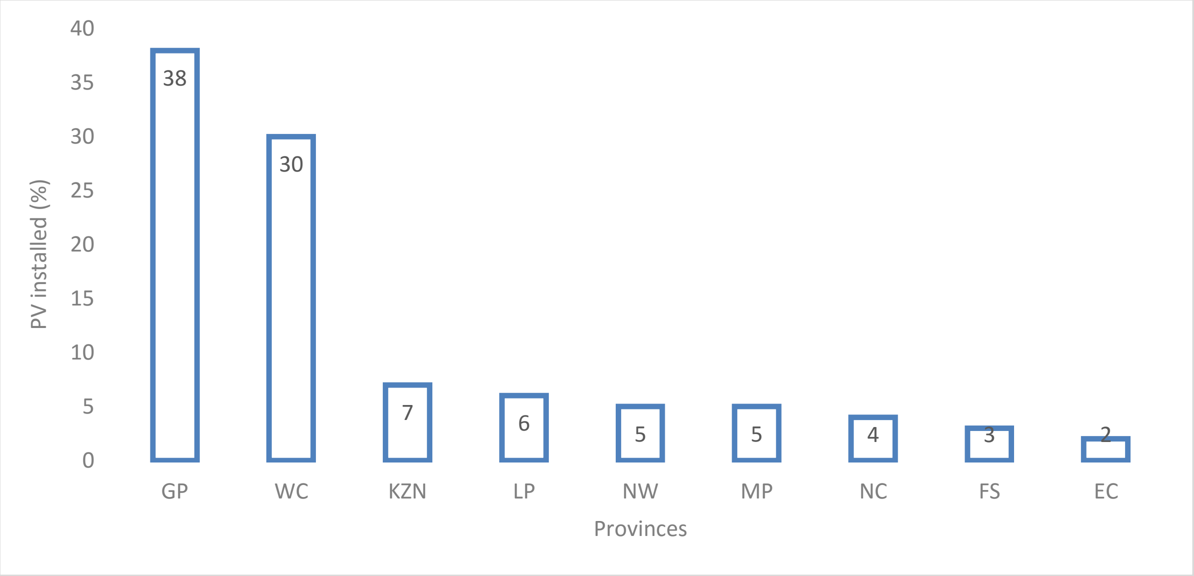

Figure 4.13: The provincial privately installed solar PV capacity by March 2016 (Source: http://pqrs.co.za, 2016)

The installation of solar PV is determined by many factors, such as the consumption of electricity in the province, business opportunities and attraction due to international recognition for green electricity, the population density, and industrial and economic activities. It was found that the current rate of installation is in line with scenario 3 findings, proving the significance of population density, electricity consumption and industrial activity.

There is no particular relationship between population, electricity consumption and the currently privately installed solar PV systems. Only Gauteng province shows similar patterns and trends in the population, consumption and installation of the private grid PV systems. However, the Western Cape Province has the highest number of privately installed PV, despite smaller population and less electricity consumption (Figure 4.14). The reason for the Western Cape having such a high volume of installed PV systems could be attributed to the green initiative campaigns in the province, specifically Cape Town, which is one of the best towns for tourists and business.

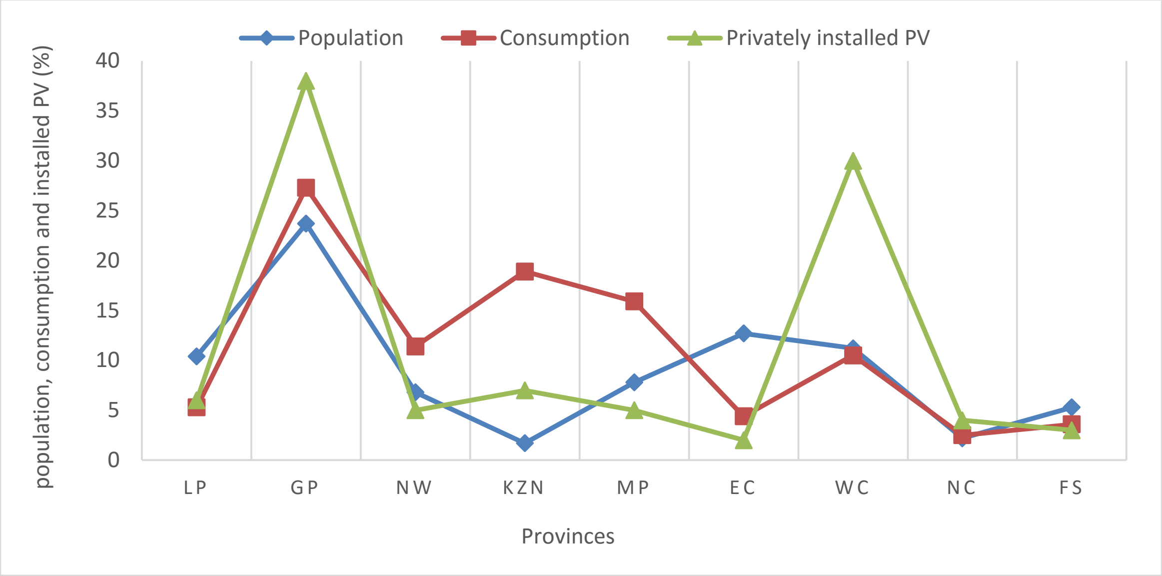

Figure 4.14: The solar PV consumption, population and installed systems pattern

The five main sectors that have contributed to 94 MW privately installed solar PV systems by March 2016 are commercial, agriculture, industrial, residential and mining consumers. The commercial sector has the highest installation of 59%, and the mining sector the lowest with 2% installation (Figure 4.15). However, this picture may change as sectors continue to install PV systems for their own generation. The commercial sector comprises mainly institutions that are service-providing facilities and equipment of businesses, national and local government institutions. These are non-manufacturing business establishments such as hotels, restaurants, wholesale businesses, retail stores, warehouses, storage facilities, and health, social and educational institutions. There is a drive to demonstrate the ability for renewable energy to contribute to the total energy mix in South Africa. Hence, most commercial buildings are having rooftop solar PV installed for power generation given the increased electricity tariffs and decline in PV module prices.

The Western Cape is one of the biggest tourist destinations in South Africa with attractions such as Table Mountain. The hotels and restaurants are among the top tourist destinations and they are transforming to green buildings and are using green electricity. This is one of the reasons for the high rate of installation of PV systems in the Western Cape, particularly the commercial sector. This chapter recommends that government should encourage the commercial sector to continue installing PV for its own use. The mining industry has the fewest privately installed PV systems, yet it is one of the biggest grid connected electricity consumers. The residential sector installed 10%, which is mostly dominated by farms that are off-grid.

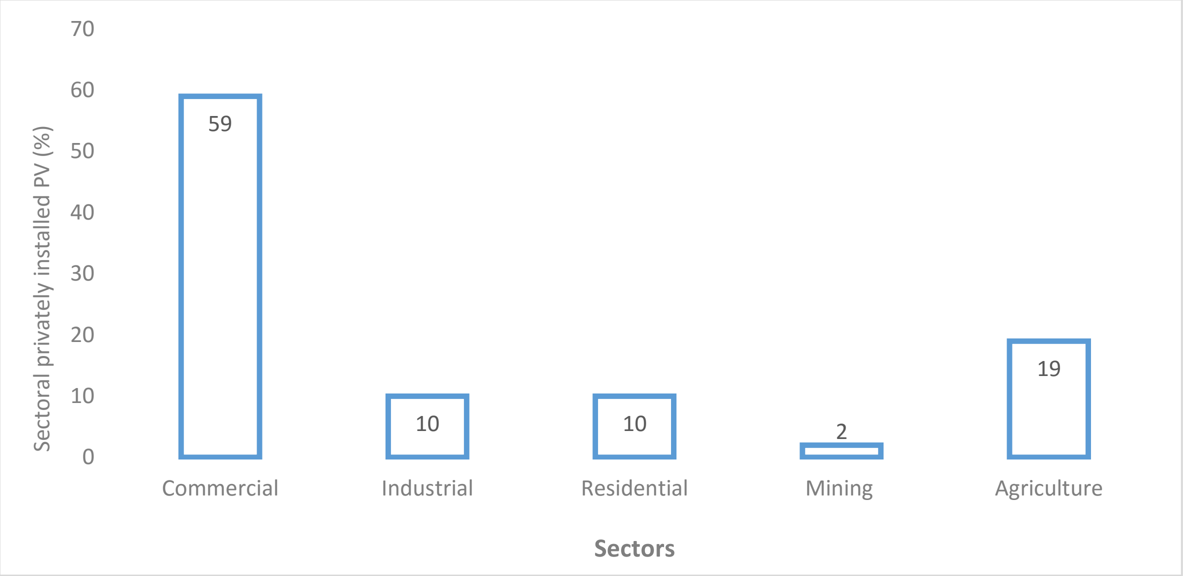

Figure 4.15: Solar PV installation per sector (Source: http://pqrs.co.za, 2016)

4.4.1.4 The South African government IPPP programme

From four bidding windows the government of South Africa has registered a total of 2293 MW solar PV capacity (DOE, 2015). By end of 2015 approximately 900 MW was online and the remaining capacity is anticipated to be commissioned in the next 2-4 years. The solar PV bidding is distributed across the provinces. Nevertheless, out of 2293 MW registered solar PV projects, 1497 MW is in Northern Cape Province, which represents more than 50% of the PV projects (Figure 4.16). The North West was next, followed by Free State and Western Cape.

The reason for such high number of projects in Northern Cape is that there is high solar irradiance and vast land space for commercial solar PV projects. North West and Free State are dominated by farms where some farmland are used for the solar PV projects in light of the perpetual drought that is straining the agricultural sector.

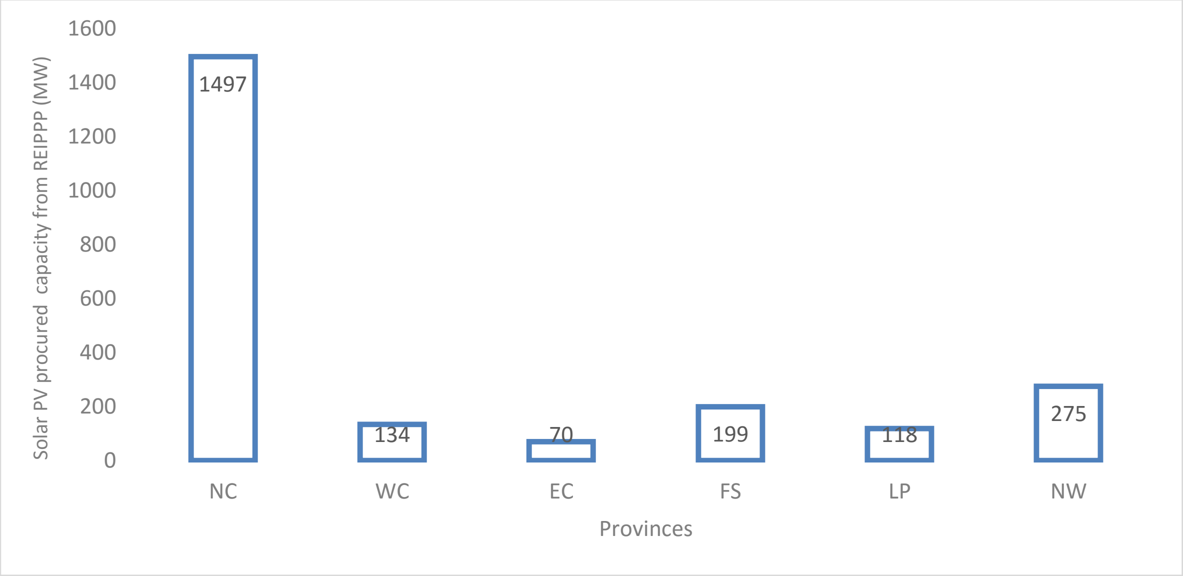

Figure 4.16: Solar PV registered in the Renewable Energy Independent Power Producer (REIPP) procurement programme (Source: DOE, 2015)

The REIPP procurement programme has validated the findings of scenario 1 and 2 specifically for Northern Cape Province. There is therefore good solar PV potential in the Northern Cape Province. Yet, the Eastern Cape was preferred for wind energy projects by the REIPP because of the high wind energy in the coastal province.

The findings of this chapter in different scenarios are supported by the technical potential, theoretical potential, South African REIPP programme and the solar PV privately installed in different provinces. Scenario 1 and 2 conclude that Northern Cape and Eastern Cape have the highest solar PV potential, this is confirmed by the technical potential mainly due to vast land space available as well as solar radiation. Moreover, the REIPP programme corroborates the potential in the afore-mentioned provinces (Table 4.6). The two main attributes that played crucial role for such massive potential in these provinces are high solar radiation and land space.

The solar PV privately installed supported scenario 3 potential, which is mainly in Western Cape, Gauteng and KZN (Table 4.6). This is the case because these provinces are economic hubs of the country, and attract tourist and foreign investment in the country. Furthermore, the electricity consumption in these provinces is high, and hence the installation of solar PV, mainly in the commercial, industrial and agricultural sectors. The theoretical potential is mainly solar radiation, which prevails in good quantity in most of the provinces, hence it cross-cuts in all scenarios.

Table 4.6: Confirmation of solar PV potential compared to other ongoing initiatives

Solar PV ongoing initiatives/potential	**Potential/installation in provinces**	**Results (potential in different scenarios)**
Technical potential	Northern Cape and Eastern Cape	1 and 2
REIPP procurement programme	Northern Cape and North West	1 and 2
PV privately installed	Gauteng, Western Cape and KZN	3
Theoretical potential	Northern Cape, Free State, Western Cape, North West, Gauteng and Eastern Cape	1, 2 and 3

4.4.2 Electricity usage per sector

In view of the 2015 load shedding in South Africa, it would be useful to understand the relationship between electricity consumption and the privately installed capacity by March 2016 in different sectors (http://pqrs.co.za, 2016). The industrial sector is responsible for approximately 36% of the total South African electricity produced in 2013 (Figure 4.17). Agriculture used least (3%), whereas mining and commercial enterprises consumed 7% each.

As discussed in section 4.4.1, in line with scenario 3, KZN and Gauteng have high energy consumption due to, among others, the industries in these provinces. Nonetheless, there is relatively low installed PV capacity in the industrial sector of around 10% (Figure 4.17).

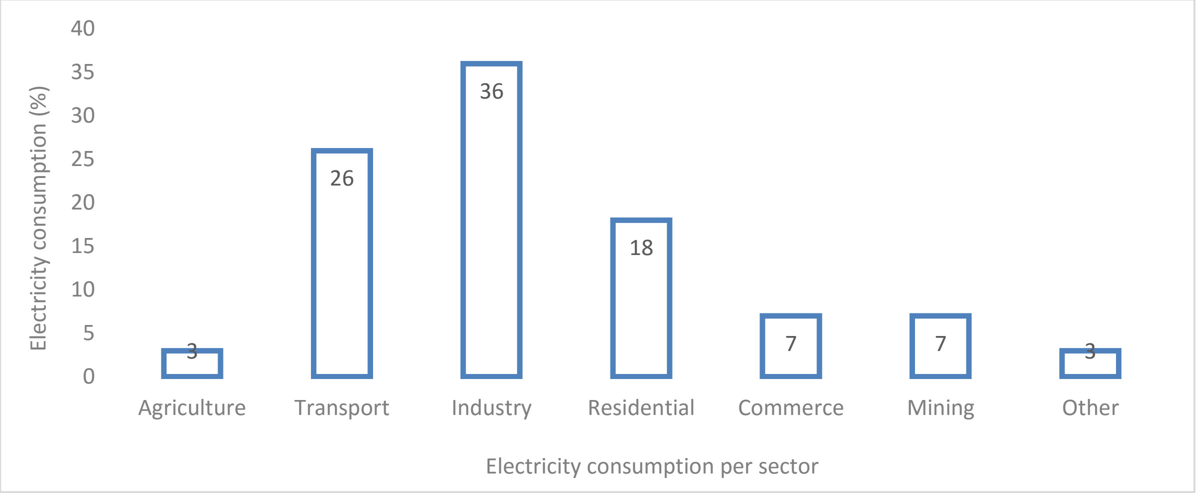

Figure 4.17: Electricity usage across different sectors (Source: Department of Energy, 2009)

Taking into consideration the electricity consumption and the installed PV capacity by March 2016, the commercial sector consumed 7% of the total South African electricity, and had installed 59% of the total privately owned PV systems by March 2016 (Figure 4.18). This figure is expected to grow, as the commercial sector is significant and becoming an attractive destination for the international community. However, this is different in the industrial sector, which is consuming close to half of the total electricity generated in the country, which is 36% and has installed only 12% solar capacity to date.

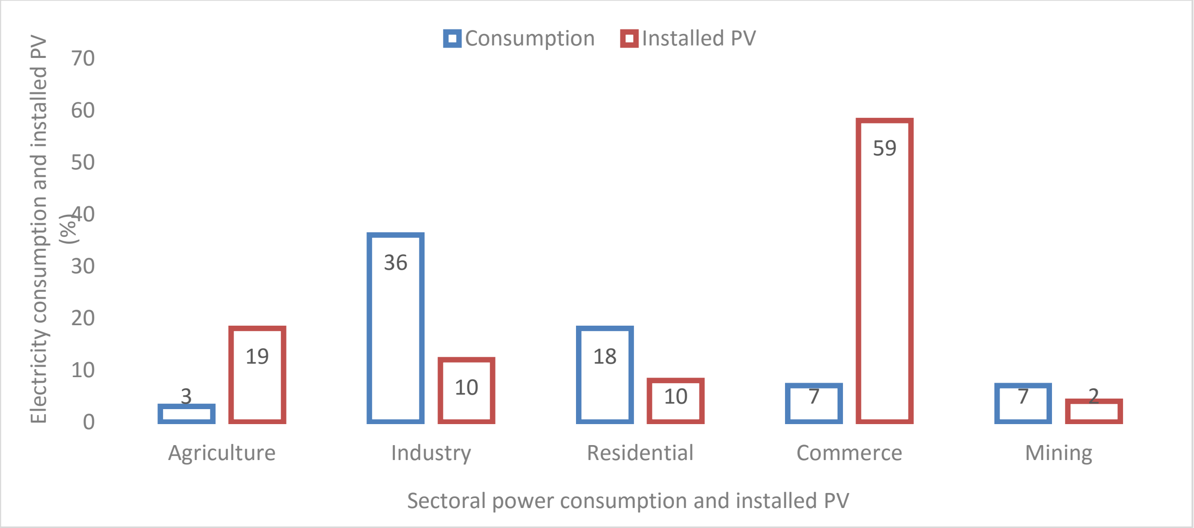

Figure 4.18: Relationship between electricity consumption and installed PV systems per sector

This chapter found that there is good PV potential in Gauteng and KZN Provinces. Furthermore, electricity consumption in these provinces is high, mainly because of the industrial sector, which is the core of the South African economy. This was confirmed by the electricity usage per sector, where the industrial sector consumed most electricity at 36%. Moreover, of the current private installed capacity of 94 MW it accounts for 10% (http://pqrs.co.za, 2016).

There is a need for promotion, awareness, subsidies and encouragement in the industrial sector to install more solar PV systems to meet own needs. In the residential sector, the gap between the consumption of energy from fossil fuels and PV generation is around 6110 MW; 9.4 MW was consumed from solar PV systems by March 2016 (Table 4.7). For solar PV generation to contribute 10% consumption in the residential sector, approximately 610 MW of PV power generation is required. At approximately 20% load factor, the total required installation is around 3050 MW to generate 610 MW of solar power for 10% electricity consumption in the residential sector alone.

Table 4.7: Comparison between PV and fossil fuel installed capacity in the residential sector

Energy source	**Current capacity (MW)**	**Consumption (%)**	**Consumption (MW)**
PV	94	10	9.4
Fossil fuels	34000	18	6120

During the survey (Energy consumption survey, 2014, Appendix A) it was found that the major driving force behind the installation of solar PV in different sectors, such as residential and commercial, is a continuous price reduction for PV systems (Figure 4.19). The electricity tariff increases every year, while the PV system price decreases every year. Although the commercial, agricultural and mining sectors invest in solar PV systems because they want to save cost, some would like to be off-grid and independent of power supply, while others want a reliable power supply, contrary to the load shedding that occurred in the first half of 2015.

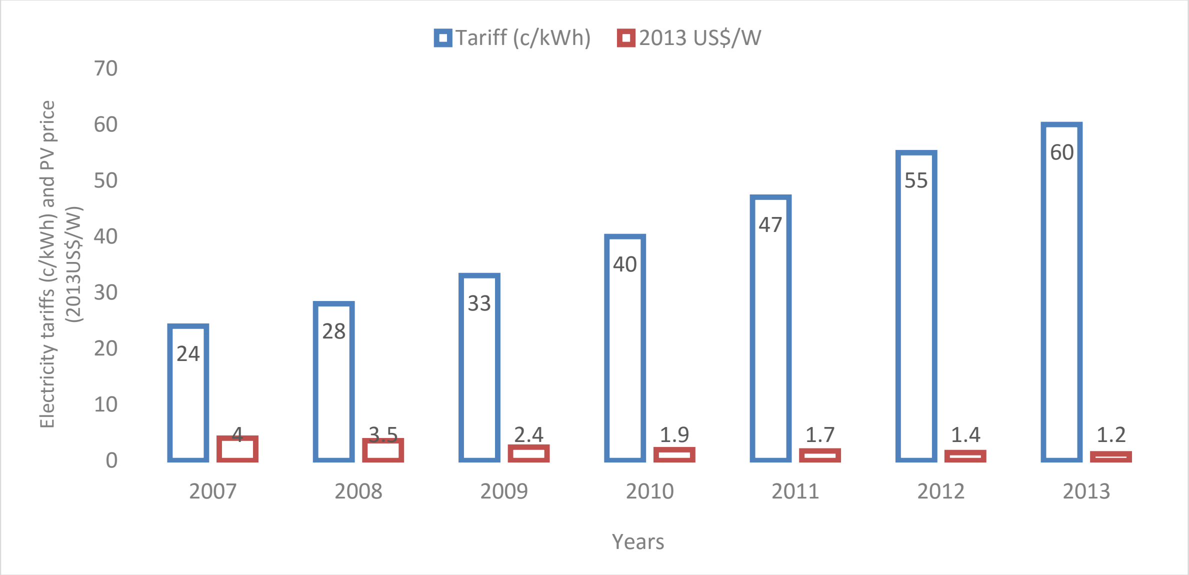

Figure 4.19: Electricity price increase and PV price reduction (Source: Feldman *et al.,* 2014; Eskom, 2014)

This report recommends that the South African government should focus on promoting solar PV systems in the residential sector. Furthermore, the government should subsidise the residential sector on PV installation, in the same way it does for SWH. The other sectors (commercial, mining, agriculture) are businesses and self-sustainable and the way to push them to install solar PV systems should be to increase the electricity tariff.

In Hawaii in the USA, most homeowners (residential sector) use off-grid energy systems (Timilsina *et al.,* 2012). For the same reason as in figure 4.19, the high rate of residences using the off-grid electricity is due to high electricity tariff, and the decrease in solar PV module prices. The residential electricity tariff in the Aloha State was at an average of 31.2 cents/kWh in May 2015, which was 2½ times higher than the average US price. Moreover, the off-grid energy system is a good option, because tapping into the power grid is expensive by itself.

4.4.3 South African renewable energy target and GHG emissions

4.4.3.1 Renewable energy target

This research found that South Africa has the technical potential to generate power of 7815 TWh/year from solar PV, from crystalline modules in particular. This result provides further support for the view that solar PV generation can make significant contribution to the South African renewable energy government target of 10000 GWh. The Northern Cape Province alone could potential generate 2598 TWh technically, which according to Munzhedzi and Sebitosi (2009), the daily power output ranges from 3.9 to 7.3 kW/m^2/day, while the figures in Limpopo and the Western Cape Province range from 4.07 to 6.66 kW/m^2/day and 2.61 to 8.13 kWh/m^2/day respectively. The afore-mentioned technical potential is undoubtedly sufficient to meet South African renewable energy targets.

These findings are in agreement with those of Munzhedzi and Sebitosi (2009), who found that the Northern Cape, Limpopo and Western Cape Provinces have good potential for solar PV application (of around 4.3-4.9 kW/m^2/day), which is better or higher than in Mpumalanga, Gauteng, the Free State and part of the Western Cape Province. For that reason, it is anticipated that solar PV will play a bigger role in meeting South African renewable energy target.

4.4.3.2 Greenhouse gas emissions from the technical potential

The potential 7815 TWh/year could play a significant role in the GHG emission mitigation in South Africa. The solar PV has potential and ability to reduce GHG emissions. The CO_2 tonnes saved from utilization of solar PV energy is calculated based on the country's emission factor. The South African emission factor is 0.900tCO_2/MWh (Thomas *et al.,* 2000). Therefore, the emission saved is calculated as follows:

$$\boldsymbol{Power\ production\ [MWh/year]\quad x\ SA\ emission\ factor\ [tCO2/MWh]}$$
$$= \boldsymbol{t}\ [\textbf{tonnes CO2}]$$

The MWh/year is Solar PV power production, tonnes of CO_2/MWh is South African emission factor, and tCO_2 is the greenhouse gas emission saved (Thomas *et al.,* 2000) from the generation of certain quantity of electricity from solar PV.

Then the potential greenhouse gas emissions that could be saved from solar PV is calculated as follows:

Tonnes of CO_2 = 7815000000 MWh/year x 0.900 tCO_2/MWh
Tonnes of CO_2 = 7 033 500 000 tonnes

The greenhouse gas emission reduction from solar PV contribution alone could be approximately 7 033 500 000 tCO_2 per annum. This reflect massive opportunity for South Africa to reduce greenhouse gas emission. The renewable energy technologies are ideally suited for meeting the emission reduction targets, and South Africa has substantial opportunity and potential to reduce emissions. The Northern Cape and Eastern Cape Provinces could potentially contribute massively in the reduction of greenhouse gas emission.

4.4.4 Transmission and distribution power loss

This study found that the Northern Cape and Eastern Cape provinces have good solar PV potential. The power generated from provinces will have to be transmitted and distributed to the customers. These are mainly areas where demand and consumption are relatively high, such as North West or Gauteng as the nearest provinces from the Northern Cape. The transmission of power usually requires high capital investment. The power passes through the grid network infrastructure such as transformers and distribution system, overhead lines, underground cables to get to the point of use (Cogdell, 1996). The power loss in South Africa is at an average of 9% between 2010 and 2015 (Eskom, 2015). Hence, the power loss trend in South Africa increased from 8.7% in 2011 to 9.6% in 2013, and decreased drastically to 8.8% in 2014 (Figure 4.20). As the length and voltage of transmission line increases, the electric energy leaking through the capacitance to earth increases too (Ching, 1998).

Utilities across the world struggle with electricity loss. In South Africa electricity loss is categorised into two, namely:

- Technical electricity losses: this is a natural result of transferring electrical energy from one point to another, with some of the electricity being dissipated as heat. The further the electricity has to travel, the bigger the losses (Eskom, 2015). The technical loss mainly comes from electricity dissipated in the conductors, equipment used for transmission lines, transformers, sub-stations and distribution lines, and magnetic losses in transformers.
- Non-technical electricity losses: This refers to losses caused by theft, which occurs in a form of illegal connections, meter tampering and illegal vending of prepaid electricity, as well as billing errors (Eskom 2012).

The Eskom Holding technical losses are higher than the non-technical ones, it is estimated at between 60% and 75% of total electricity losses in the distribution networks. This high loss rate is influenced by factors such as network design, network topology, load distribution and network operations (Eskom, 2015). Out of the total loss, 60% is lost in the distribution and 40% is lost in the transmission.

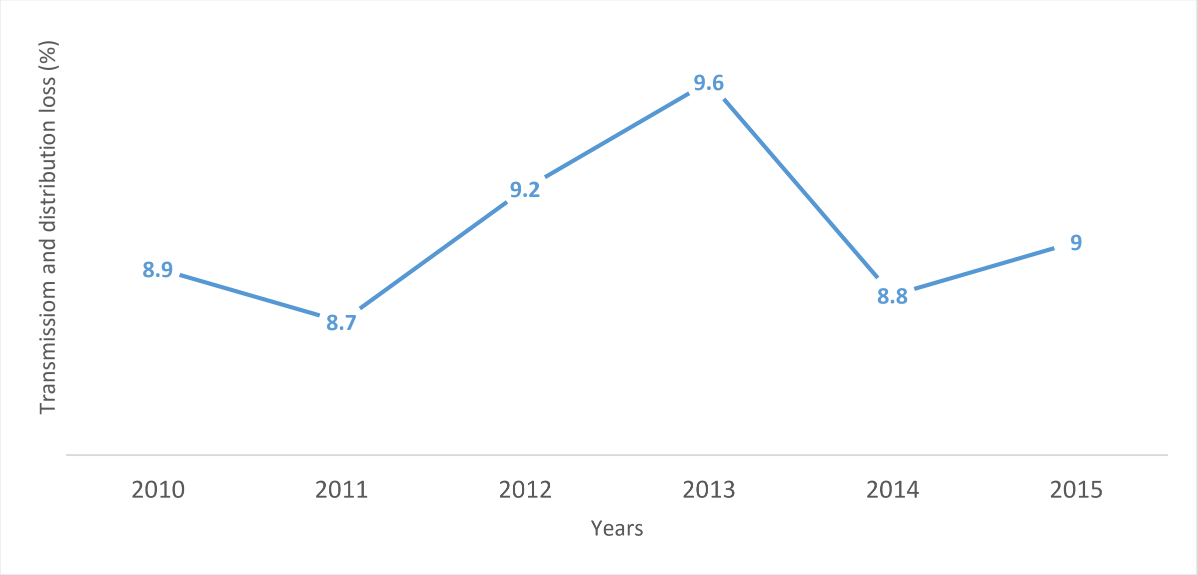

Figure 4.20: Transmission and distribution power loss (Source: Eskom, 2011; Eskom 2012, Eskom, 2015)

Approximately 9% of the solar PV power generated in Northern Cape or Eastern Cape Provinces is likely to be lost through transmission and distribution, due to long distance to the end-users. Then, more power is saved if the generation is closer to a point of use (Bollen and Hassan, 2011).

In order to avoid and/or minimise the 9% power losses through transmission and distribution networks from Northern Cape and Eastern Cape to other provinces that have high energy demand, this study recommends two factors to be implemented, they, however, does not solve the South African energy demand problem though, but does help to reduce GHG. The factors are as follows:

- The chemical storage mechanism as an alternative to electric transmission and distribution. This is a process where power can be stored and transported to the end-users with minimum loss. The power could be stored in chemical storage such as batteries and shipped or transported to areas where power is needed. Nonetheless, further research on the viability of this mechanism is needed.
- The power generated in Northern Cape Province could be sold to Namibia as a neighbouring country, which is closest to Northern Cape Province. Similarly, power generated in Eastern Cape could be sold to Lesotho as a closest province to the source of power. In this case it would be short distance transmission and less power loss, and further promote trade through selling clean energy to the neighbouring countries.

4.4.5 Maximising energy exploitation and extraction in South Africa

4.4.5.1 Roof-top solar PV

Millson (2014) conducted a study in Cape Town, South Africa to investigate the potential of roof-top in commercial sector. He found that Managers of the grocery stores, offices and distribution centres generally believe that solar PV is already worth considering for the rooftop of their buildings. Over 76% of respondents valued reduction of their company’s CO_2 emissions through reducing reliance on grid power. This is similar to the privately installed solar PV system in which the commercial sector has installed 59% by March 2016 (http://pqrs.co.za).

In Cape Town commercial buildings, the motivation for installation of roof-top solar PV was the rising cost of grid-connected electricity (Millson, 2014). Similarly, the middle and high income residents in South Africa are interested to install roof-top solar PV due to rising cost of grid connected electricity (Energy consumption survey, 2014, Appendix A). Consequently, there is significant interest in the commercial and residential sector to install roof-top solar PV. Nonetheless, in the absence of FIT where surplus power could be injected to the grid, it is difficult for the residential customers to install roof-top solar PV, except those that are off-grid such as farms.

4.4.6 Solar PV module efficiency and degradation

Section 4.3, scenario 1 and 2 found that the Northern Cape has significant solar potential of over 21.7% and 19.1% respectively, which is over 8 kWh/m^2/day of solar irradiance according to SWERA, 2008. Moreover, section 4.4.1.1 presented the technical potential of around 7815 TWh/year. Nonetheless, the technical potential does consider other factors such as efficiency of the PV modules. The efficiency varies from time to time in different hours of the day and seasons of the year.

The efficiency of the solar module is measured by its ability to convert sunlight into usable energy for human consumption. The performance efficiency of the PV module decreases over the years mainly because of aspects such as dust, soiling and degradation. The accumulation of dust can have severe impact on the efficiency of a PV module during windy and dry seasons in particular, which unfortunately is the period when the highest solar irradiance occurs (Mejia *et al.,* 2014). The solar PV power output is highly dependent on the amount of solar radiation absorbed by the solar cells on the PV module.

However, because of variations in the sun’s position and angle each day throughout the year, the total irradiance received at a particular site is different and fluctuates from time to time, and from one season to another (Hamou *et al.,* 2014). Therefore, the solar output found and presented in section 4.3 and 4.4 may not be fully realised at that level for long; the PV might generate that power output only for the first three or four years. Performance and efficiency may decrease over time, and that should be taken into consideration before a conclusion is reached on the likely power to be generated over the lifespan of PV modules. This section intends to provide an understanding of the impact of PV efficiency and degradation on total power output.

4.4.6.1 Solar PV module efficiency

The manufacturers usually assess the performance of solar PV modules under standard indoor test conditions. This is a solar panel output performance testing condition used by manufacturers in order to ensure relatively independent comparison and output evaluation of different solar PV modules. For example, the polycrystalline module is generally known to perform between 14 - 18% efficiently, measured under standard test conditions (Ndiaye *et al.,* 2013; Hamou *et al.,* 2014). The three test conditions are temperature of the cell (which has significant effect on the efficiency reduction), solar irradiance (1000 Watts per square meter) and the mass of the air. However, the performance of the same modules under real conditions may differ from the expected results that were derived from the standard test conditions owing to a variety of continuously changing weather conditions. Many researchers have done experiments on testing the PV module and the efficiency rate differed from what the manufacturers had indicated.

Hamou *et al.* (2014) measured the efficiency of PV modules marked to have an efficiency of 11% by the manufacturer. The test results under real conditions found that when solar radiation reaches a value of 1000 W/m^2, the efficiency output does not exceed 9%. Hence, the solar PV modules may not perform to the expected level of efficiency, which would have severe implications for power generation, especially in a large-scale commercial PV power plant.

The relationship between solar irradiation and efficiency is linear: when solar irradiance increases, efficiency increases too. In winter, on rainy days, in the morning and late afternoon, efficiency drops significantly in response to the solar spectrum and angle of incidence. However, when efficiency reaches a maximum, such as 12%, it remains steady as the solar irradiation increases (Chimtavee *et al.,* 2011). Efficiency starts at as low as 1% when solar irradiation is at 0.1 kW/m^2 and picks up as the solar irradiation increases until it reaches maximum efficiency (Figure 4.21). Therefore, efficiency is highly dependent on the level of irradiance to reach its maximum. On days where the solar irradiance does not go above 300 W/m^2, the efficiency will not reach maximum percentages, and this will have significant impact on the power output.

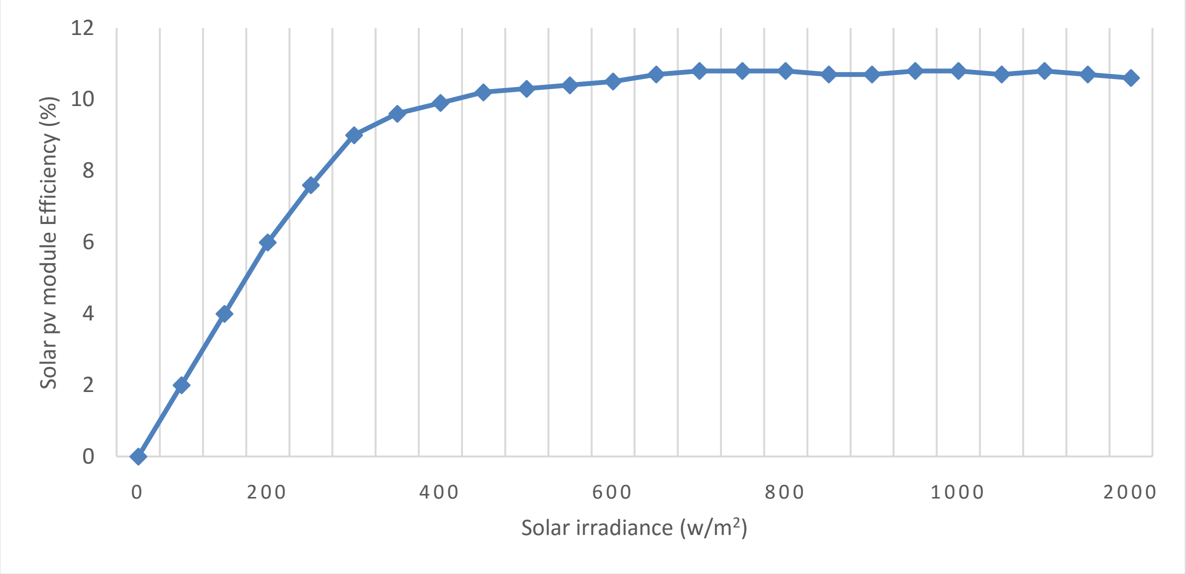

Figure 4.21: Relationship between efficiency and solar irradiance (Source: Chimtavee *et al.,* 2011)

Efficiency has a direct impact on power production. There are many factors that make efficiency drop, such as dust or fluctuation of irradiance during the day and if the solar irradiance does not exceed a particular W/m^2 count such as 300, efficiency will not pick up to the maximum. These factors reduce the ability of the PV module to perform to its maximum potential, which disadvantages the solar PV technology. The price of solar PV modules is decreasing over time, but the efficiency of the module also decreases as time goes by. Consequently, the solar PV output that is measured to be generated from the PV modules over the lifespan of a module is not constant; rather it decreases in efficiency over the years.

The current direct normal irradiance of 2000 kWh/m^2/year in the Northern Cape Province may not be constant for the entire duration of the lifespan of PV modules, hence the output is likely to decrease gradually over the years in a particular order such as in year 2, 5, 10, 15 and 20 by a certain percentage. This will have direct implications for the power output and profit of IPPs. By the time the IPP or community members have paid the loan on PV system for the household, the power output may be much lower. Therefore, the accurate efficiency of solar PV module will be witnessed after 5-10 years in the South African REIPP procurement programme.

4.4.6.2 Solar PV module degradation

Degradation is the gradual decline of the quality and characteristics of solar PV components that affects the ability to operate within the limits of the acceptable level, which is usually caused by operating conditions and the environment (Ndiaye *et al.,* 2013). It is a method of quantification of the power decline over time (Jordan and Kurtz, 2013). In a large-scale solar PV rollout, the investors would be interested in answers regarding the degradation rate of the solar PV system in order to obtain a proper and accurate analysis of the financial and technical facility of the investment, despite the available potential. So accurate predictions of return on investment require accurate prediction of decreased power output over time (Jordan and Kurtz, 2013). Hence, degradation rate become crucial for investors and has to be known in order to predict power delivery.

Monitoring the degradation of the PV system is crucial, because a high degradation rate is equivalent to a loss of power output and hence a reduction or loss in profit and return on investment (Ndiaye *et al.,* 2013). There is little information on PV modules' degradation modes, specifically the frequency, speed of evolution and degree of impact on module lifetime and reliability. The absence of reliable information on the rate of degradation increases the financial risk of the PV system, and hence investors become reluctant because of uncertainty about the degradation rate and magnitude. The higher the degradation rate the less power produced.

Degradation rates have been studied and reported for over 40 years in different countries. Different climate and weather conditions have an important influence on degradation rate (Jordan and Kurtz, 2013). Therefore, degradation rate studies from diverse geographical locations are of great interest and important in analysing and assessing the degradation rate of South African solar PV projects.

The degradation rates were calculated from continuous data of over 10 years using the PV utility scale method and compared with literature values. Most mono-crystalline exhibited degradation rates of less than 1% per year, while thin-film technologies showed rates above 1% per year (Jordan and Kurtz, 2013). The greatest change is that before year 2000, indoor measurements were not frequently used to test and determine degradation rates. However, after year 2000, the indoor measurements percentage has grown almost to the levels of outdoor and performance ratio methods. The accuracy of Standard Test Condition (STC) measurements has significantly improved during the last three decades. There are many researchers that have done degradation rate measurements for longer than 10 years, hence the accuracy level is anticipated to be good.

Various researchers (as cited in Jordan and Kurtz, 2013) have measured degradation over the past 2-4 decades, the results are presented below:

- Vaassen (2005) measured degradation rate for the six PV modules over 4 year's period. The degradation rate was found to be slightly below 0·5% per year in Germany.
- Jordan *et al.* (2010) measured degradation rate for more than 44 PV modules. It was found that technology and date of installation were the most important factors determining degradation rates. The crystalline silicon module degradation was less than 1% per year.
- Reis *et al.* (2002) measured degradation rate for 192 mono-crystalline silicon modules in Arcata, USA, over 11 years of exposure. It was found the degradation rate was 0.4% per year. Furthermore, it was found that high degradation rates in PV system were usually due to individual module failures or other electrical components.
- Realini *et al.* (2003) conducted degradation rate on a 10 kW PV system in Southern Switzerland, it was found that system degradation rate was 0·2% per year after approximately 20 years.
- Hedström and Palmblad (2006) presented data on 20 PV modules exposed for more than 25 years in Sweden. The average degradation rate was 0.17% per year.

- Saleh *et al.* (2009) studied and found degradation rate of approximately 1% per year for a stand-alone PV system in the desert climate of Libya after 30 years.
- Similarly, Tang *et al.* (2006) found 1% per year degradation rate for a PV system of almost 30 years located in the similar climate as Libya in Phoenix, USA

A record of the last 30-40 years' degradation rates using field tests was reported in the literature. Nearly 2000 degradation rates were measured on individual modules or entire systems. It was therefore found that a mean degradation rate was 0·8% per year and a median degradation was 0·5% per year (Jordan and Kurtz, 2013). Some degradation rate measurement done in different continents and climatic zones were reported in the afore-mentioned section.

The solar PV system average degradation rate of 0.8% per year would mean that the system would be 8% degraded in year 10, and hence 16% degraded in year 20 (Figure 4.22). The average degradation of 0.8% per year was studied and measured by over 2000 researchers in different continents (Jordan and Kurtz, 2013). However, the rate differs from one area to another, though the difference is minor.

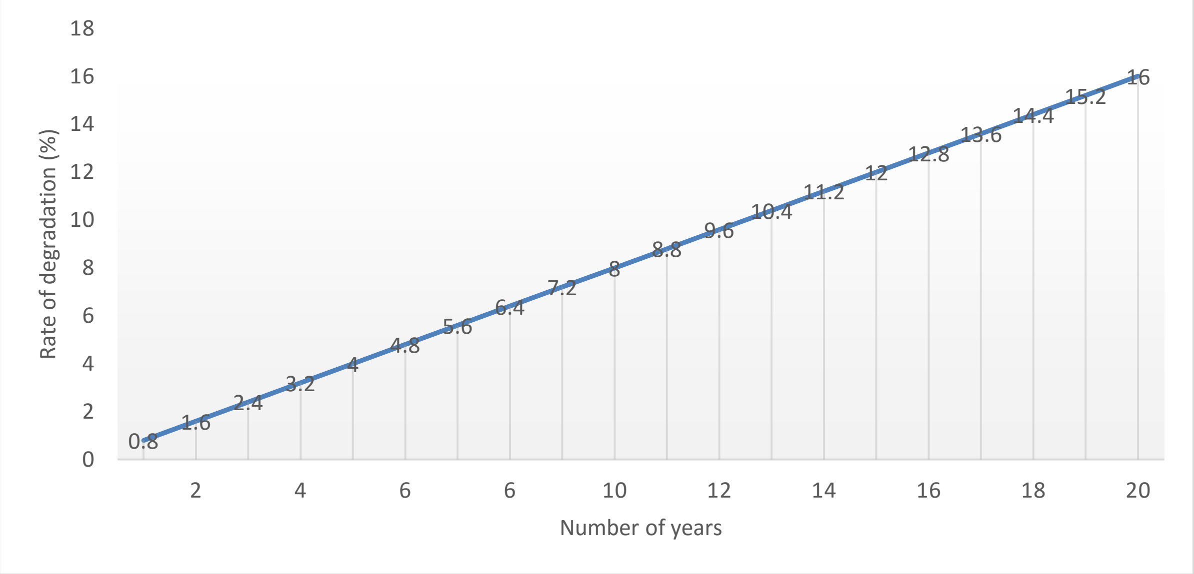

Figure 4. 22: Solar PV degradation rate in 20 years period (Source: Jordan and Kurtz, 2013)

The Northern Cape has the technical potential of generating 2598 TWh/year in year 1 of installation. At a rate of 0.8% per year generation could drop to 2510 TWh in year 5 and to 2430 TWh in year 10 for PV systems installed at the same time. Similarly, South Africa has a technical potential of 7815 TWh/year. At a degradation rate of 0.8% per year, the PV system is anticipated to generate 7440 TWh in year 5, and the power output is likely to reduce up to 6628 TWh in year 20 due to degradation (Figure 4.23). There would be power loss of 1187 TWh over a 20-year period at an average of 60 TWh a year. Degradation is anticipated to have negative impact in the power generation from the solar PV projects.

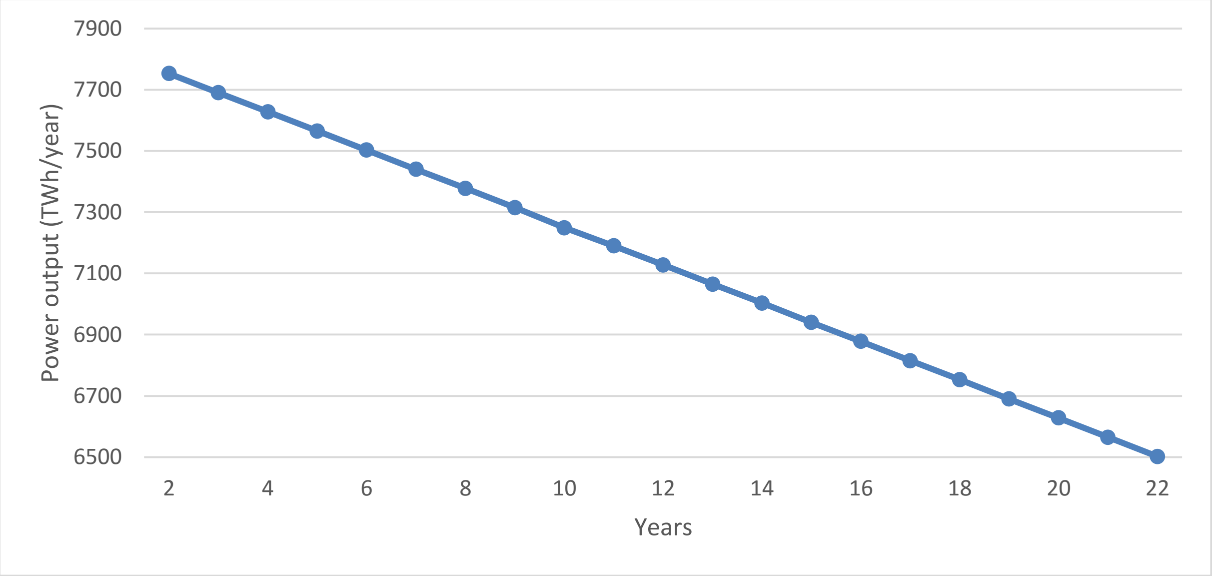

Figure 4.23: Solar PV power output over 22 years and the effect of degradation

The factors that determine the degree and magnitude of degradation are the quality of materials used to manufacture the equipment, the process followed during the manufacturing phase, the quality of assembly and packaging of the cells into the module, and the frequency and interval of maintenance at the site (Jordan *et al.,* 2010 cited in Jordan and Kurtz, 2013). Some factors that may reduce the frequency and rate of degradation are regular maintenance and cleaning regimes. However, the main influence would be the characteristics of the module being used, e.g. the type of PV module. The main modes of PV module degradation are corrosion, discoloration, delamination and breakage of the module. Moreover, other environmental parameters, such as temperature, humidity and UV radiation, can be important in PV module degradation (Ndiaye *et al.,* 2013).

4.4.6.3 Solar PV system dust and soiling

Soiling and dust contribute to the decrease in efficiency and degradation of PV modules, especially during the dry season and drought. In Santa Clara, California, USA it was found that during the summer drought most of the sites where there were PV modules registered losses of about 1.6% in efficiency, therefore the PV modules' efficiency went down from 7.2% to 5.6% (Mejia *et al.,* 2014). The question would be how much additional solar energy could be harvested through module washing, and at what frequency washing of the PV modules can be done. In addition, is the automated washing system efficient? Manual washing is labour-intensive and can be costly. Rain is a natural phenomenon that washes and cleans PV modules, but does not occur as frequently as one would want it to occur. Besides, it comes with cool to cold weather and that would affect the efficiency level of the module.

Soiling and dust have serious negative effects in the generation of electricity from PV modules. They lower efficiency by an average of 1.6%, which would be a substantial amount of power. This would ultimately affect the total power production modelled to be produced from the PV power plant, and hence affect the productivity of the entire plant.

4.5 Conclusion and summary

Solar radiation, population, electricity consumption and land space are key parameters that play significant role in determining solar PV power generation potential. There is significant solar PV potential in the Northern Cape and Eastern Cape Provinces. This is influenced and determined by the solar radiation and land space parameters in the two provinces. Indeed, it is concluded that the two provinces are suitable for large scale solar PV that would be transmitted to other provinces or exported to the neighbouring countries due to low electricity consumption in these provinces. Nonetheless, the challenge of grid infrastructure and transmission power loss remain for this option.

Similarly, Gauteng and KZN Provinces have good solar PV potential. They have high electricity consumption, they consumed more than half of South Africa in March 2016. This report recommend that government prioritize construction of solar PV projects in these provinces because there would be less transmission distance and hence less power loss. Moreover, there is high electricity consumption in these provinces, and hence solar PV power could contribute significantly in the total energy mix consumed in these provinces. It should be noted that Gauteng is constrained by land space, as it is the smallest province in South Africa. Therefore, the decision-making system regarding the province where solar PV projects are to be constructed should be entirely based on the purpose of the solar project and choice of parameters to be satisfied. Hence, *'optioneering'* is the best method to determine the potential in accordance with the purpose of the project.

This research found that South Africa has the potential to generate 7815 TWh/year from solar PV technology. It is anticipated with PV technological advancement and enhancement in which efficiency is anticipated to increase beyond 20%, the South African PV potential is likely to be more than 7815 TWh/year in future. The solar PV technology has the potential to contribute in carbon reduction of up to 7 033 500 000 tCO_2 per annum. Equally, solar PV could contribute all of the renewable energy target in South Africa. Hence, this represents a massive opportunity for renewable energy in South Africa.

The findings of this chapter for different scenarios were validated by the following, namely: 1) solar PV technical potential (validated scenario 1 and 2); 2) theoretical potential (validated all three scenarios); 3) privately installed PV across the country (validated scenario 3); and 4) the REIPP procurement programme (validated scenario 1 and 2). Thus, it is recommended that the provinces that were found to have substantial solar PV potential should be considered for the construction of solar PV plants,

The hourly solar PV output does not match the load profile pattern in South Africa. The hours in which electricity consumption is high (early hours in the morning and later on in the afternoon) are the hours where PV is not generating maximum power. Therefore, there is no match between the peak hours and PV maximum power generation hours.

Similarly, there is significant mismatch in the seasonal power production and consumption. Solar power production declines in winter, yet the power consumption increases in winter. Clearly, there is a need to solar PV power generation storage in order to reduce the mismatch for the hourly and seasonal power consumption and production.

Out of the country's solar PV potential of 7815 TWh/year there would be power loss during the operations of the projects over the years. Approximately 9% power loss would come from the distribution and transmissions, which is mainly technical and non-technical causes. Therefore, approximately 7315 TWh/year may be the actual power delivered by the plants. Moreover, the reduced efficiency and degradation will further reduced power production from the solar PV plants. It is concluded that 6628 TWh would be generated in year 2020 due to the average degradation rate from other studies.

This chapter is summarised as follows:

- The Northern Cape and Eastern Cape Provinces have good solar PV potential, they are favourable and ideal provinces with massive potential for large scale solar PV projects. The transmission and distribution have certain magnitude of power loss, approximately 9% of power could be lost in the transmission and distribution lines from Northern Cape to Gauteng Province. This is, nonetheless, a setback for this option.
- It is recommended that the solar PV plants be constructed in Gauteng Province because it has reasonably good solar irradiance and relatively high power consumption, mainly due to high population and industrial development. There would be less power loss in view of the short distance transmission/distribution to a point where power is consumed. It is worth noting that limitation for this solar PV could be land space because these provinces are densely populated.
- Therefore, a combination of both solar PV plants and rooftop solar PV would be ideal for Gauteng Province.
- The KZN and Eastern Cape Provinces have the highest electrification backlog rate in South Africa. Perhaps South Africa should consider taking most parts of these

provinces into off-grid solar PV, especially taking into account the terrain, slopes and sparsely residential pattern in some of the rural areas in these provinces. China has reached 100% electrification in 2015, mainly due to off-grid electrification.

- There is a mismatch for the hourly and seasonal PV power generation and consumption in South Africa. The PV generate maximum power in the afternoon, whereas the consumption is high in the morning and late evening. Equally, the solar PV produce maximum power in summer months, yet the power consumption is high in winter month.
- South Africa should consider harnessing roof-top solar PV. Most of the middle and high income residents are willing to install roof-top PV. However, due to unavailability of the renewable energy tariffs and selling back to grid mechanism, the roof-top potential remains untapped thus far. The roof-top solar PV has significant advantage that power is produced in close proximity to where is needed, as electricity consumption is also taking place mainly in buildings, therefore there is little if no power loss through distribution. Moreover, there is no space required, like in the large commercial installation. The biggest reduction in power loss is realised when the generation is located at the same premises as the consumption (Bollen and Hassan, 2011).
- The South African REIPPP, the current solar PV privately installed, theoretical and technical potential confirm the findings of this chapter.
- The impact and effect of solar PV degradation and efficiency has the potential to ruin the reputation of the technology. Therefore, the energy modelling and forecasting prior to the construction of the project should include an extra 15% capacity to accommodate the degradation and efficiency reduction that occurs gradually over a lifetime of the technology (15-20 years).

CHAPTER 5: THE POTENTIAL FOR HYBRID RENEWABLE ENERGY GENERATION IN THE COASTAL PROVINCES OF SOUTH AFRICA

5.1 Introduction

Renewable energy sources are unpredictable, fluctuating in nature and known to produce less power compared to fossil fuel power generation. Therefore, some ways and means of integrating multiple sources are required to provide more reliable and sustainable energy (Arul *et al.,* 2015). The hybrid diesel/photovoltaic/wind generator has become competitive in remote communities that are not connected to the grid network infrastructure across the world, mostly in rural and/or isolated areas. Hybrid energy refers to a combination of solar PV, wind turbine, biomass or any other renewable energy source for power generation (Maouedj *et al.,* 2014).

There is wide consensus that hybrid energy system would play significant role in increasing access to electricity, mostly in developing countries where conventional grid extensions are not cost-effective (DfID, 2013; Nema *et al.,* 2009). This system has been widely used for electricity generation and supply in isolated locations that are far away from the grid network, because it exhibits higher reliability and lower cost of power generation than systems that use only one source of energy (Saheb-Koussa *et al.,* 2009; Rehman *et al.,* 2012). Furthermore, this decentralised system requires less land than a utility-scale renewable project, experiences less distance-related transmission power losses (as it serves only locally based customers), and provides electricity just as traditional grid connection does (Kempener *et al.,* 2015).

Complementarity between energy sources such as wind and solar PV power produced in different geographical areas is an important aspect that needs to be carefully considered during the planning and design phase of the hybrid energy system (Monforti *et al.,* 2014). The PV module and wind turbine generate power simultaneously to meet the load demand. When the power generated by the wind turbine and PV modules is sufficient to satisfy the demand, the excess power goes to a battery bank until it is fully charged (Bilal *et al.,* 2013). The battery supplies energy to help the system to cover the load requirements when primary generation is insufficient. Moreover, when energy from PV modules, the wind turbine and battery is insufficient to meet the demand at a particular time, such as peak hours, the load could be supplied by diesel generators (Bilal *et al.,* 2013). The principal advantage of hybrid energy is the enhancement of system reliability when solar, wind and diesel power production occur simultaneously (Singh, 2013). The hybrid energy system provides a more reliable and sustainable power supply than a single source, such as a stand-alone wind generator or solar PV system.

The most common sources of power for hybrid energy system are wind energy and solar radiation. Wind energy refers to the kinetic energy that is associated with the movement of large masses of air. This motion results from uneven heating of the atmosphere by the sun, creating temperature, density and pressure differences (Khare *et al.,* 2013). Thus, wind power is the conversion of wind energy into a useful form of energy by using wind turbines to generate electrical power (Khare *et al.,* 2013). Solar PV generation entails the conversion of solar radiation into DC power, and its performance is primarily influenced by the type of PV solar system used (Dubey *et al.,* 2013). As discussed in Chapter 2, crystalline modules are more efficient than thin-film modules. The solar PV system absorbs approximately 80% to 90% of incident solar radiation; typically only 6% to 20% of the incident solar radiation is converted into electricity. The remainder is dissipated as heat and is lost (Haurant *et al.,* 2014; Dubey *et al.,* 2013).

The hybrid energy system is known in different countries across the continents and has been implemented in various locations, mainly in Asia, where it proved to be effective. Fluctuations in solar and/or wind energy generation do not generally match the time distribution of the load demand on a continuous basis in a particular area. However, additional means of power such as batteries and diesel generators are part of the hybrid energy system and responsible for provision of power whenever solar and wind are not generating power (Notton *et al.,* 2011). Approximately 15% of the residential sector has no access to electricity in South Africa (StatsSA, 2015; Department of Planning, Monitoring and Evaluation, 2014). It may be uneconomical to extend the grid network to some of the locations because of difficult terrain and limited accessibility, especially in rural areas (Kusakana, 2014). Therefore, in this chapter, the potential of a hybrid energy system was investigated in the three coastal provinces, namely KZN, the Eastern Cape and the Western Cape where such conditions are commonly observed.

5.2 Methods and materials

5.2.1 Potential of hybrid energy system

A similar method as in Chapter 4 was adopted in this chapter. Identification of the potential for a hybrid energy system in the coastal provinces warrants modelling of critical parameters such as wind levels, solar radiation, land space and population. In this chapter, modelling of the parameters was conducted through the '*optioneering*' technique discussed in Chapter 4. This approach sought to identify potential areas in the coastal provinces for setting up a hybrid energy plant.

The wind data was obtained as secondary data from Mortensen *et al.* (2014) and the data for other parameters was obtained from the same sources as explained in chapter 4. The units for all parameters/attributes were converted into percentages (%) to enable the model to run in a uniform manner and the raw data is presented in table 5.1. The coastal provinces are highlighted in red, with the Northern Cape Province highlighted in light pink, as it has small coastal part bordering the Atlantic Ocean.

Table 5.1: The data on different parameter for the coastal provinces

Parameter/attributes (%)	Options (designs)								
	LP	GP	NW	KZN	MP	EC	WC	NC	FS
Solar radiation	11	10.7	11.1	9.4	10.2	11.1	11.3	12.7	11.9
Wind energy	9.4	9.2	10.6	11.2	9.2	13.3	14.2	12.2	10.6
Electricity tariff	10.2	11.9	9.9	11.4	9.9	10.7	13.2	12	10.4
Land space	10.3	1.3	8.7	7.7	6.2	13.8	10.6	30.5	10.6
Population	10.4	23.7	6.8	19.7	7.8	12.7	11.2	2.2	5.3
Electrification backlog	9.5	15.4	14.8	20.7	11.6	19.6	9.5	8.1	8.5
Electricity consumption (2013)	5.3	27.3	11.4	18.9	15.9	4.4	10.5	2.5	3.6

The same three scenarios as in Chapter 4 were modelled. The rationale for three scenarios was to assess the impact and effects of different weighting of different parameters/attributes. The scenarios were derived from the same stakeholders as in Chapter 4. Scenario 1 was represented by the government departments, scenario 2 represented by the Academic sector (Universities) and scenario 3 represented by South African Wind Energy Association (SAWEA).

The scenario 1 weighting of attributes was averaged from different government departments (Table 5.2). The average weights were then used in the modelling process of hybrid potential.

Table 5. 2: The average weight for scenario 1 model from government departments

Requirements (%)	**DOE**[10]	**DST**[11]	**DTI**[12]	**NERSA**[13]	**Total**	**Average**
Solar radiation	25	30	30	20	105	26
Wind energy	25	30	25	20	100	25
Electricity tariff	10	5	0	10	25	6.5
Land space	20	15	15	20	70	17.5
Population	5	10	10	15	40	10
Electrification backlog	5	0	10	5	20	5
Electricity consumption	10	10	10	10	40	10
Total	100	100	100	100	500	100

In scenario 2, the matrix table was sent to 23 Universities for them to allocate weight for different attributes in accordance with their knowledge and expertise. Six Universities responded (University of Venda, University of South Africa, University of Fort Hare, North West University, Stellenbosch University and University of Johannesburg). The weights were averaged and final weights for scenario 2 were generated (Table 5.3).

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[10] Department of Energy
[11] Department of Science and Technology
[12] Department of Trade and Industry
[13] National Energy Regulator of South Africa

Table 5.3: The average weight for scenario 2model from academic sector

Requirements (%)	Univ.1	Univ.2	Univ 3	Univ. 4	Univ.5	Univ.6	Total	Average
Solar radiation	40	35	40	30	35	30	210	35
Wind energy	30	35	30	40	35	40	210	35
Electricity tariff	0	0	0	0	0	0	0	0
Land space	0	0	0	0	0	0	0	0
Population	10	0	15	0	0	5	30	5
Electrification backlog	15	20	15	25	25	20	120	20
Electricity consumption	5	10	0	5	5	5	30	5
Total points							600	100

The same responses as in Chapter 4 were received. Eleven solar PV industry company of out 28 responded **(Appendix B).** The average was calculated (Table 5.4).

Table 5.4: The average weight for scenario 3 model from solar PV industry

Requirements (%)	Total weight from companies	Average
Solar radiation	330	30
Wind energy	330	30
Electricity tariff	0	0
Land space	55	5
Population	55	5
Electrification backlog	220	20
Electricity consumption	110	10
Total points	1100	100

5.2.2 Districts suitable for the hybrid energy systems

The hybrid energy systems are particularly beneficial in remote and non-electrified areas, which some of them are rural. The identification of districts that are suitable for the hybrid energy system projects was done using two indicators:

- Districts that are less than 60% electrified, that is 40% or more backlog; and
- Districts with more than 40% unemployment rate.

The districts have various municipal areas, and hence this research zoomed into the municipal areas in order to identify communities that fall within the above-mentioned parameters. There is a linkage between unemployment and lack of electricity in the society. Lack of access to electricity contributes to poverty to an extent that the community has limited economic activities. The socio-economic growth and improved standard of living are directly linked to the use of electricity (Bhandari and Stadler, 2011).

5.3 Hybrid energy potential in the coastal provinces

Hybrid energy system is a good solution to supply energy loads in a small load demand community (Notton *et al.,* 2011). Hybrid energy projects have often been proven to be more profitable than other electrification solutions for rural areas, particularly in comparison to diesel generator utilisation (Notton *et al.,* 2011). However, solar PV has higher capital cost than wind, but moderate maintenance cost (Table 5.5). Wind power generators are generally the cheapest to operate (Apt, 2015). Balancing and matching the quantity and capacity of renewable energy technologies is crucial for continuous power generation and supply in a hybrid energy system (Shah *et al.,* 2015). The two energy sources have different characteristics and qualities that warrant good match and synthesis for a reliable and sustainable hybrid energy system.

Table 5.5: Comparison of the characteristics of solar PV and wind energy technologies (Sources: Shah *et al.,* 2015; *Royal Academy of Engineering, 2014; Apt, 2015, #Clerici, 2013)

Characteristics	Solar PV	Wind
*Capital cost	High	Moderate
Maintenance cost	Moderate	High
Capacity factor	Very low	Low to moderate
#Annual growth in the electricity sector	Very high	High

The Northern Cape Province has the highest solar radiation with up to 8.1 kWh/m^2 (SWERA, 2008). It has 12.7% solar radiation followed by the Free State, Eastern Cape, North West and Limpopo Provinces with above 7 kWh/m^2 solar energy. The KZN Province has the lowest solar energy with 9.4% (Figure 5.1). Only the coastal provinces have higher wind energy than solar, these are Western, KZN and Eastern Cape Provinces (Figure 5.1). This mainly refers to the theoretical potential, which describes the amount of resource available without considering any conversion efficiencies and losses; it equals the maximum amount of energy that is physically available from the climatic conditions. Hence, this is the total potential wind energy and solar radiation impinging on the evaluated surface (Herman *et al.,* 2014).

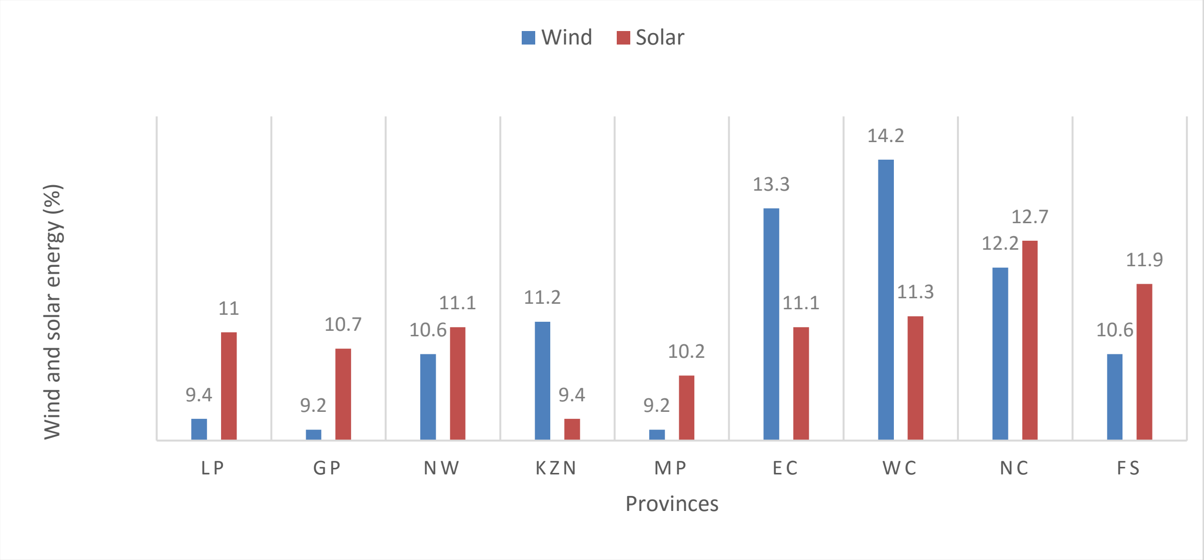

Figure 5.1: Comparison of the theoretical wind speed and solar energy potential (Source: SWERA, 2008; Mortensen *et al.,* 2014)

5.3.1 Hybrid energy system for scenario 1: Government

In scenario 1, 51% weight was allocated to wind energy and solar radiation (combined) as energy sources, and 49% for other parameters. Solar radiation was allocated 26%, while wind energy was allocated 25% and land space 17.5% (Table 5.3). The least weight was 5% for the electrification backlog. Of the three coastal provinces, the Eastern Cape has the highest hybrid energy system potential of 13%, followed by the Western Cape and KZN Provinces with 12.1% each (Figure 5.2). From figure 5.1, it was found that the Eastern Cape and Western Cape Provinces had similar pattern of solar radiation and wind energy, with wind energy being higher than solar radiation. However, the difference in these windy coastal provinces is land space, which is 13.8% for the Eastern Cape and 10.6% for the Western Cape, with KZN having the least land space of 7.7% (Table 5.1). Land space was allocated 17.5% weight, which contributed to the Eastern Cape Province having the highest hybrid energy system potential.

It was found that KZN and Western Cape Provinces have the same/equal hybrid energy system potential (Figure 5.2). The Western Cape Province has higher solar radiation and wind energy of 11.3% and 14.2% respectively than KZN with 9.4% and 11.2%. However, KZN has a larger population (19.7%) and higher electricity consumption (18.9%) than the Western Cape Province, with just 11.2% and 10.5% respectively. Population and electricity consumption (in 2013) had both been allocated total weight of 20% combined. This results in similar potential; the four main parameters for scenario 1 are therefore solar radiation, wind energy, population and electricity consumption.

As explained in section 5.2.1 that the Northern Cape Province is not entirely in the coastal area; however, it has small portion of coast, which gives it good wind energy potential. In this scenario this province has the highest hybrid energy potential by far of all the coastal provinces with 18%, the second highest being the Eastern Cape Province with 13%. The Northern Cape Province should be considered for the establishment of a hybrid energy system, despite its lower population and electricity consumption.

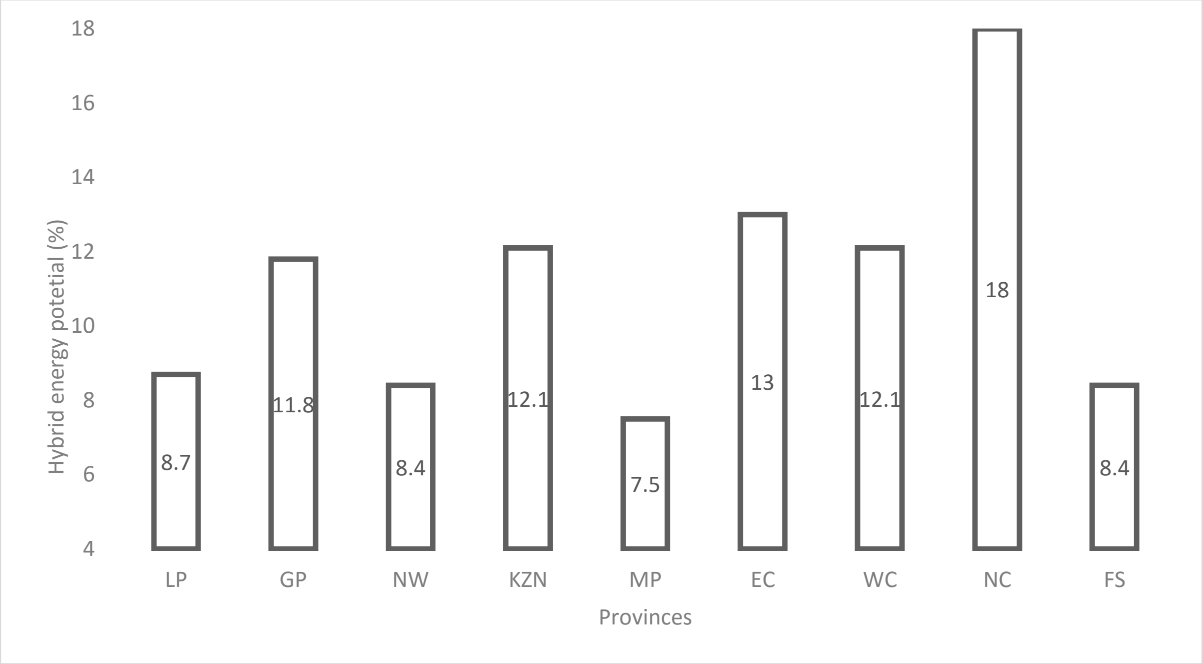

Figure 5.2: Hybrid energy system potential for scenario 1

Approximately 80% of areas lacking access to electricity in sub-Saharan Africa are in rural and remote locations (Birol, 2014). The hybrid energy system has the ability to provide good and reliable power to the rural communities of the Eastern Cape and KZN provinces that do not have access to electricity. A comparison between solar PV and wind generation indicates that much of the power is likely to be generated from wind, as it has more theoretical potential than solar PV radiation (Figure 5.1). Thus, during the design much capacity should be assigned to wind energy. Since the Northern Cape and Western Cape Provinces have the least electrification backlog of 8.1% and 9.5% respectively, than the Eastern Cape and KZN are recommended to be prioritised for the hybrid system in this scenario in order to provide power to rural communities that are not electrified.

In other parts of the world solar PV energy is allocated higher capacity than wind, depending on factors such as financial resources, wind and solar radiation in a particular location. Maouedj *et al.* (2014) conducted a hybrid energy system study in Adrar Province in Algeria. It was found that the power supplied by PV arrays (84%) was more important than power from wind turbines (16%). Therefore, circumstances differ from one project to another in the hybrid energy system. The feasibility study would usually advise which one of the two energy sources should be installed in higher capacity than the other. In Adrar Province it was found that there was a daily complementary relationship between solar energy and wind energy. Moreover, the hybrid energy system had the ability to meet the load demand, and the peak electricity production of the wind-solar system coincided with peak house electricity demands (Maouedj *et al.,* 2014).

5.3.2 Hybrid energy system for scenario 2: Academic institutions (Universities)

Scenario 2 allocated equal weight for solar radiation and wind energy production of 35% each, while 5% weight was allocated to population and electricity consumption. The electrification backlog was allocated 20% because the hybrid energy system would be ideal for provinces with a high electrification backlog and good solar radiation and wind energy (Table 5.3). The Eastern Cape Province has the highest hybrid energy potential of 18%, followed by the KZN and Western Cape Provinces with 16% and 13% respectively (Figure 5.3). Limpopo, Mpumalanga and the Free State have the least potential because they have a relatively low population, electricity consumption and electrification backlog, which account for 30% weight in the data input parameters.

The weight allocation in different parameters plays a key role in determining the hybrid energy system. Scenario 2 prioritised the electrification backlog, population and electricity consumption because the hybrid system is suitable for provinces with many locations that are not electrified and relatively higher population and likelihood of high electricity consumption. The provinces with high potential for a hybrid energy system in scenarios 1 and 2 are the Eastern Cape, KZN and Western Cape Provinces.

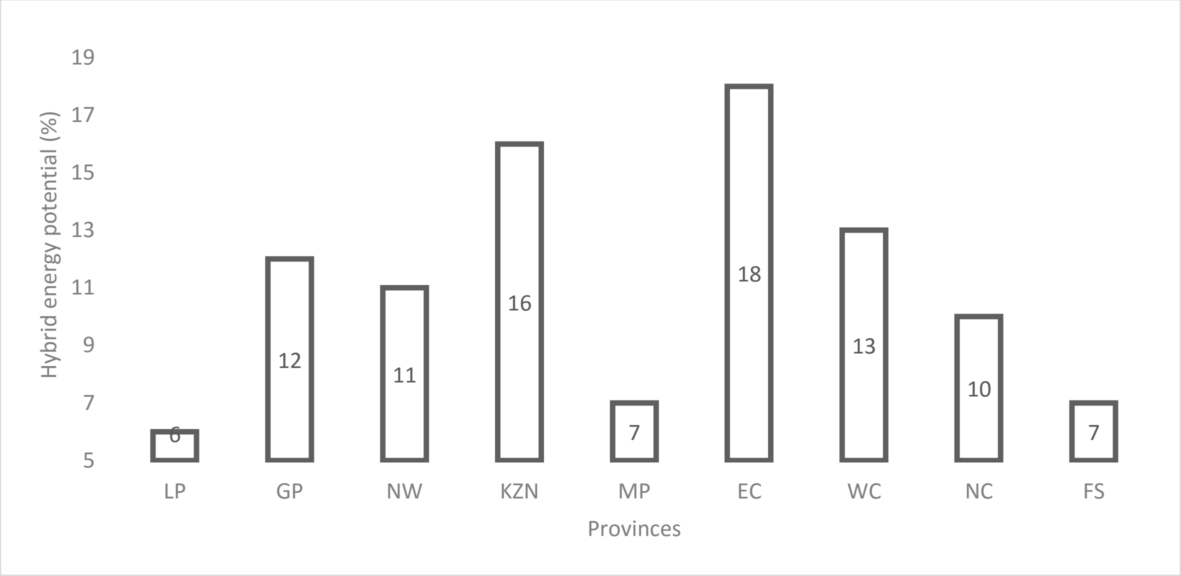

Figure 5.3: Hybrid energy system potential for scenario 2

Notwithstanding factors such as terrain, slope, the electrification plan from the local municipality and Eskom and the distance to the transmission network line, the hybrid energy projects should be built in KZN and Eastern Cape to reduce the electrification backlog and enhance the socio-economic lives of citizens. This would be a cost-effective mechanism to supply the population of the Eastern Cape Province and KZN with electricity, especially taking into account that these two provinces are mountainous and have dispersed settlements (Figure 5.7 and 5.8).

Locations with similar characteristics to the Eastern Cape and KZN Provinces are the Middle East and Asians countries. Saudi Arabia is relatively large country with small villages that are scattered in remote and hilly locations where grid extension is neither cost-effective nor feasible, just like the coastal provinces of South Africa. Most of these remotely located villages get power from diesel generating power plants in Saudi Arabia (Rehman *et al.,* 2012). It is often difficult to maintain a regular supply of fuel and to ensure a continuous electricity supply during breakdowns and scheduled shutdowns of the diesel units.

Rehman *et al.* (2012) established that small villages such as Rowdat Ben Habbas, which is located in the north-eastern part of Saudi Arabia, has load profile that could be satisfied with a hybrid energy system of 35% renewable energy penetration (26%

from wind and 9% from solar PV) and 65% diesel power contribution (five units of 1120 kW each), which was found to be the most economical power system with cost of electricity of 0.212 US$/kWh at a diesel price of 0.2 US$/l. The cost of energy for a diesel-only system at the same diesel price was found to be 0.232 US$/kWh, that is, around 9.4% more than the hybrid system. In rural and remote areas of the Eastern Province and KZN, most of the population use firewood and paraffin for domestic purposes. Use of firewood is likely to result in deforestation that could contribute to climate change and biodiversity degradation, such as species extinction.

5.3.3 Hybrid energy system for scenario 3: Solar PV industry

The solar PV industry allocated slightly similar weight as of academic institutions. Solar radiation and wind energy were allocated 30% each. The electrification backlog was the second highest allocated weight of 20%, with electricity consumption having allocated 10% and population and land space with 5% each. Nonetheless, electricity tariffs were allocated 0% weight.

This scenario demonstrated similar pattern and trend as scenario 2 mainly because of the weighting ratio. The KZN has the highest potential of 17%, followed by the Eastern Cape Province with 15%, and the Western Cape Provinces with 12% (Figure 5.4). However, the rationale for the KZN to having the highest hybrid energy potential in the coastal provinces is that it has the highest electrification backlog and consumes more electricity compared to other coastal provinces, and a total of 30% weight was allocated to such parameters in the modelling. The Northern Cape Province has relatively low hybrid potential, although Chapter 4 indicated its solar PV potential as the highest. In the hybrid energy system, the main criteria are solar and wind potential, as well as the electrification backlog, because, as discussed in section 5.3.2, locations with high mountains and steep slopes are likely to make grid extension costly, therefore many nations prefer to electrify such locations with hybrid systems while grid extension plans are under way and budgeted for.

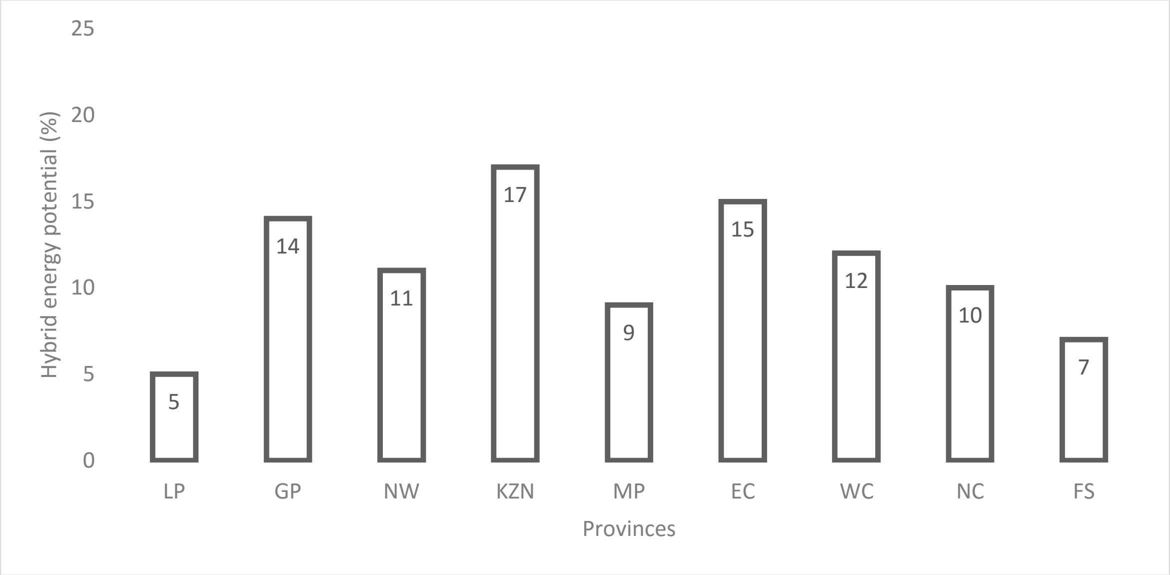

Figure 5.4: Hybrid energy system potential for scenario 3

Different organisations and individual researchers have conducted hybrid energy studies in many parts of the world. Again, depending on the climatic conditions and the annual seasonal pattern, the design of hybrid systems would differ from one place to another. Ma *et al.* (2014) conducted a hybrid study on Hong Kong Island, in which a load profile of 250 kWh/day was estimated. It was found that solar PV provided almost 86% of the total production during the simulation year at a rated capacity of 145 kW. However, the PV output was extremely high in the summer months from July to October. In many islands, this is a favourable characteristic, since electricity demand is strong in summer because of the high cooling load. In contrast, the wind energy contribution was found to be significant in April and September, but less in other months, with a rated capacity of 10.4 kW.

The Eastern Cape, KZN and Western Cape Provinces have similar patterns and trends, with substantial potential for hybrid energy system application. However, scenario 1 presents different dynamics from the other two scenarios, with the Northern Cape Province having the highest potential, despite its low population and electricity consumption rate (Figure 5.5). The overall results for the three coastal provinces proved that the Eastern Cape, KZN and Western Cape Provinces have fairly good hybrid energy system potential, which warrants consideration of the establishment of hybrid systems in order to curb the electrification backlog, while providing a sustainable electricity supply.

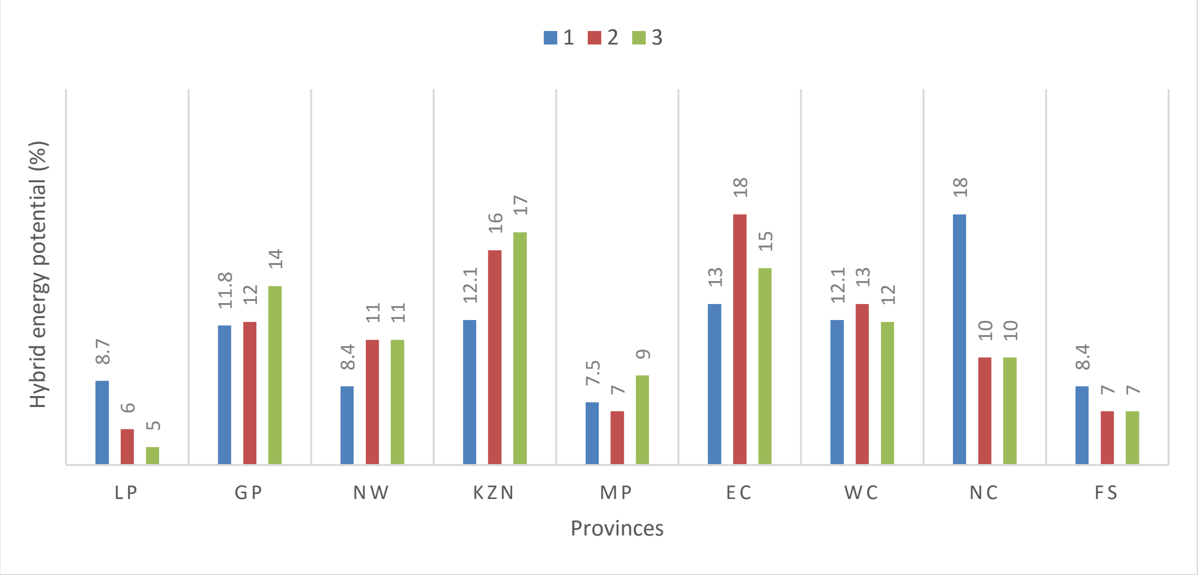

Figure 5.5: Hybrid energy system potential for three scenarios

Indeed, there are other countries that have implemented the hybrid energy projects. There are rural communities that are using diesel generator as single power source, and it is far more expensive than hybrid as approximately 77% of the cost goes to diesel fuel (Alsharif *et al.,* 2015). This study was conducted in five sites on Corsica Island. It was concluded that the hybrid energy system was viable in remote areas. For windy sites, more than 40% of the total production was provided by the wind generator, while in non-windy regions, the wind generator contributed approximately 20% of the total production electricity. The hybrid energy system was proven to be the best option for all the sites in Corsica Island as it yielded a lower levelised cost of electricity. Consequently, it yielded higher system performance than a PV or wind system alone.

This section concludes that the Eastern Cape and KZN have good hybrid energy system potential. The main factors that determined hybrid in these provinces through *'Optioneering'* are wind and solar radiation availability and electrification backlog. Therefore, these provinces should be considered for the establishment of the hybrid energy projects. Further studies in the Eastern Cape and KZN need to be conducted to find out whether the two main sources of energy (wind and solar) would be able to support each other, taking into account the slope, wind intensity and other factors.

5.4 Hybrid energy system potential consequent to electrification backlog in the Eastern Cape and KZN

The percentage of households that are connected to the electricity supply has increased from 77% in 2002 to 85% in 2014 in South Africa (StatsSA, 2015; Department of Planning, Monitoring and Evaluation, 2014). The Eastern Cape and KZN provinces have high electrification backlog of over 20% (StatsSA, 2015). This is an opportunity for hybrid energy systems to make significant contribution in providing sustainable energy. Electrification backlog eradication is almost impossible because of population growth and expansion of households' over time. Some of the communities that are not electrified are rural based and low income, therefore they would ideally be suitable for hybrid energy system as they are expected to have a low load profile. The Eastern Cape and KZN provinces were analysed and districts that would be suitable for hybrid energy systems have been identified as follows:

5.4.1 Eastern Cape Province

The Eastern Cape has 82% electrification rate, and 18% backlog in 2015 (StatsSA, 2015). 71% of the residents use electricity for cooking, 13% use firewood, 10% use paraffin, and 4% use gas. The use of firewood is mainly in communities that do not have access to electricity. The hybrid energy system has the potential to reduce energy poverty for the community members that do not have access to electricity for cooking. There are districts that have high electrification backlog, for which a hybrid energy system should be prioritised.

The Eastern Cape Province comprises of 6 districts and 2 Metropolitan areas. The Buffalo City and Nelson Mandela Bay Metropolitan areas have more than 80% electrification rate with less than 35% unemployment rate (NMBM, 2015). Similarly, the Chris Hani and OR Tambo districts have more than 80% electrification rate with a lower unemployment rate than other districts (StatsSA, 2016).

The Alfred Nzo and Amatole districts have higher electrification backlog and unemployment rate than others. Mbhashe municipal area in Amatole district has 49% electrification rate, with 51% backlog (Table 5.6). The Eastern Cape Province has approximately 59% of population that depend on the government grants (StatsSA, 2015). This represents high proportion of population that is either not working or have informal jobs, then some municipal areas such as Umzimvubu in Alfred Nzo district has only 45% employment rate (Table 5.6). Almost 90000 people are unemployed in Umzimvubu area, and without access to electricity, there is no hope for business and economic activities that create jobs.

Table 5.6: Eastern Cape municipal areas with high electrification backlog (Source: StatsSA, 2016)

Alfred Nzo district area			
Municipal area	**Electrification (%)**	**Population**	**Unemployment rate (%)**
Umzimvubu	45	191620	45
Matatiele	44	203843	38
Mbizana	60	281905	43
Amatole district area			
Mbhashe	49	254909	42
Mnquma	61	252390	44

This study concludes that Umzimvubu, Matatiele, Mbizana, Mbhashe and Mnquma areas are suitable for the hybrid energy system. The high unemployment rate is likely to be reduced once electricity is provided in the areas. It is anticipated that hybrid energy project is most likely to enable the community members to realise and initiate business and economic activities, which will create jobs, eliminate poverty and uplift economy of these areas.

5.4.2 Kwazulu Natal Province

There is 81% electrification in the KZN province with 75% of the population using electricity for cooking, 16% use fuel wood and the remainder depend on coal and gas (StatsSA, 2015; COGTA, 2013). This province has higher electrification backlog compared to others. The KZN has 46% of population living in non-urban areas called traditional, 47% in urban areas and the remainder living in farms (HDA, 2013). Most of the rural communities are characterised by poverty, which leads to urban migration.

The KZN province has one metropolitan area and ten districts. In 2013, the electrification backlog was higher than 35% in Umkhanyakude, Sisonke and Umzinyathi district areas (Figure 5.6). The eThekwini metropolitan area had 10% electrification backlog followed by uMgungundlovu with 13.9% in 2013 (COGTA, 2013). The challenge with metropolitan areas in South Africa is rapid migration from people that are seeking employment opportunities. Therefore, this results in increased informal settlements that are not electrified. However, there are business and employment opportunities in the metropolitan areas around South Africa with a lower unemployment rate compared to rural municipal communities.

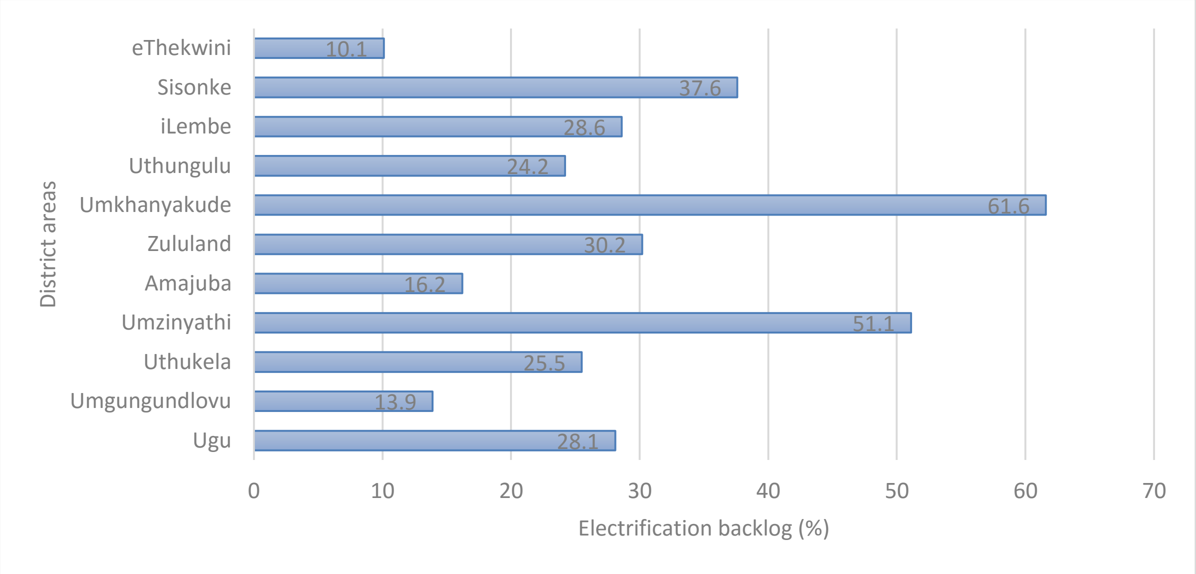

Figure 5.6: Electrification backlog in KZN districts areas (Source: COGTA, 2013)

Umkhanyakude district is located in the North East of KZN along the coast. It has, on average, 50% electrification rate, with Hlabisa and The Big 5 False bay municipal areas having 55% and 42% electrification rate (COGTA, 2013). However, the Jozini and Umhlabuyalingana municipal areas have substantially lower electrification rate of 29% and 14% respectively (Table 5.6). Therefore, there is high electrification backlog in Umkhanyakude district. The Hlabisa municipal area has a 52% unemployed rate with population of 71925 (COGTA, 2013). This means that over 35000 people are unemployed in the area.

Umzinyathi district is located in the interior part of KZN province. It is equally faced with high electrification backlog with Nquthu municipal area having 53% electrification rate (Table 5.7). The worst case scenario is Msinga municipal area, which has 25% electrification rate, with a population of 177577 and the unemployment rate 49% (StatsSA, 2016). Sisonke district has more than 50% electrification rate on average. However, two of its municipal areas still have significant electrification backlog. Ingwe municipal area is 49% electrified with 39% unemployment rate, this gives a relatively high number of unemployed, which is approximately 39200 (Table. 5.7).

Table 5.7: KZN municipal area with high electrification backlog (Source: StatsSA, 2016; COGTA, 2013)

Umkhanyakude district			
Municipal area	**Population**	**Unemployment (%)**	**Electrification (%)**
Hlabisa	71925	52	55
Jozini	186502	44	29
The Big 5 False Bay	35258	26	42
Umhlabuyalingana	156736	47	14
Umzinyathi			
Umvoti	103093	30	58
Msinga	177577	49	25
Nquthu	165307	44	53
Sisonke			
Ubuhlebezwe	101691	34	53
Ingwe	100548	39	49

The districts in table 5.6 (above) have relatively high electrification backlog. Consequently, lack of access to electricity and high unemployment rate worsen the situation and in most cases, the youth end up migrating to urban districts seeking for a better life. In the worst case scenario, high unemployment rate often ends up resulting in increased crime in those areas.

Hybrid energy projects have the potential to bring positive change in those areas. This includes provision of power that would improve the living standards of community members and enhance communication (watching TV, listening to radios and charging cellular phones), education (using electric light in the evening for school work and accessing internet) and business start-up, ultimately creating jobs. This research is therefore recommending that the municipal areas that are identified in table 5.5 and 5.6 should be electrified with hybrid energy projects. Further study should be done to determine the suitable sites in those municipal areas, HOMERGIS is recommended to simulate the most economic system configuration. Critical aspects such as location, size, energy sources, funding, load etc. for the hybrid energy projects should be investigated.

5.5 South African experience on hybrid energy pilot projects

This research found that the Eastern Cape and KZN Provinces have the highest hybrid energy potential due to their climatic conditions, low economic growth, relatively higher rural communities and electrification backlog, among others. The South African government piloted the hybrid energy system project in the Eastern Cape Province in 2002 **(Appendix E).** This work supports the decision taken by the government to establish this pilot project in the Eastern Cape Province. The choice of project site is in line with the recommendations of this study. The pilot project confirms the results of this study, which found that the province with the highest hybrid potential was the Eastern Cape.

A hybrid energy system provides a reliable power supply to communities. The South African hybrid energy projects could have been implemented, sustained and managed better than the way they were handled. Poor management and lack of ownership and authorities to look after and take care of the infrastructure (hybrid energy system) led to the collapse of the system. This study takes into account the mistakes made in the two pilot projects, but still indicates substantial potential for a hybrid system. The lessons learnt from the previous pilot projects will strengthen and tighten processes for the next hybrid projects to ensure that similar challenges do not recur.

The hybrid energy system challenges and lessons learnt differ from one country to another; just as in South Africa, other countries have implemented hybrid projects of which some were unsuccessful. Palit and Chaurey (2011) confirm that most of the remote rural villages in South Asia do not have access to grid electricity. In Bangladesh, the overall electrification rate was 41% in 2009, with only 28% of the rural population having access to electricity. Therefore, off-grid generation was a better and more sustainable solution in these communities. Furthermore, the number of Indian rural households that are being connected to the network remain low compared to urban households and poor households have a much lower electrification rate than richer households (Palit and Chaurey, 2011).

Similarly, the Saierlong township of China, which is located in the south-east of Qinghai, has around 400 households and 1800 inhabitants. According to Shyu (2013), the township is powered by one small hydropower system, built in 1998, and one 30 kWp stand-alone mini-grid solar PV power station. The solar PV stand-alone system comprises 410 PV modules that have capacity of 75 W each, a controller 220 VDC/180 A, battery set, and inverter and distribution box of 20 kW. The installed capacity of the system in 2007 was 75 W per household. The electricity tariff was 0.27 US$/kWh, according to the exchange rate on 1 December 2007. Lack of revenue collection was one of the mistakes made in the Lucingweni hybrid project in South Africa, where the project was commissioned prior to enabling community members to pay the tariffs.

Furthermore, during the survey conducted by Shyu (2013) in Saierlong township, only 9% of the community members supplied by the PV project were satisfied, 55% were more or less satisfied, and 36% were not satisfied. The challenges that led to the dissatisfaction of the community members were:

- The electricity supply from the solar PV power stations was insufficient for household needs, probably because the power was limited to a certain number and wattage of appliances.
- The schedule of electricity supply was irregular, unpredictable and consequently unreliable.
- The frequency of unnoticed disruptions in electricity supply was high.
- Electricity was provided for only few days in a week, and households were not informed on which days there was to be no electricity supply.
- The period of daily electricity supply was not stable and reliable.
- The number of hours for which electricity was supplied daily decreased dramatically from 12 hours to three hours a day.

- Households were unable to predict the starting and ending times of the daily electricity supply.

Some of the challenges Saierlong township experienced are similar to those in the Lucingweni location. Dissatisfaction with the power limit is the main problem because community members view the hybrid system as a complete solution for their energy needs. However, lack of awareness and education on the difference between hybrid and grid electrification are at the forefront of the matter. Most of the community members in Lucingweni indicated that they would not be able to afford the fees for power received from the hybrid project. This was a similar challenge in Saierlong township. Shyu (2013) confirmed that more than 30% of the households could not afford the electricity fee in Saierlong. These households relied entirely on the government's food subsidy and did not pay their electricity fees regularly.

This study takes into account lessons learnt from previous projects and recommends the supply of 50 kWh/month in line with the FBE policy, and community members would pay the balance of power consumption over and above the FBE allocation. In most cases the community members are poor and unable to pay, which usually leads to collapse of the project. Nevertheless, there should be awareness among community members about the power limit and suitable appliances to be used.

5.7 Conclusion and summary

The peak hours for electricity consumption and the wind & solar power peak generation period may not correlate, depending on the time of the day in which the community consume much energy. Nevertheless, the diesel generator and batteries are options to supplement wind and solar power during peak hours. Then, this makes hybrid energy system more reliable.

The Eastern Cape and Western Cape Provinces have higher wind energy potential based on wind speed (m/s) than solar radiation, while the Northern Cape Province has higher solar power potential than wind energy. The Eastern Cape, KZN and Western Cape Provinces have substantial hybrid energy potential, specifically for scenarios 2 and 3. This is the case mainly because the parameters that were allocated higher weights are solar radiation, wind and electrification backlog, which took up to 90% of the total weight. The KZN Province has the highest electrification backlog. This makes it more suitable for a stand-alone or off-grid hybrid energy system, followed by the Eastern Cape Province with relatively lower electrification rate, making it the second-best suitable province for the stand-alone hybrid energy system.

This chapter concludes that the Northern Cape Province is not viable for hybrid energy systems, rather it is good for large scale solar PV projects. Similarly, the Western Cape Province is not ideal for hybrid energy system either, because it has the lowest electrification backlog, though it has fairly good hybrid energy system potential. KZN and Eastern Cape are suitable for the establishment of hybrid energy system. They have good potential and relatively high electrification backlog. These provinces are in mountainous areas and some of the terrains make it difficult for the grid network to reach them (Figure 5.7 and 5.8). This chapter concludes that the hybrid energy systems should be established in the KZN and Eastern Cape Provinces to close the electrification gap.

The districts that are identified in KZN and Eastern Cape provinces would benefit from the hybrid energy projects. The socio-economic benefits that come along with hybrid projects would transform the districts in many ways including enhancing the communication, improving education and create business opportunities, which lead to job creation and reduce poverty level. Further study is recommended to zoom in to the identified districts and municipal areas and establish suitable sites for hybrid energy system, software such as HOMERGIS should be used to enhance to system configuration and for optimum design. The lessons learnt in the hybrid energy projects experience in South Africa should be taken into consideration when identifying the suitable sites, planning and executing the hybrid energy projects.

This chapter is summarised as follows:

- The Eastern Cape and KZN provinces are ideal for the hybrid energy system taking into consideration that they have high electrification backlog, good wind and solar irradiance. The hybrid energy system project may not need vast land as compared to grid connected solar PV.
- Most parts of the communities that are not electrified are in rural areas, which are mountainous with terrain not conducive for grid connected electricity, and the population is sparsely distributed in some parts of these provinces (Figure 5.7 and 5.8). The Eastern Cape has low electricity consumption, and is therefore ideal for hybrid energy system project
- Further study is recommended for the identified districts in the Eastern Cape and KZN provinces in order to identify sites where the hybrid energy projects could be implemented.
- The hybrid energy system projects have the great deal of potential to transform socio-economic conditions of remote areas. These projects provide opportunities to community members thereby improving their lives in many ways such as communication (radio, TV etc.).

Figure 5.7: Residential settlement in the Eastern Cape Province (Source: http://www.google.co.za/search?q=hybrid+energy+systems&biw)

Figure 5.8: Mountainous areas of the Eastern Cape Province (Source: http://www.google.co.za/search?q=hybrid+energy+systems&biw)

CHAPTER 6: HOUSEHOLD ENERGY CONSUMPTION PATTERN

6.1 Introduction

The household energy consumption in South Africa is characterised by different factors such as Living Standards Measure (LSM), household income, residential type and others. The LSM provides segmentation of the South African market according to living standards using criteria such as degree of urbanisation and ownership assets and major appliances (Department of Planning, Monitoring and Evaluation, 2014). South Africa had a population of 55.1 million by mid-2016 (StatsSA, 2016), and it generated over 45% of African electricity capacity (Birol, 2014a). The total annual electricity generated by Eskom (South African electricity generation utility) in April 2015 to March 2016 was 214487 GWh, with 5.6% sold to the residential sector, and 41.8% sold to municipalities that sell more than 50% to the residents within their jurisdiction (Eskom, 2016). Then, approximately 25% of South African electricity is consumed at the residential sector.

The household energy consumption in South Africa depends on size and type of the house, household income, temperature, season and electricity price (Heunis and Enerweb, 2010). Furthermore, Heunis and Enerweb (2010) found that consumption is determined by appliance ownership and usage, cooking habits, the usage of alternative energy sources such as firewood, gas and solar water heating, household members and demographics such as education, age and employment. Appliance ownership is linked to disposable income, which is determined by the household income level. Therefore, this chapter aims to investigate the characteristics and factors that determine and contribute to electricity consumption in different income groups across the country.

This chapter presents electricity utilisation in different South African provinces and across different household income groups. Moreover, the appliance ownership, size of the household, number of inhabitants in the households and the basis for electricity payment are analysed and presented in this chapter. These are the factors that determine the energy use pattern across society (Heunis and Enerweb, 2010). The awareness of solar PV and the extent to which it could be utilised to reduce household electricity bills is analysed. This chapter explores the multiple use of energy across different income groups in the country.

6.2 Methods and materials

The household energy survey (Appendix A) was explained in Chapter 3, section 3.3.1.1. During the first three days of data collection, there was over 50% of rejection of questionnaire from the respondents because of the income bracket question in the questionnaire. Most of the respondents felt that the question was too private and personal for them to disclose such information. Furthermore, the income question was a turn off to some respondents to an extent that they were no longer willing participate in the survey.

The researcher decided to remove the income question from the questionnaire. The income level was determined in accordance with the StatsSA (2015a) [Table 6.1]. The questionnaire was distributed as per settlement pattern (informal settlement, town houses, suburbs etc) in the low/no, middle and high income households (Table 6.1) as described by StatsSA (2015a). The low/no income reside in the informal settlements, and hence hardcopies questionnaires were distributed for completion. The middle and high income groups’ questionnaires were mainly distributed electronically.

The Statistics South Africa data was used as a guideline to categorise and determine the low/no, medium and high income household categories (StatsSA, 2015a). Household income refers to all receipts by all members of a household, in cash and in kind, in exchange for employment or in return for capital investment or receipts obtained from other sources such as social grants and pensions (StatsSA, 2012; StatsSA, 2015a).

Table 6.1: Definition of the income households' categories (Source: StatsSA, 2015a)

Income category	Definition
Low/no income household	Households with annual income of between R0-R19200
Middle income household	Households with annual income of between R19201 – R307200
High income household	Households with annual income of R307201 and above

The following indicators were used for the settlement pattern was as follows:

- **Low/no income household**

The low income residential group is characterised by villages, informal settlements such as *shacks* (Figure 6.3) and locations in towns with the Reconstruction and Development Programme (RDP) houses, the government freely allocated houses for the poor (Figure 6.4). Over 60% of the low income households are based in rural areas in South Africa (StatsSA, 2015a). They mostly stay in traditional thatched roof houses (6.5). Rural areas refer to farms and traditional areas characterised by low population densities, and low levels of economic activities and infrastructure (StatsSA, 2015a). Furthermore, this research used the Department of Planning, Monitoring and Evaluation (2014) categorised the low income group in LSM 1-2 (maximum of R2218 per month).

The RDPs, *shacks* and thatched roofing houses are the settlements occupied by residents that are mostly either not working, *i.e* no income, or are domestic workers, farm labourers, gardeners, security guards, workers in the local saloons, and general informal occasional work in the villages. 65.5% of the population is earning a salary in South Africa and 46.2% depend on government grants as their main source of income (StatsSA, 2015). Government grant holders include the old aged citizens above 60 years, people with disability and children whose parents are unemployed with no source of income. The data was collected door to door using a hardcopy questionnaire for this group.

- **Middle income household**

The middle income households are characterised by flats as accommodation in City centres and at the periphery of Towns and Cities, low cost houses, duplex and simplex estates residences. Approximately 72% of middle income households are in urban areas, i.e. formal cities and towns characterised by higher population densities, high levels of economic activities and high levels of infrastructure (StatsSA, 2012). The Department of Planning, Monitoring and Evaluation (2014) categorised the middle income group in LSM 3-9, which monthly income ranges from R2218-R23539.

The middle income group have stable jobs in government, private institutions, retail and are self-employed. Approximately 70% of the electronic copy for this group was sent through to the respondents with an e-mail database obtained from the provincial departments, extracted by salary grade in line with the StatsSA (2015a) determination for middle income group. The remaining 30% was door to door hard copy collection mainly on weekends when people were at home.

- **High/upper income household**

The high and upper income residents are characterised by semi-suburbs and suburbs accommodation. 92% of high income households are in urban areas, which are formal cities and towns characterised by higher population densities, high levels of economic activity and high levels of infrastructure (StatsSA, 2012). In government salary grade this is middle management and above. The LSM group is 10, which is R36883 and above per month (Department of Planning, Monitoring and Evaluation, 2016).

The high and upper income residents are employed and have occupied positions in the middle, senior and executive management. Others are self-employed such as business people, the difference with the self-employed middle income being the residential type. The data in this income group was collected through the electronic questionnaire.

There are 44.4% of total household numbers that are in the low/no income category, the highest fraction is middle income category with 48.3% and the high income category has 7.3% (Figure 6.1). The high income category thus represents a small fraction of the South African population. 45.5% of the high income households are based in Gauteng Province, followed by Western Cape with 17.3%, Northern Cape has the least with 1.5% (StatsSA, 2015a). Of low/no income households, 20% are based in Kwazulu Natal Province, followed by Gauteng and Eastern Cape with 18% and 15% respectively.

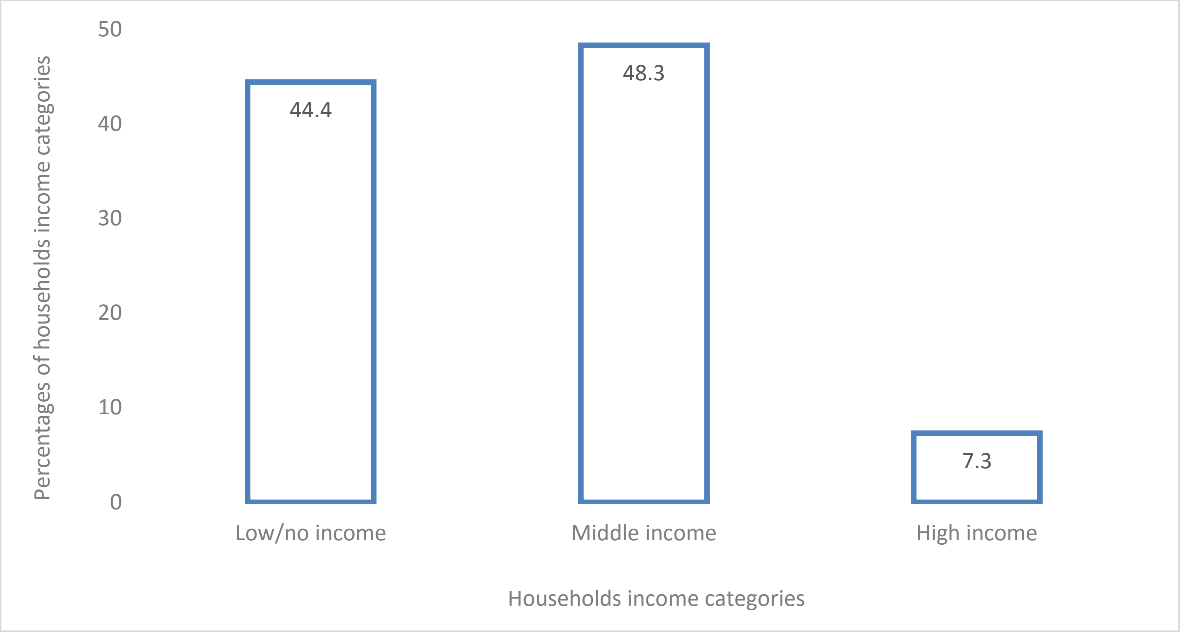

Figure 6.1: South African household income categories (Source: StatsSA, 2015a)

6.3 Household electricity consumption pattern

The electricity consumption pattern differs from one household to another. There are many factors that determine electricity consumption, such factors could be change in season, appliances and income, amongst other things. The general trend is that low income households consume less than middle and high income. This section analyses the electricity consumption pattern in the low/no, middle and high income households across the country and factors that influence and affect such consumption.

Furthermore, this section provides an analysis on the factors and characteristics that determine electricity consumption in different income groups.

6.3.1 Low/no income household electricity consumption

There are 82% of the low income residents that spend less than R500 per month on their electricity bill. There is 14% and 4% spending between R500 – R1000 and R1000 – R1500 respectively. Furthermore, 90% of the low income households in Limpopo, Western Cape, Northern Cape, Eastern Cape and Gauteng Provinces spent R500 (US$35.76)[14] or less per month on electricity bill in 2015. This is equivalent to 300 kWh of electricity consumption or less per month, which is an average of 8 kWh per day[15]. Nonetheless, 60% to 70% of the low income households in the other remaining provinces spend the same amount. In general, at least 60% of the low income households are only able to afford R500 or less on electricity (Figure 6.2). Thus, more than 90% of 44.4% of South African population spend R500 or less on electricity on a monthly basis.

The North West province has 37% of low income households spending between R5001 to R1000 on their electricity bill monthly, followed by Mpumalanga with 29% and the rest of the provinces are less than 20%. The rationale for such spending is the economic activities that are taking place in the households' yards. Most of the residents have small businesses in their yards, which contribute and boost local economic development. The common businesses that are being conducted in the yard include the following:

- Hair saloon;
- Welding business;
- Spaza shops selling food items; and
- *Shebeens or* pubs (informal liquor trading stores).

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[14] US$1 equivalent to R13.98 and £1 equivalent to R17.25-(Exchange rate on 21 December 2016)

[15] City of Cape Town 2014 residential electricity tariffs

Therefore, electricity consumption for these households is relatively higher than in other ordinary low income households that use electricity only for their own indoor activities.

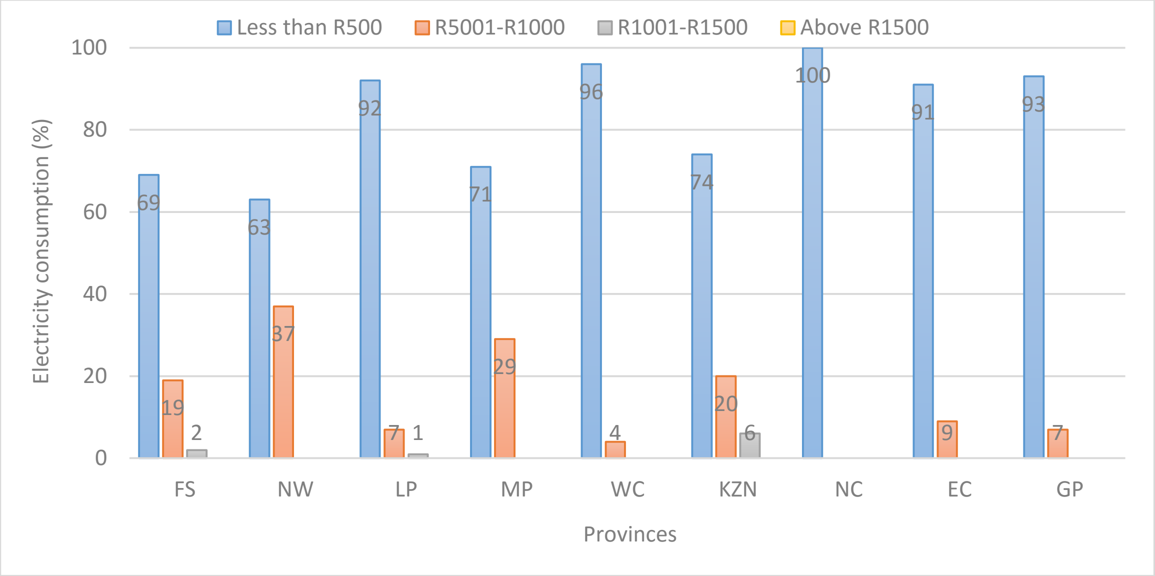


Figure 6.2: Low income household electricity consumption

There are certain factors that were established, which determine electricity consumption in the low income households across the provinces. The factors differ from one province to another, some are common in provinces that are largely influenced by sectors such as mining or farming activities. The factors that influenced electricity consumption in the low income group are as follows:

- **Household source of income**

More than 60% of the low income households stay in rural areas in South Africa (StatsSA, 2015a). The common settlement type for these households is the RDP houses (in villages and formalised low income areas in the periphery of the towns), traditional thatched roof houses (in the villages) and *shacks* (in the informal settlement in towns). The houses are low energy consumers as they are small in size (Figure 6.3, 6.4 and 6.5). Government grants, domestic work and informal labouring dominate the source of income for these communities. In the Eastern Cape Province, 59.8% of the population depends on government grants, these are old age grant, disabled social grant, children with parents with no income (StatsSA, 2016).

Similarly, Northern Cape Province has lowest population in the country of 5%, it has 100% of low income households spending less than R500 monthly electricity bill (Figure 6.2). Approximately 60% of the Northern Cape Province population depends on government grants (StatsSA, 2015). There is 37% of the low income households that are not employed in South Africa, they depend on grants (StasSA, 2015a). For that reason, household income is one of the factors that contribute to less electricity consumption in the low income households' category. It would be uncommon if most of the low income households spend more than R500 on electricity bill per month, with an exception of those households that run a business in their yard.

Figure 6.3: Shack house in the informal settlement

Figure 6. 4: The RDP houses in the low income residential settlement

Figure 6.5: Traditional thatched roof house in the village

- **Source of energy for cooking**

Cooking is mostly a daily activity, which starts with breakfast, lunch and dinner in the villages and towns. There is energy used for this activity throughout the day. The source of energy for cooking determines energy consumption pattern in the low income households. Some households in the villages are electrified, however, they still use firewood for cooking. More than 90% of low income households in Limpopo Province spend less than R500 on their electricity monthly bill. Nonetheless in some villages that are electrified they use electricity for TV, lights, radio, charging cellular phones only. One of the reasons for not using electricity for cooking is that hotplates, irons and stoves consume too much electricity and they are unable to afford it.

The Elim village in Limpopo Province is dominated by the traditional thatched roof houses with electricity reticulation cables (Figure 6.6). The prepaid electricity has been connected over two decades ago. Nonetheless, the source of energy for cooking is mainly firewood despite the availability of electricity in the village (Figure 6.7). Therefore, the firewood as a source of energy results in low electricity consumption. The availability of firewood in the nearby forest means that community members are most likely to depend on firewood unless deforestation occurs and/or for as long as this energy source is freely available.

Figure 6.6: Electrified traditional thatched roof house in Elim village, Limpopo Province

According to StatsSA (2015) at least 35% of the low income households use firewood as a source of cooking in Limpopo Province (Figure 6.7). Similarly, KZN and Mpumalanga have over 15% of the low income households using firewood for cooking. Hence, more than 70% of low income households are spending less than R500 on their monthly electricity bill.

In some informal settlements, the source of energy for cooking is paraffin, the Eastern Cape Province uses 10% of paraffin apart from firewood, as a source of energy for cooking (StatsSA, 2015). Therefore, the source of energy for cooking contributes significantly to low electricity consumption in the low income households. Then, the use of firewood and paraffin for cooking contributes significantly in the low income group of spending less than R500 on their monthly electricity bill.

Figure 6.7: Firewood as a source of energy for cooking in Elim village, Limpopo Province

- **Electricity theft and illegal connection**

In the informal settlements that are dominated by *shack* houses, the most common challenge is illegal electricity connection. Eskom Holding's non-technical energy loss of electricity was estimated at approximately R4.8 Billion in the 2015/2016 financial year, this revenue loss was due to electricity theft that include illegal connections and meter tampering and by-passing; 46% of such theft is from residential and 54% is business, industry commerce and agriculture (Eskom, 2015). Thus, illegal connection is rife in the informal settlements.

The community members that connect electricity illegally and interfere the metering process, some of them ended up paying a lower amount of monthly electricity because the meter would have been tempered with, whereas others pay nothing due to illegal connection. In some informal settlements in Pretoria, there are local people whose role in the community is to connect electricity in the *shacks* illegally; every time when the City of Tshwane disconnects, they are contracted by the locals to re-connect for a fee. In 2016, the City of Tshwane planned to replace overhead cables with the underground ones in order to curb illegal connection (Pretoria News, 12 May 2016).

Therefore, illegal connection of electricity is another factor that makes low income households pay less than R500 per month on electricity bill, particularly in the informal settlements at the periphery of the Cities.

- **Provision of Free Basic Electricity (FBE)**

South Africa has Free Basic Electricity (FBE) for the poor residents. The DME (2003a) FBE policy aims to address ways and means through which government interventions can bring about relief to poor electrified households and ensure optimal socio-economic benefits from the national electrification programme. The FBE policy made an allocation of free basic electricity that is set at 50 kWh per month for poor community members. In 2003, the 50 kWh per month was considered adequate electrical energy to meet the basic needs for lighting, media access and limited water heating for poor households (DME, 2003a). To date, the FBE is between 50-80 kWh, depend on the local government authority in a particular community.

Most of the beneficiaries are residents that stay in the RDP houses and thatched roofed houses in the villages (Figure 6.4 and 6.5). Some of the informal households are occupying the land illegally and others are illegal immigrants, hence they are unable to register and receive the monthly FBE. Hence, the FBE enables low income category to purchase fewer units and hence contribute to less electricity consumption.

- **Unemployment rate**

The unemployment rate contributes towards electricity consumption in various provinces. The South African unemployment rate in the second quarter of 2016 was 26.6% (StatsSA, 2016a). Free State Province has the highest unemployment rate of 32%, followed by Gauteng and Eastern Cape provinces with 29% and 28% (StatsSA, 2016a). However, the relationship between unemployment rate and electricity consumption depends on the population in a province. A low population is likely to have lower unemployment rate and less electricity consumption.

The unemployment rate in Gauteng is proportional to its population, there is high rate of population from all other parts of South Africa and foreign citizens that are migrating to Gauteng for job and economic opportunities. More than 90% of low income households, which spend less than R500 on their monthly electricity bill are linked to unemployment. Consequently, the unemployment rate contributes towards low electricity consumption. It is most likely to be noticeable in industrial and economical provinces such as Gauteng, KZN and Western Cape.

- **Electricity price**

Electricity price is another factor that determines consumption in the low income households. Since they are low income group they are unable to spend more money on things such as electricity, rather than on food. One of the reasons for majority of the low income households to spend less than R500 per month on electricity bill is the cost of electricity. This is linked to the energy source for cooking as discussed earlier in this section. Electricity in Cape Town is the most expensive in all municipalities across the country. In the 2014/2015 financial year the electricity tariff comprised two blocks; block 1 was 0-600 kWh that cost R153,63 c/kWh per month, which means that 600 kWh cost R918,00 (City of Cape Town, 2014). In the same financial year, Durban electricity was the cheapest, it was R1,16 c/kWh (Ethekwini Municipality, 2014).

There is higher electricity consumption in the low income household in KZN, 74% spend less than R500 per month, 20% spend between R500 and R1000 and 6% spend between R1000 and R1500 per month. The low electricity tariffs enable low income households to consume lots of electricity without applying energy saving measures because of affordability. Nevertheless, the consumption of above R1000 is mainly in households that have business activities. In Western Cape, 96% of the low income households spend less than R500 on electricity bill per month, one of the reasons is that electricity is expensive.

- **Quantity and types of household appliances**

Household appliances determine electricity consumption. In this study, appliances were grouped into two categories based on electricity consumption, namely: light appliances and heavy appliances. The light appliances include kettle, TV, radio, microwave and toaster. The heavy appliances are stove, fridge, geyser, iron, heater, hotplate and washing machine. All provinces demonstrated similar pattern of possession of appliances. The kettle, TV and radio are very common and dominant in all provinces. The radio and television are frequently used appliances throughout the day as media. The kettle is equally used frequently because hot water is used more often for different reasons ranging from making tea, cooking, boiling water for bath etc.

However, some provinces such as Northern Cape, Western Cape and Eastern Cape do not have appliance such as toasters (as the toaster data is not connected by lines in these provinces), this is associated with the high level of dependence on government grants and unemployment rate (Figure 6.8). The Northern Cape Province has low percentages of light appliances, hence the 100% low income households spending less than R500 is because of a lower quantity of appliances. Furthermore, this province has the least population in the country.

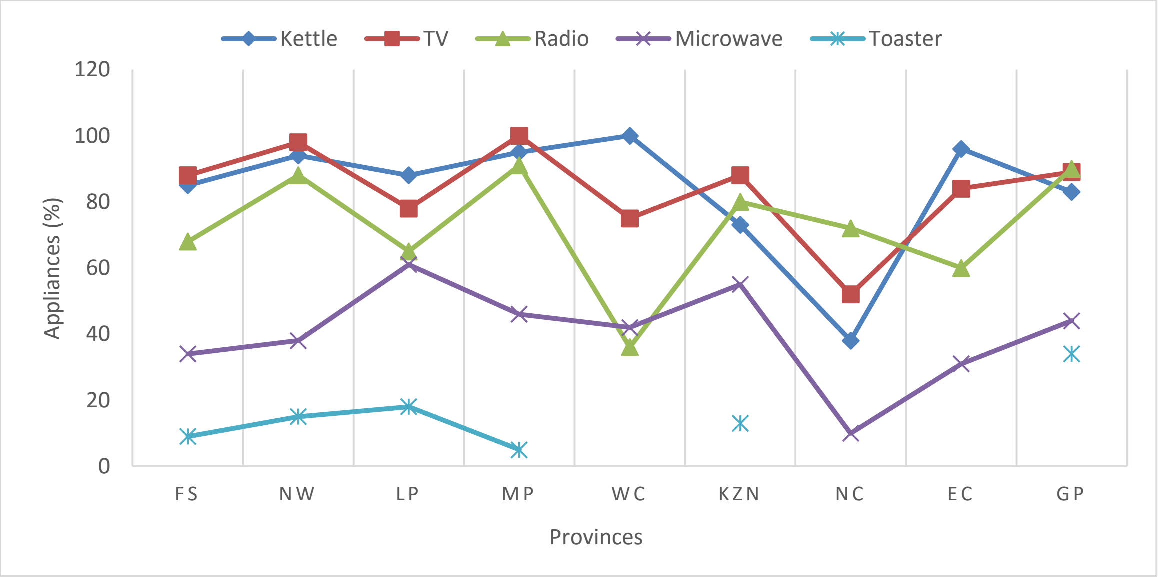


Figure 6.8: Light appliances in the low income households

There is high percentage of availability of refrigerators, stoves and irons in the low income household category. The Free State, North West, Western Cape and Eastern Cape Provinces have electric geysers, however, it is less than 7% of population with such appliances (Figure 6.9), which are in old low income stylish houses. Thus these appliances do not make a significant difference regarding electricity consumption. The Free State and North West have less than 70% of residents that pay less than R500 monthly electricity, this is because they have more than 70% of residents using stoves, refrigerators and irons, and these appliances are high electricity consumers. The Northern Cape Province has fewest appliances and consumes the least electricity amongst all other provinces because of high dependence on government grants and high level of poverty (StatsSA, 2016).

The lines do not connect some of the data because other appliances are not used in some provinces. The Northern Cape Province do not use heater or iron appliances. The rationale for the lack of these appliances, which make result in low electricity consumption, is believed to be the following:

- Low population;
- High unemployment rate; and
- High dependency on government grants

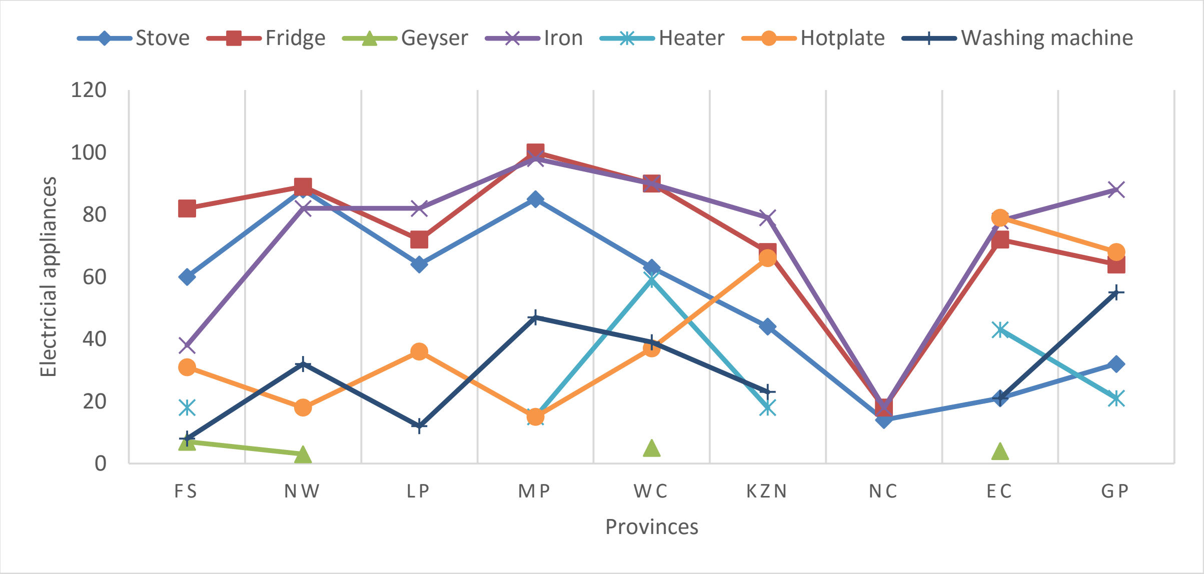


Figure 6.9: Heavy appliances in the low income households

- **Weather pattern**

The coastal areas of South Africa experience more cold weather than inland. More electricity is distributed in winter months across the country than in summer (Figure 6.10). The residential sector accounts for about 20% of such consumption. Yet, load shedding prevails in the winter season because the demand is higher than the supply. The winter season is characterised by the cold front that starts from the coastal provinces and moves to the interior part of the country. There is a high rate of heater usage in winter in the coastal provinces than inland. Western Cape has 59% of the low income households using heaters, and Eastern Cape has 43% heaters usage. The consumption pattern is, therefore higher in winter in the coastal provinces than inland. The weather pattern contributes to seasonal high electricity consumption in the coastal provinces.

Some provinces do not use heaters, hence electricity consumption is relatively low. The Northern Cape is the hottest province in South Africa, for that reason, the low income residents do not use heaters during the winter season.

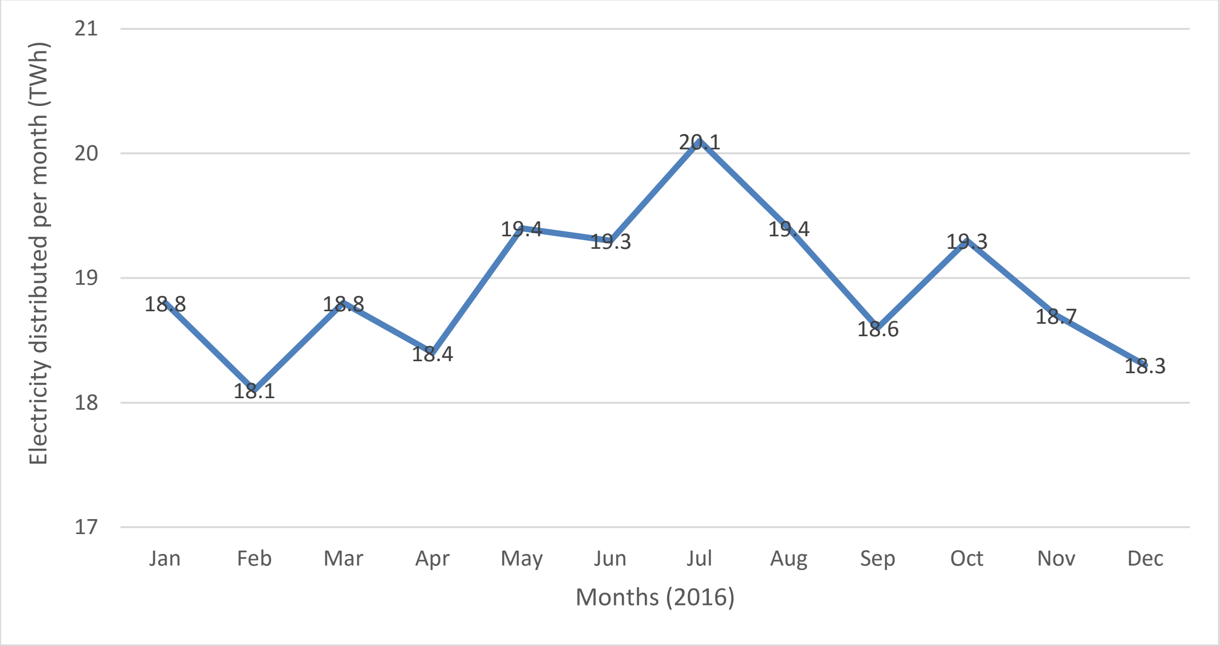


Figure 6.10: Monthly electricity distributed from January to August 2016

The factors that determine electricity consumption differ from one province to another. The household income affects electricity consumption more in Limpopo, Northern Cape and Gauteng Provinces than in other provinces. However, high electricity prices affected the consumption pattern in the Western Cape and Northern Cape (Table 6.2).

Other factors such as FBE, unemployment rate and household appliances are common in all provinces in the low income households in South Africa (Table 6.2).

Table 6.2: Factors that determine electricity consumption pattern in low income households

Province	Factors
Limpopo, Northern Cape and Gauteng	Household income
Limpopo, Gauteng, Eastern Cape, KZN and Mpumalanga	Energy source for cooking (firewood and paraffin)
Gauteng, Western Cape and KZN	Electricity theft and illegal connection
All provinces	Free basic electricity, unemployment rate, household electricity appliances
Western Cape and Northern Cape	High electricity price
Western Cape, Eastern Cape and KZN	Weather pattern

The households' monthly income differs from one province to another. In Northern Cape Province, most of the low income households are unemployed and dependent on government grants. Hence, their income is relatively low compared to the households in North West, Gauteng and Mpumalanga due to substantial number of mining labours and general workers, which stay in the *shacks* in the informal settlement in and around mining areas. These earn more than what their counterparts in Northern Cape get from government as social grants.

Similarly, Western Cape, Kwazulu Natal, Limpopo and Mpumalanga Provinces have a high number of employees in the agriculture sector, and some low income households' work as some seasonal labourers. The agricultural activities include plantation, animal husbandry, fruits, vegetables and vineyards. Therefore, the low income households in this provinces have higher income than those in Northern Cape and Eastern Cape Provinces.

6.3.2 Middle income households

The Northern Cape is the only province with 78% of the middle income household that spend less than R500 on their monthly electricity bill (Figure 6.11). Mpumalanga and Free State Provinces have more than 50% of the middle income that spend between R500 and R1000 on their electricity monthly bill. Moreover, the Western Cape, KZN and Eastern Cape Provinces have more than 30% of the middle income households that pay between R1000 and R1500 for their electricity bill per month, with 23% in Gauteng province (Figure 6.11). These are manufacturing based provinces, wherein are employed over 73% of South African workers in the second quarter of 2016 (StatsSA, 2016).

Thus, there is high number of middle income households that contribute significantly to such higher electricity consumption. Mpumalanga, Limpopo, Gauteng and North West provinces are dominated by the mining sector in South Africa, they employed 81% in this sector during the second quarter of 2016 (StatsSA, 2016). Therefore, a substantial number of skilled and professional labourers work as middle classes in these provinces. Then more than 40% of the middle income spend between R500 and R1000 electricity bill per month (Figure 6.11).

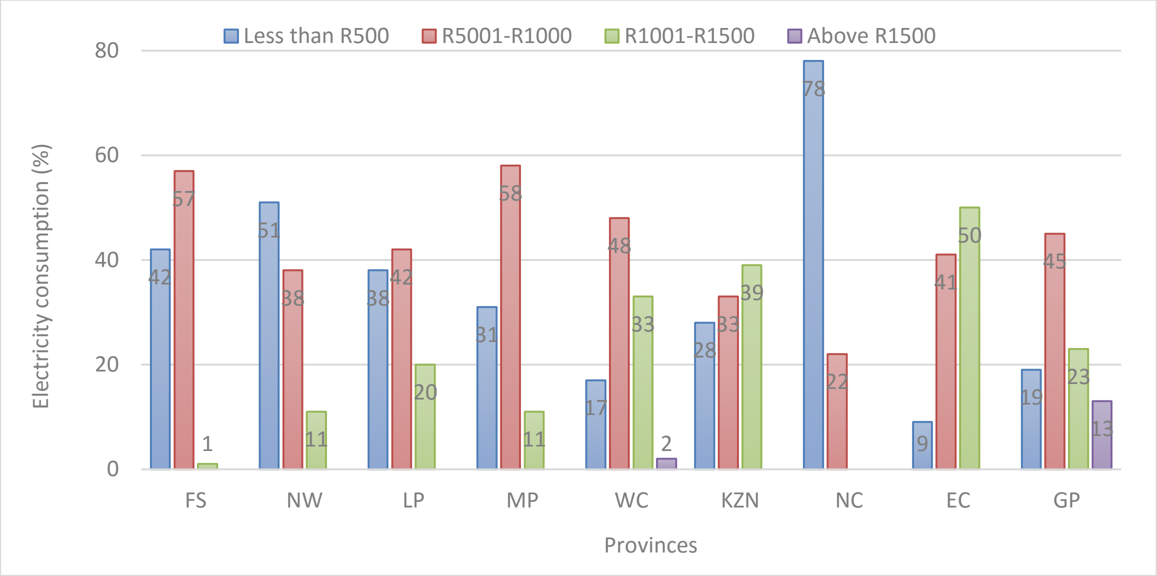


Figure 6.11: Middle income household electricity consumption

The middle income residents consume more electricity than low income. There are 35% spending less than R500 on the monthly electricity bill, and 43% spending between R500-R1000, with 21% spending R1000-R1500 and 1% spending over R1500 on the monthly electricity bill. The electricity consumption in the middle income households is characterised the following factors:

- **Electricity price**

The middle income households are not necessarily restricted by electricity price for consumption. A significant number of respondents indicated that they would be willing to pay more for clean energy. The level of understanding of the electricity price is higher than in the low income households. In Gauteng Province, there is 13% of middle income households that pay more than R1500 electricity bill per month. Some of them are residents that have extended their houses for the purpose of hiring other rooms for rental purpose in order to make additional income, hence consumption is higher.

This is similar to Western Cape that has 2% of the middle income households that pay more than R1500 for monthly electricity bill. Therefore, electricity price is not necessarily a barrier for high electricity consumption, especially to those with extra income from the rental of other rooms. It would seem that the middle income group is willing to pay more for electricity, hence the consumption is relatively higher than in the low income group.

- **Household income**

Gauteng had approximately 28% of the middle income households in the province 2011. Similarly, Eastern Cape, Western Cape and KZN had more than 10% of the middle income households in 2011 (StatsSA, 2015a). The middle income category seems not to have any financial difficulties in spending more money on electricity, despite how much it costs in a month. The middle income group is able to afford the basic services such as electricity, education and accommodation. Hence, the household income is most likely sufficient to cover the electricity bill without any concern on consumption in the household.

- **Household electrical appliances**

The middle income residents in all the provinces have over 90% of the household appliances available, this includes the light appliances such as kettles, TV, radio, microwaves, toasters and the heavy appliances, which are stoves, fridges, geysers, irons, heaters, fans and washing machines. The middle income households have substantial number of these appliances. The other difference is that there is an average of 10% houses with hotplates and 90% with stoves. Gauteng has 5% middle income households that use hotplates, whereas Northern Cape and Eastern Cape have 42% and 22% of middle income that use hotplate respectively (Figure 6.12). With 90% of the middle income using stoves for cooking, the electricity consumption is likely to be high, unlike in the low income category where some communities use firewood and paraffin for cooking.

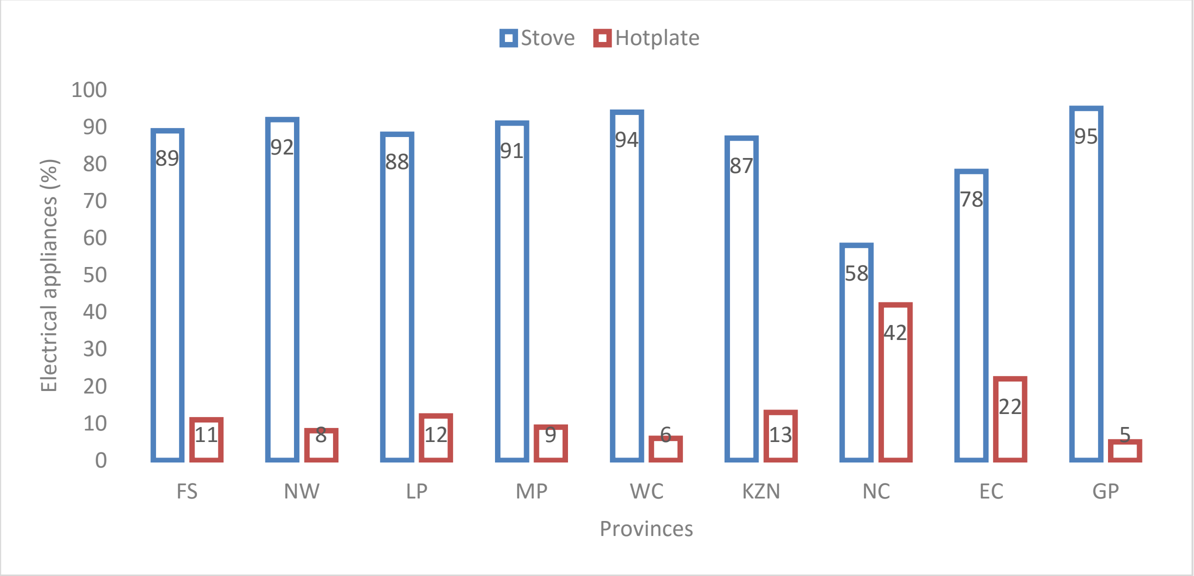


Figure 6.12: Proportion of stoves and hotplate for the middle income households

The quantity of middle income households in Northern Cape are fewer and thus do not have the same employment opportunities as in Western Cape, Gauteng and KZN Provinces. These are economic hub provinces with different sectors such as trade, construction, utilities and manufacturing, therefore there are more employment opportunities and most of the middle income households are able to afford stoves rather than hotplates. Furthermore, Mpumalanga, Limpopo, North West have more middle income households in the mining sector. Thus, the household appliances contribute significantly in the electricity consumption in the middle income households.

Thus household income, appliances, electricity tariff do not influence or reduce electricity consumption for the middle income households in a significant way. The consumption is higher than for the low income group.

6.3.3 High income households

The high income households have the most appliances compared to the middle and low income categories with an exception of two factors, 1) the absence of the hotplate in this category; and 2) Northern Cape with 92% of stoves instead of 100% as in other provinces (Figure 6.14). Most of the high income households spend between R500 and R1000 on their electricity monthly bill, these are mainly in the Free State, Northern Cape, North West and Eastern Cape Provinces (Figure 6.13). Nonetheless, the Western Cape, KZN and Gauteng spend over R1000 on their electricity monthly bill specifically, 40% of households in these capital provinces spend between R1000 and R1500, and these are capital provinces with high economics activities. There is high consumption in Gauteng with 36% spending over R1500 on their monthly electricity bill (figure 6.13).

The high electricity bill is not only based on the number appliances that are available in the houses, but the tariff structures of the municipalities, the electricity tariffs are based on blocks, the higher the block the more expensive electricity becomes. This differs from one municipality to another. For example, City of Cape Town has two blocks, in 2014/2015 financial year, block 1 was 0-600 kWh, which the rates were R153,63 c/kWh per month, and block 2 was over 600 kWh per month, which the rates were 186,81 c/kWh. Furthermore, some of the low and middle income categories use firewood and paraffin stoves, which result in low electricity consumption, and none of the residents in the high income category use such energy source, hence electricity consumption becomes high in this income category.

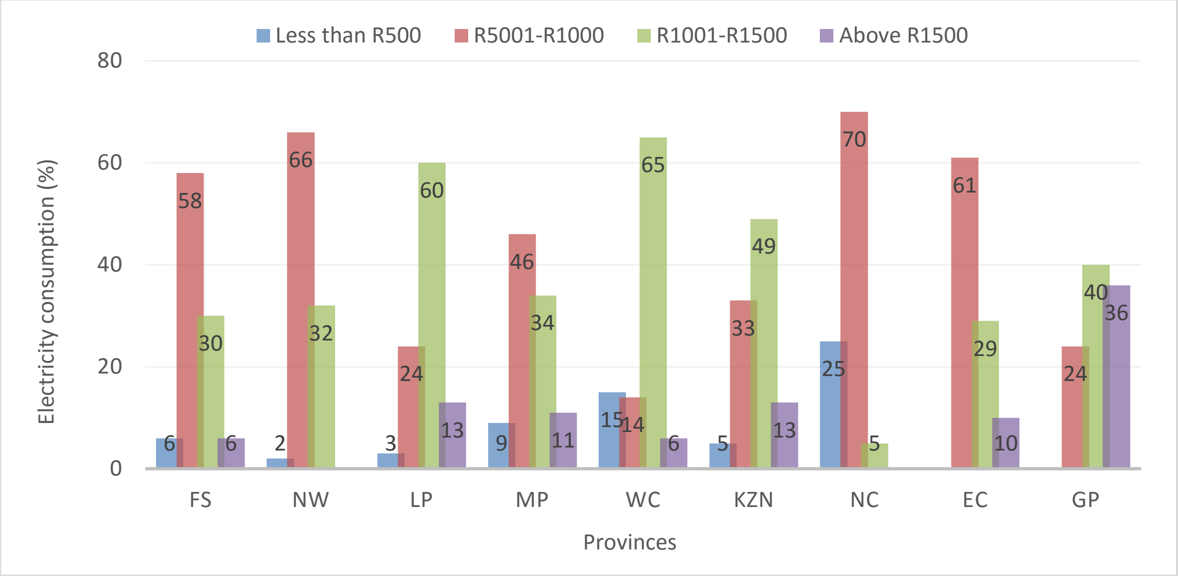


Figure 6.13: High income households' electricity consumption

There are a substantial number of gas stoves and solar water heating systems in the high income households. Between 6% and 20% of the households, have gas stoves (Figure 6.14). Most of these are dual gas and electric stoves that enable the households to switch to any source of energy for cooking on any given day. More than 80% of the gas stoves were installed after the 2008 and 2009 load shedding and households decided to have a back-up for cooking instead of relying on electricity only. Between 9% and 32% of the households have installed solar water heating, almost all of them are newly built instead of retrofitted. A subsidy encouraged most of the high income households to install solar water heating.

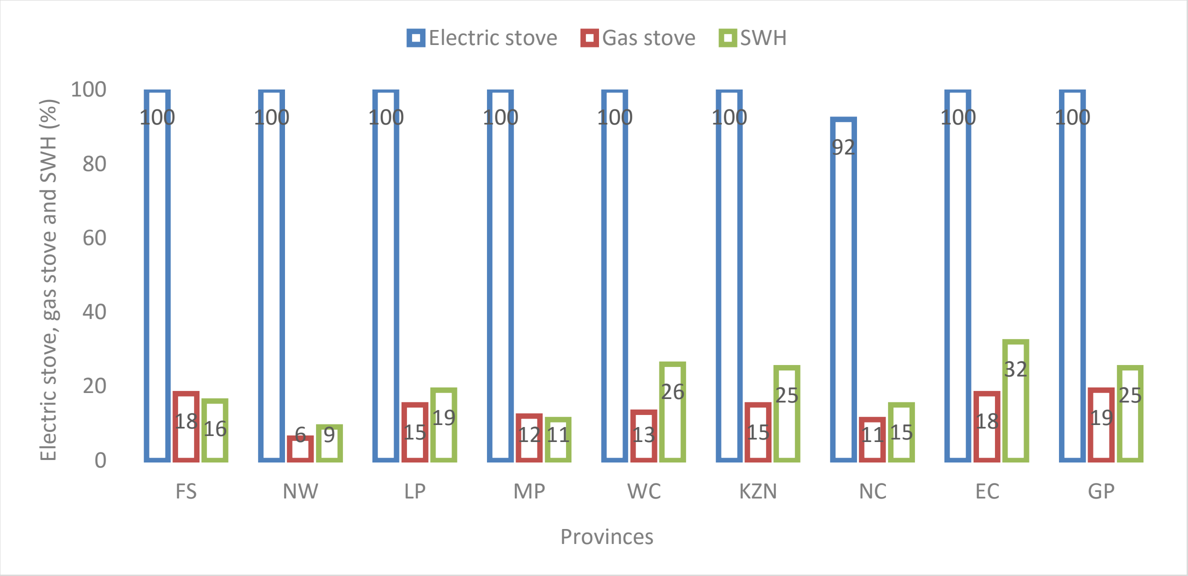


Figure 6.14: Proportion of gas stoves and Solar Water Heating in the high income households

The factors that contribute to electricity consumption in the high income households are:

- **Electricity tariff structure**

The electricity tariff is structured in such a way that the households that consume more electricity per month pay the higher rates than those consuming less. High income households have more electrical appliances than the middle and low income categories and this influences electricity consumption, therefore the monthly electricity bill is high and hence the tariff per kWh is higher than in the middle and low income.

- **Air conditioners**

There is higher air conditioner usage than heaters in the high income households except in Northern Cape where a heater is used more than an air conditioner (Figure 6.15). The air conditioners are not seasonal, unlike heaters, hence they are used throughout the year. Limpopo and North West Provinces have over 80% of high income households using air conditioners, for the reason that these two inland provinces are extremely hot during summer months, with temperature that goes to 40 ^{0}C (Gbetibouo, 2009). Similarly, Western Cape and Gauteng have 89% and 87% of high income households using air conditioners, it could be because these are provinces than are known for the high profile and rich people as economic hubs of the country. Then, these provinces have higher number of people in the high income category than others.

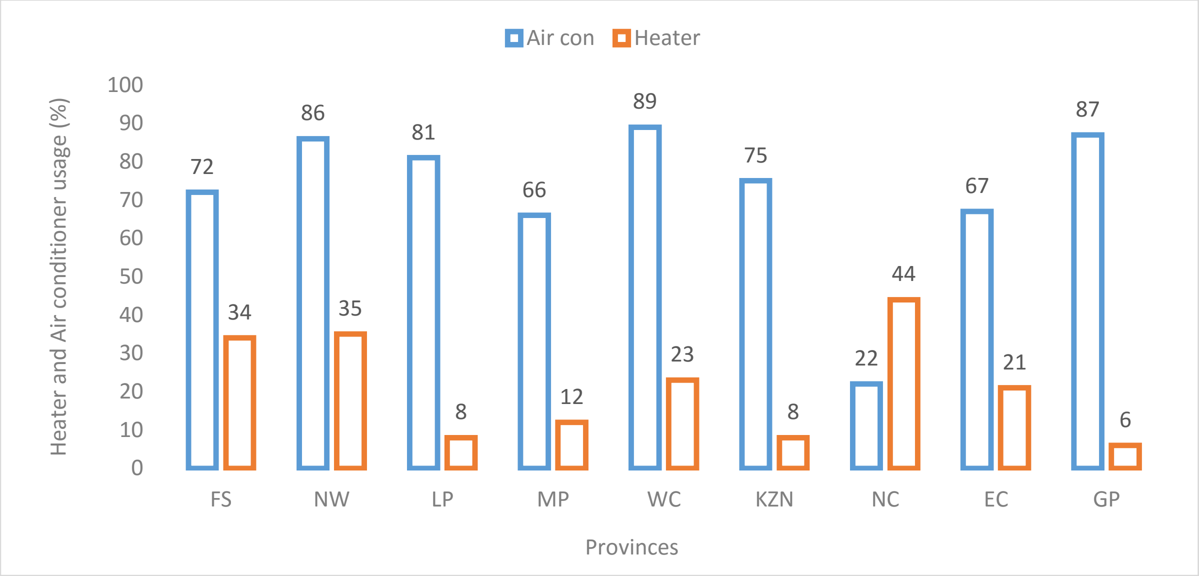


Figure 6.15: heater and air conditioner usage in the high income households

The air conditioners are used in all seasons throughout the year as opposed to the heaters in the middle and low income households, which are used in winter only. High electricity consumption in the high income households is influenced by many more factors such as too many electricity appliances and high usage of air conditioners than in the middle and low income households.

6.4 Impacts of South African electricity tariffs on consumption

South Africa has two types of electricity tariffs, namely: Utility (Eskom) tariff, which is at 8.46 US$ c/kWh, and the municipal tariff, which the average is at 8 US$ c/kWh (Business Tech, 2015). The South African electricity price is comparable at an international level. South African tariff at utility level is ranked 10th compared to European countries (Business Tech, 2015). At an international level, South Africa is ranked 16th including African countries such as Swaziland, Zimbabwe, Lesotho, Mozambique and Malawi that are relatively higher (Figure 6.7). The electricity tariff in 2015 was at 8.46 US$ c/kWh (Figure 6.16). The most expensive tariff is Italy at 15.70

US$ c/kWh, followed by Germany and United Kingdom at 15.22 and 14.16 US$ c/kWh respectively.

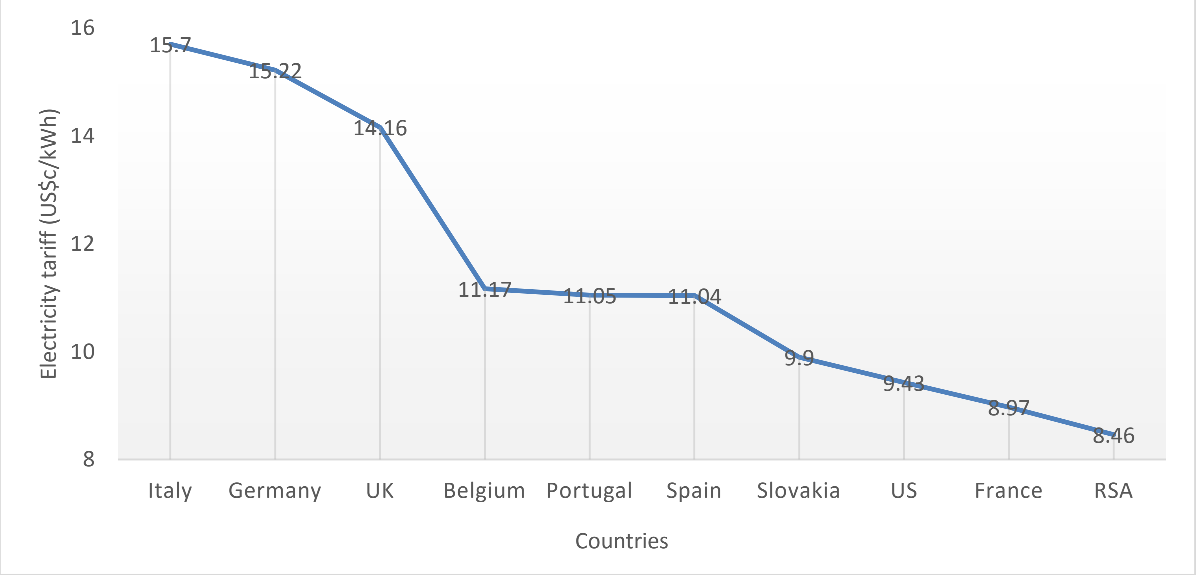


Figure 6. 16: Global top 10 highest electricity tariffs (Source: Business Tech, 2015)

At the residential level, Eskom directly supplies only 5.6% of the South African population, however, the municipalities supply electricity to the remainder of the population. The municipal tariffs differ from one municipality to another. The average tariff is at US$11.7 c/kWh (ESI, 2016). Hence, at the municipal tariff level, South Africa is ranked the 5th in the world after Belgium, UK, Germany and Italy. The South African municipal electricity tariffs are relatively high at an international level. With the rate of electricity consumption as depicted in Figure 6.9 and 6.11, the medium and high income seem not to be affected by such higher tariffs in South Africa. It would seem that high municipal tariffs are not the barrier for electricity consumption in the middle and high income categories.

In the Southern African countries, South African electricity is the third cheapest at a utility level after Zambia and Angola (Figure 6.17). Consequently, South African electricity is affordable at a utility level in the region. It is worth noting that at a municipal level, South African electricity tariffs become the most expensive in the region at US$11.7 c/kWh (ESI, 2016). Yet, the municipalities serve more than 90% of South African residents. Despite this, it would, 2016 electricity prices seem that it is still affordable especially by the medium and high income groups taking into consideration the rate of consumption as shown in Figure 6.11 and 6.13.

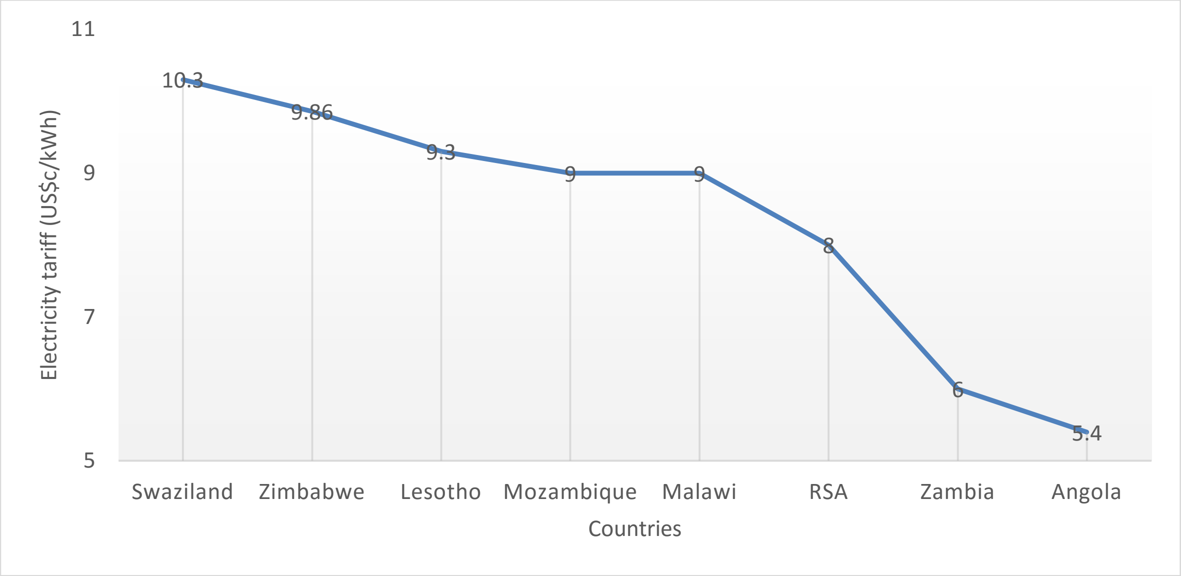


Figure 6.17: Southern African countries' electricity tariffs (Source: ESI, 2016)

Electricity tariff in South Africa is comparable at an international and regional level. The medium and high income groups would by all means not be restricted to consume electricity based on the tariff. The municipal tariffs are relatively high (5th at an international level), and highest at a municipal level. The higher the household income the greater the electricity consumption, despite the high electricity tariff in the region. Hence, electricity tariff does not influence consumption especially in the middle and high income categories.

6.5 Provincial electricity consumption and PV potential

Linking the households' electricity consumption (Chapter 6) and Potential of solar PV (Chapter 4), Gauteng, and KZN provinces have good solar PV potential taking into account several factors such as land space and solar radiation. It is recommended that Gauteng and KZN provinces are ideal for the construction of solar PV plants and roof top PV. The overall provincial electricity consumption is largely dominated by Gauteng and KZN Provinces because these are economic hub provinces with industrial activities. Moreover, Limpopo, North West and Mpumalanga are equally high electricity consuming provinces because of the mining activity, which is one of the core economic sectors in South Africa. In September 2016, Gauteng and KZN were the highest electricity consuming provinces with 4691 and 3445 GWh respectively (Figure 6.18). The trend is the same throughout the year where the afore-mentioned provinces are highest electricity consumers in the country.

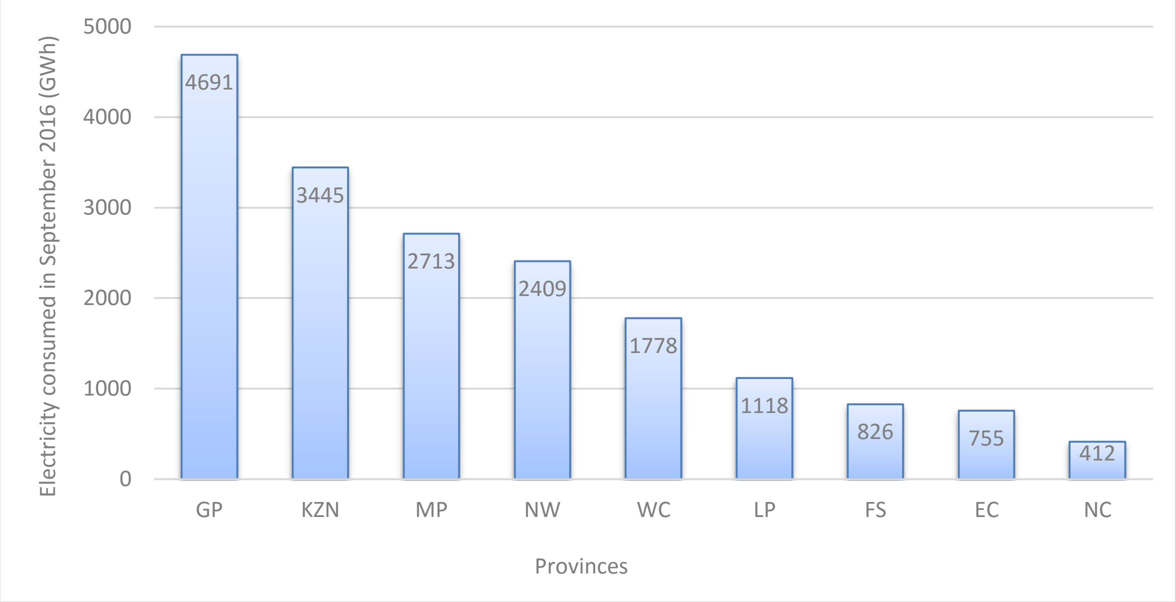


Figure 6.18: Provincial electricity consumption in September 2016 (Source: StatsSA, 2016)

The solar PV potential depends on the combination of parameters in each province. The Eastern Cape and Northern Cape Provinces have substantial solar PV potential taking into account the land space and solar radiation, whereas Gauteng and KZN provinces have substantial potential based on high electricity consumption and solar radiation parameters. Considering the electricity consumption pattern in different provinces, solar PV plants should be established in Gauteng and KZN provinces in order to supplement and reduce the dependency on coal-fired electricity.

This chapter found that in terms of the actual electricity consumption, Gauteng and KZN are the highest, hence the solar radiation and electricity consumption parameters seem to be the most viable ones in decision making (Table 6.3). In contrary, the Eastern Cape and Northern Cape provinces have the least electricity consumption in September 2016 (Figure 6.18). The parameters for these provinces were solar radiation and land space. Therefore, these are not ideal parameters to be considered as far as the current electricity consumption pattern is concerned.

Table 6.3: Provincial solar potential and parameters

Provinces with substantial solar PV potential	Main parameters	Actual electricity consumption (South Africa)
Gauteng and Kwazulu Natal	Solar radiation and electricity consumption	Highest
Northern Cape and Eastern Cape	Solar radiation and land space	Lowest

This chapter concludes that the main causes of high electricity consumption in Gauteng and KZN provinces are:

- High construction and manufacturing dominated provinces
- Population growth (5% in each province)
- High population consequent to migration from other parts of the country and immigrants from other African countries
- Energy saving awareness (explained in detail in section 6.5)

Furthermore, this chapter concludes that the main causes of low electricity consumption in the Northern Cape and Eastern Cape provinces are:

- Low population
- Less industrial activities compared to other provinces

6.5 Household size and number of inhabitants

The electricity consumption pattern is determined by the size of the house, being the number of rooms as well as the number of people in the households. The general trend in all provinces is that the number of rooms is fewer in the low income category mainly because of the type of house they live in, such as the *shack* house in the informal settlement and the government free allocated house to the poor, which is smaller in size (45m^2). The number of rooms and size of the house in the high income group is higher than in the middle and low income groups (Figure 6.19).

6.5.1 Size of the house

The number of rooms and appliances has direct impact on electricity consumption in the household. In Gauteng province, there is 100% low income with number of rooms being 3 or less. There is 70% of high income group with more than 7 rooms, hence the size of the house is bigger (Figure 6.20). In Northern Cape Province, 85% of high income class have 7 rooms or more, whilst 66% of the low income households have less than 3 rooms (Figure 6.19). The Northern Cape Province has less population, the high income group amounts to 2% at a national level (StatsSA, 2015a). Then, the 85.7% of the high income group occupying a 7 or more rooms' house would result in higher electricity consumption at a provincial level.

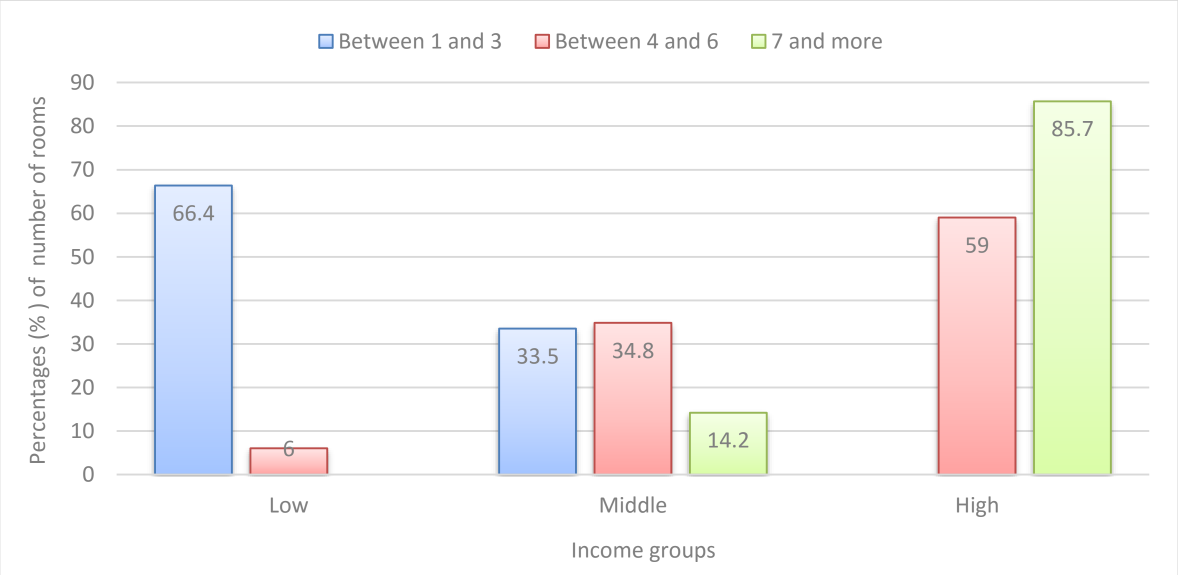


Figure 6.19: Number of rooms per income category in the Northern Cape Province

The number of room per income group has the same trend in all provinces across the country. In Gauteng Province, there is 100% of low income class residing in less than 3 room houses, whilst more than 70% of the high income class stay in 7 or more rooms houses (Figure 6.20). Gauteng has 45.5% of South African high income group

(StatsSA, 2015a), therefore the consumption based on number of rooms is high, and hence much of electricity is distributed to Gauteng province as shown in figure 6.18.

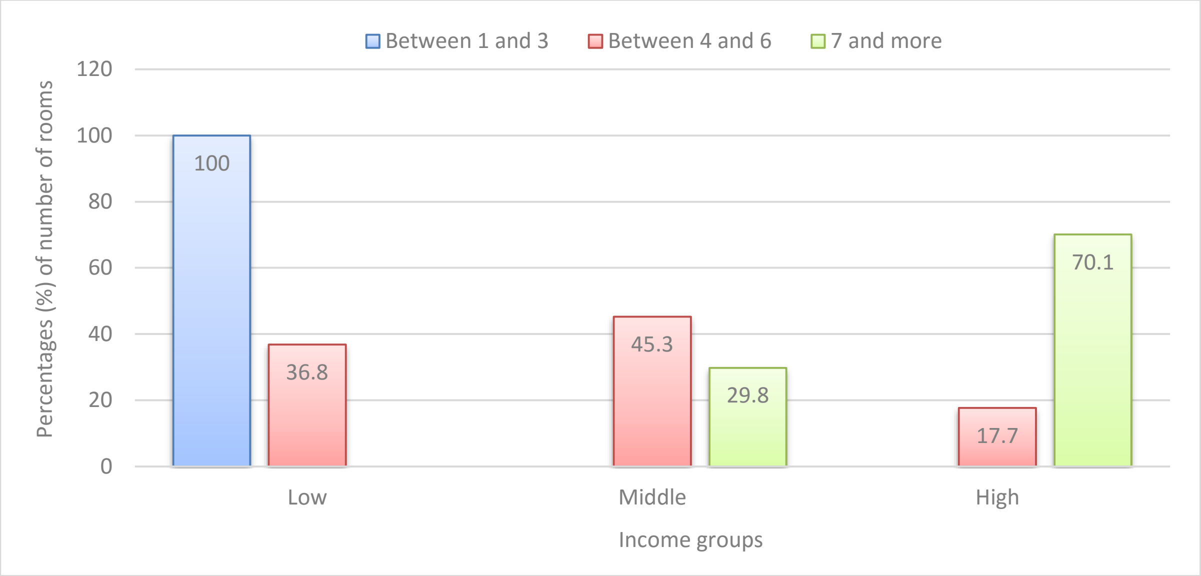


Figure 6.20: Number of rooms per income category in Gauteng Province

Gauteng Province has 93% of low income class spending R500 or less on monthly electricity bill. This is the case because 100% of such income class stay in a 3 or less rooms' house. More than 76% of the high income class spend at least R1000 on a monthly electricity bill. Hence, the number of rooms contributes in determining the electricity consumption in different income classes.

The high income class has substantial amount of appliances with 100% electric stoves in all provinces except Northern Cape (Figure 6.14). Less than 10% of this class spend R500 or less on monthly electricity bill. The size of houses contributes significantly to higher electricity consumption in the high income category. Similarly, middle and low income categories have smaller houses with relatively lower electricity consumption compared to high income categories. Therefore, the electricity consumption per size of the house confirms the section 6.3 findings per income class as depicted in figure 6.2; 6.11; and 6.13. These figures demonstrated that more than 90% of low income class in Gauteng, Eastern Cape, Northern Cape, Western Cape and Limpopo Provinces pay less than R500 per month on electricity bill. This category consists of 44.7% of South African population. Furthermore, more than 60% of high income in

Gauteng and Western Cape Provinces spend more than R1000 per month on electricity bill.

6.5.2 Number of inhabitants in the house

The number of inhabitants in the households is smaller in the high income residents and vice versa. 60% of high income group has less than 3 household members and 73% of the middle income group has more than 7 household members with 52% of the low income group having between 4 and 6 household members (Figure 6.21). This would mean that there is least number of household members in the high income category. The low and middle income categories have more household members.

The implication of number of inhabitants in the household is that the higher the number the higher the electricity consumption. This is the case because households with many members tend to cook more than others, the rate of watching TV, Radio, washing clothes, taking showers is higher than the others. This may not be case in the low income category as they also use firewood and paraffin for cooking and boiling water.

However, one may argue that the number of type of appliances may be a better determinant of electricity consumption than the number of inhabitants in a household. The low income group may have smaller house with lesser number of electrical appliances and many inhabitants, hence there may not be many appliances to be switched on. On the other hand, medium and high income groups may have more electrical appliances with a smaller number of inhabitants, hence more appliances may be used and consumption is still higher than the low income group with high number of inhabitants.

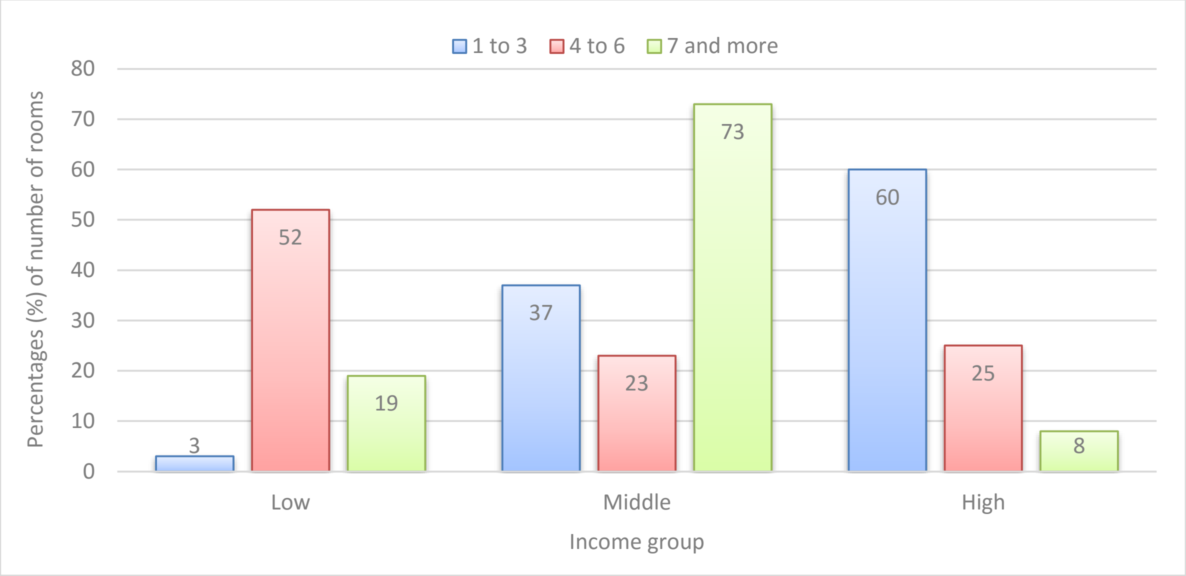


Figure 6.21: Percentages of the inhabitants per income category

The size of household and number of inhabitants plays a crucial role in electricity consumption. Nevertheless, the low income household with more than 50% of 4-6 inhabitants in a house and middle income group with more than 70% of 7 or more inhabitants in a household should be spending more money on monthly electricity bill.

The critical part of determining the level of electricity consumption in this section is the split of the percentages of low, medium and high income groups. The Western Cape and Gauteng Provinces have the most high-income group members than the rest of the provinces (Figure 6.22). Therefore, electricity consumption is proportional to the extent of the high income group in these provinces because income category influences electricity consumption, Gauteng province has the highest electricity consumption of above R1500 (Figure 6.23 and 6.24). For instance, 44% of the high income group households spend between R1000 – R1500 on their electricity bill monthly. Furthermore, Gauteng Province contains 36% of the high income category spending over R1500 on monthly electricity bill. Thus, electricity consumption is much higher in Gauteng than the rest of the other provinces as depicted in figure 6.18.

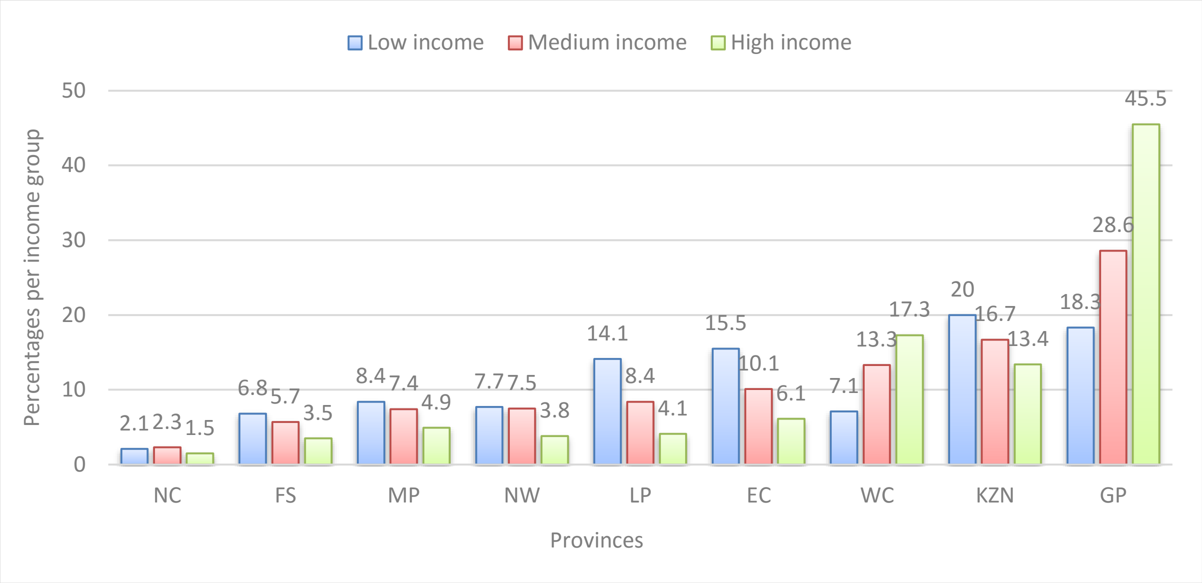


Figure 6.22: Proportion of income category per province

The high power utilization bracket was R5001-R1000 per month in most of the provinces. The Northern Cape being the highest province with 70% of high income category paying between R500-R1000 on electricity bill per months (Figure 6.23). However, Gauteng province has the highest percentage of high income residents of 36% that pay over R1500 of electricity per month (Figure 6.23). This is the province that has 23.7% of the South African population.

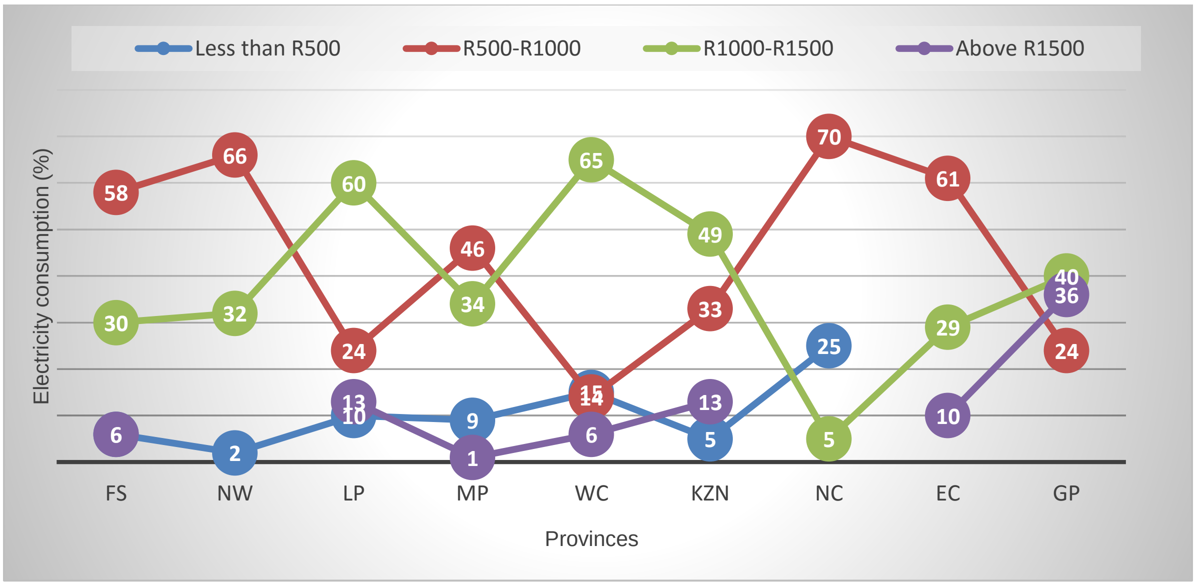


Figure 6.23: Electricity consumption of high income residents

The electricity consumption in Gauteng is proportional to the income group. The low income category consumes less electricity, which is mainly below R1000 per month, followed by middle income category that has 45% residents paying between R500 and R1000 of electricity bill per month (Figure 6.24). The high income category consumes the highest electricity with 36% paying above R1500 on monthly electricity bill (Figure 6.24). Thus, electricity consumption in Gauteng province is proportional to the extent of income category.

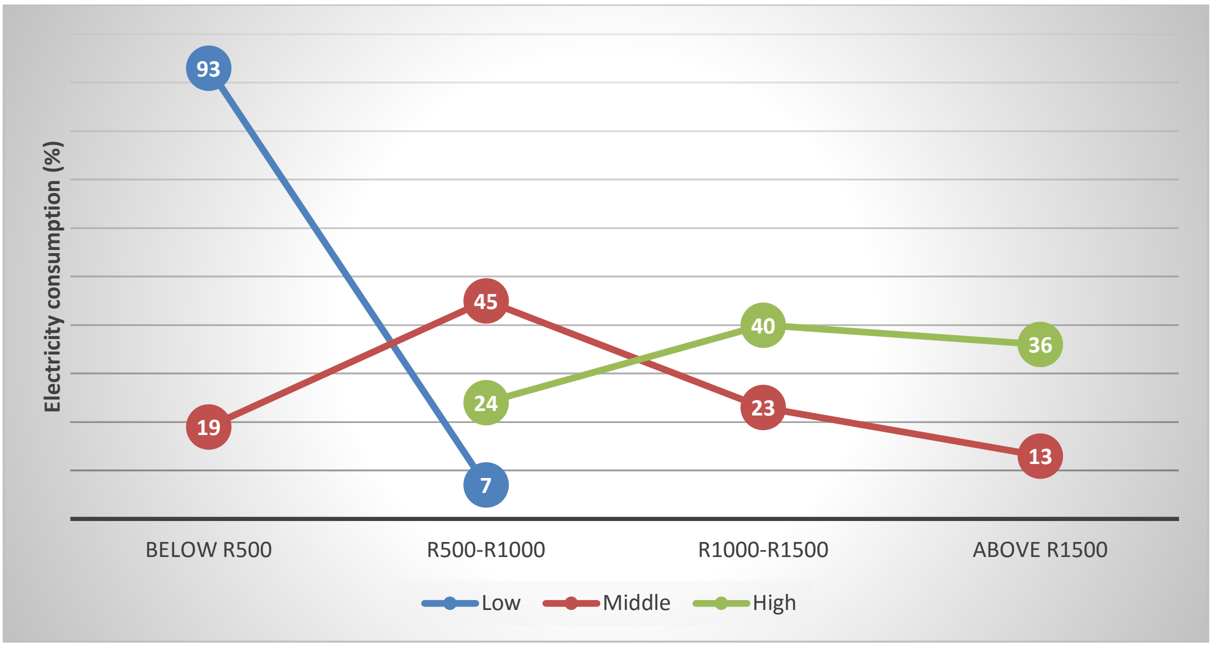


Figure 6.24: Electricity consumption per income category in Gauteng province

6.6 Perception and awareness on solar PV

The potential of solar PV to be successful depends on many factors including awareness and the perception of such technology. These are key factors that the PV's success at the community level depends on. The different households' income groups demonstrated different levels of knowledge on solar PV technology in different provinces. The low income residents demonstrated a lack of knowledge of solar PV technology. The community members are well aware of solar water heating technology, but do not know solar PV and what it does and entails. This is worrisome in so far as the successes of solar PV projects are concerned in such areas. Awareness raising and education would be needed in such communities should a project of this nature implemented.

6.6.1 Low income residents

The low income residents demonstrated lack of knowledge and awareness on the solar PV technology. More than 50% across the provinces do not know about solar PV, nonetheless over 60% of residents in the North West, KZN, Western Cape and Free State Provinces knew a little bit of solar PV technology (Figure 6.25). Most of the community members in these provinces attributed the solar PV to the solar home system that was once brought by the government in their respective areas. This demonstrates that with good knowledge and understanding of solar PV, the success prospects would be enhanced if such projects can be installed in these provinces.

The Northern Cape Province has approximately 88% of the low income residents that do not know solar PV technology (Figure 6.25). This is the province with high solar PV potential, and yet this technology is not known in the province. However, the population is low, this province has 2.1% of the low income residents in the country (Figure 6.22). Limpopo and Gauteng Provinces are the second and third highest with 58% and 55% of the low income residents that do not know solar PV (Figure 6.25). The low income group in these provinces is 14.1% and 18.3% respectively. This is substantial amount of population that do not know solar PV and this would have negative effect in the promotion and success of solar PV projects.

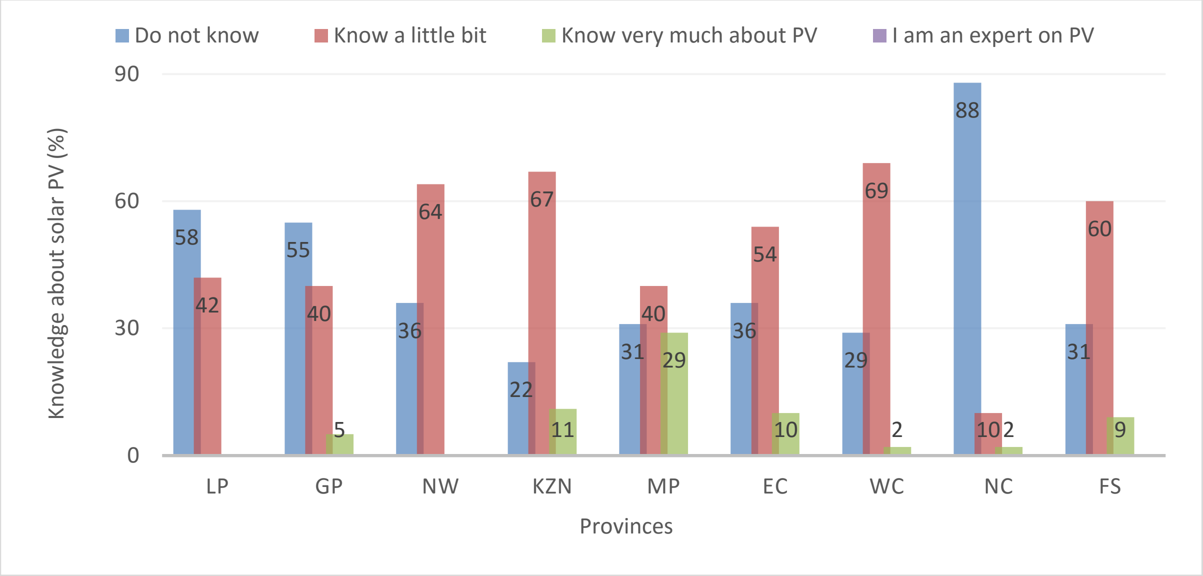


Figure 6.235: Knowledge and awareness of solar PV in the low income residents

Less than 11% of low income residents know very much about solar PV, with an exception of Mpumalanga Province having 29% of low income residents knowing about it. The rationale for such a high percentage in this province is attributed to the informal settlements that are next to the mines and the Sasol petroleum company that have installed solar PV for their own power generation and use.

The low income residents across the provinces indicated that if solar PV was to be installed in their area, community members would appreciate it for the following reasons:

- It could make electricity cheaper and save money for the residents;
- More electricity is needed to prevent outages;
- Job creation;
- There is too much heat that could be used to generate electricity; and
- Government would spend less money on purchasing coal to generate electricity

Other low income residents are of the view that community members may not appreciate the solar PV in the area because of the following reasons:

- The community members do not know solar PV technology; and

- The community members cannot depend on the sun because sometimes it becomes cloudy and there would be no electricity

The basis for electricity payment differs from one community and province to another. Some residents prefer to consume and pay for electricity based on the cheapest price, whilst others may opt to pay based on the green source (wind, solar etc). The basis for electricity payment for the low income residents is 100% on cheapest price for 5 provinces and over 90% for 2 provinces (Figure 6.26). The Eastern Cape, Western Cape and Free State Provinces have less than 11% of low income residents that would prefer to pay electricity based on green source (Figure 6.26). The three factors that influence the majority of low income households that prefer to pay for electricity based on cheapest price are:

- Low household income;
- Low level of awareness and knowledge of solar PV technology; and
- Perceived high electricity cost per kWh and the annual tariff increase.

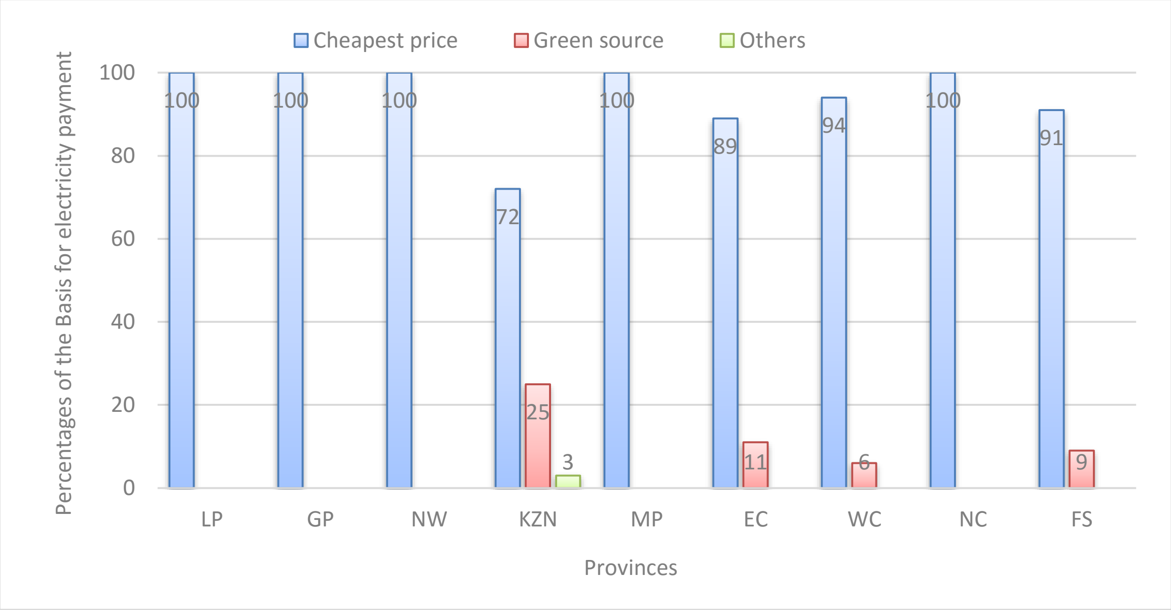


Figure 6.246: Basis for electricity payment in the low income residents

The KZN electricity is still the cheapest at the household level in South African municipalities. Consequently, 25% of the low income group is willing to pay for electricity based on the green source of such electricity and 3% could pay for electricity based on other factors apart from the cheaper source and the green source. Moreover, KZN has demonstrated high percentages of the low income group that know solar PV (67%) and those that know solar PV very well (11%). Nevertheless, the 25% of low income residents that are willing to pay for electricity based on source may not be aware of the fact that green electricity may be slightly more expensive than that from coal-fired power generation.

The low income residents demonstrated low knowledge of solar PV, hence this affects the growth and development of such technology amongst the low income residents across the country. Furthermore, the low income residents would appreciate if solar PV can be installed in their area for several reasons including possibility of them paying a lower price on monthly electricity bills. The basis for electricity payment is largely on the cheapest price, despite the source and the implication of it. This makes sense because the residents have low income and could not afford high priced electricity based on its source.

6.6.2 Middle income residents

The middle income residents demonstrated a higher level of knowledge of solar PV than the low income residents. There is high proportion of community members that know solar PV technology across the country (Figure 6.27). On average, over 70% of the middle income residents know of solar PV technology. There is a higher rate of knowing a little bit about solar PV in KZN, Mpumalanga, Eastern Cape, Western Cape and Northern Cape Provinces. Nevertheless, in Gauteng and Free State Provinces there is higher percentage of knowing a lot about solar PV in the middle income residents (Figure 6.27). The higher knowledge in the middle income residents is attributed to the following factors:

- The high level of education;
- The settlement pattern and type; and
- The jobs of this income group, which are formal and professional compared to the low income residents.

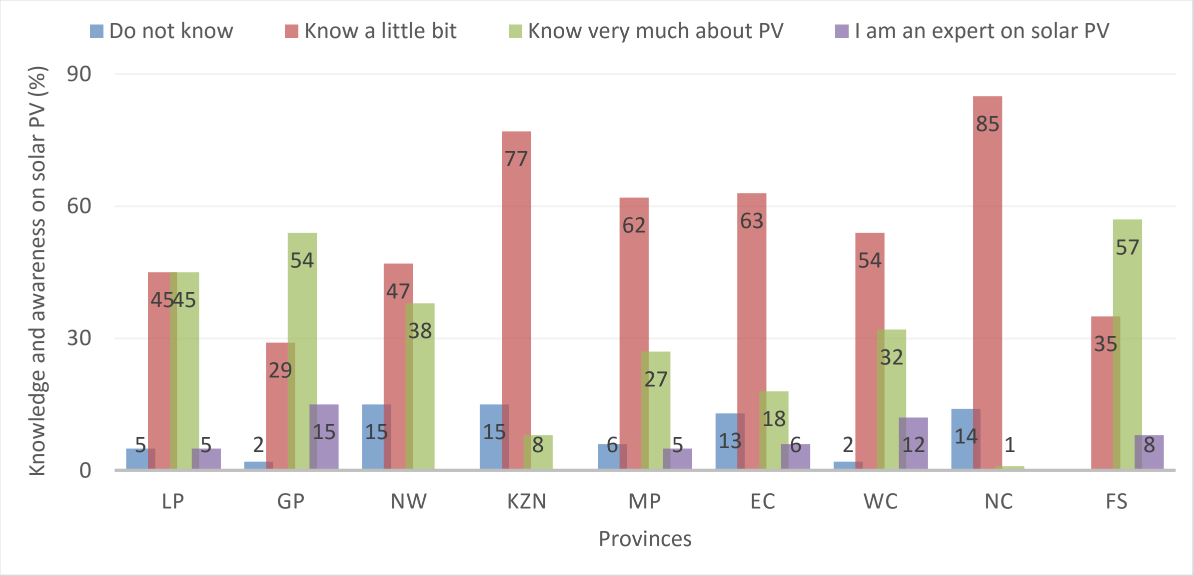


Figure 6.257: Knowledge and awareness of solar PV in the middle income residents

The middle income residents are very aware of the benefits of solar PV technology, less than 15% is not aware of this technology. There is therefore good probability of the success of solar PV in the middle income group in South Africa.

During the interviews, the middle income residents demonstrated higher degree of appreciation of solar PV if it were to be installed in their areas, the basis for appreciation was the two points raised below. More than 80% of the middle income residents recognise the significance of solar PV technology. Over and above the reasons mentioned in section 6.6.1 from the low income residents, the middle income residents recognise that solar PV would come with the following advantages:

- It would be a good commitment to reduce carbon foot print by the country; and
- it would generate more electricity for winter demand

The only side effect that the middle income residents are concerned is that the PV technology depends on sun, hence less power is likely to be produced in the winter season, which the demand is most likely to increase.

Gauteng Province has 38% of middle income residents that are willing to pay for electricity based on the cheapest price, while 25% would pay based on the green source and 27% would base their electricity payment on other reasons (Figure 6.28).

An interesting choice for the basis of electricity payment was found in the Free State province, where 50% of middle income that would base their payment on cheapest electricity and 50% would base it on green source. There is the greatest interest in paying for the electricity based on green source in this province, despite the tariff consequent to such particular source.

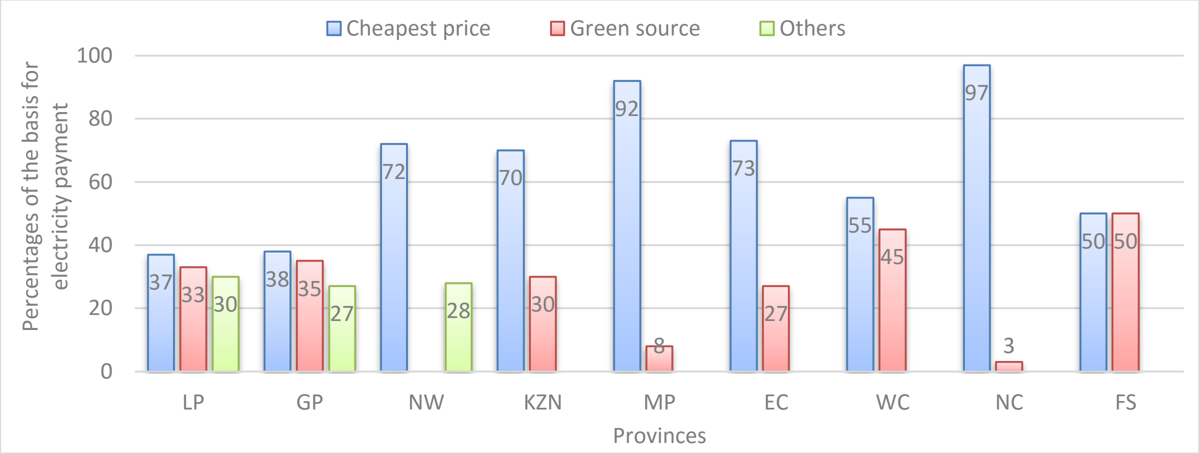


Figure 6.268: Basis for electricity payment in the middle income residents

The majority of the middle income residents in Mpumalanga, Eastern Cape, Northern Cape, KZN and North West Provinces are more likely to base their electricity payment on the cheapest electricity (Figure 6.28). Nevertheless, the middle income residents in the Western Cape, Free State, Gauteng and Limpopo Provinces have shown reasonable consideration and willingness to pay for electricity from green sources rather than the cheapest source. The greater awareness and good perception of PV technology in the middle income residents influences the choice and basis for electricity payment. The more the awareness and knowledge of solar PV the better the choice of electricity supplier; and the understanding of the fact that a green source of electricity could help the country to reduce the carbon footprint.

On average, 25% of the middle income group is interested to pay electricity based on green source (Figure 6.28). This group constitute 48.3% of the South African population. There is 16122000 number of households in South Africa (StatsSA, 2015). Therefore, the number of middle income group households is approximately 8000000. Around 42% of the middle income group spend between R500-R1000 on their monthly electricity bill. This is equivalent to 350 to 450 kWh per month of electricity consumption, meaning 2000000 (25% of the middle income group) households consume up to 450 kWh per month and is interested to pay the price of electricity based on green sources.

To determine the potential of middle income households that are interested to pay electricity price based on the green source, the following calculations are made:

$$\mathbf{Potential} = \mathbf{25\%\ x\ kWh/month}$$

Where 25% refers to the middle income group that is interested to pay the price of electricity based on the green source, kWh/month is the average electricity consumption by the middle income group.

Potential =2000000x400 kWh/month

= 800 GWh/month

=9.6 TWh/year

Therefore, it is evident that 2000000 households in South Africa that consume approximately 9.6 TWh/year is interested to pay electricity based on green source. It was found in chapter 4 that South Africa has a technical potential of 7815 TWh/year.

Based on the level of knowledge and awareness of solar PV in the middle income group, the FIT scheme is most likely be a successful method to increase and promote solar PV technology in South Africa. The roof-top solar PV installation is probably going to increase based on the following factors in the middle income group:

- Relatively higher income compared to low income group;
- Higher knowledge, appreciation and awareness on solar PV technology; and
- High willingness to pay electricity based on source.

6.6.3 High income residents

The high income residents know much about solar PV, there are also experts in the field of this technology in the group. There is however, low percentages of the high income group in some provinces that do not know solar PV. Nevertheless, the level of awareness and knowledge of solar PV is much greater in the high income residents. Less than 10% of high income group in Limpopo, North West, KZN, Eastern Cape and Gauteng Provinces do not know about solar PV technology (Figure 6.29). Northern Cape Province has 26% of high income residents that do not know solar PV, yet it is the province with many of the large scale solar PV projects from the government IPP programme. The level of awareness of solar PV in the high income residents is greater than the middle and low income residents.

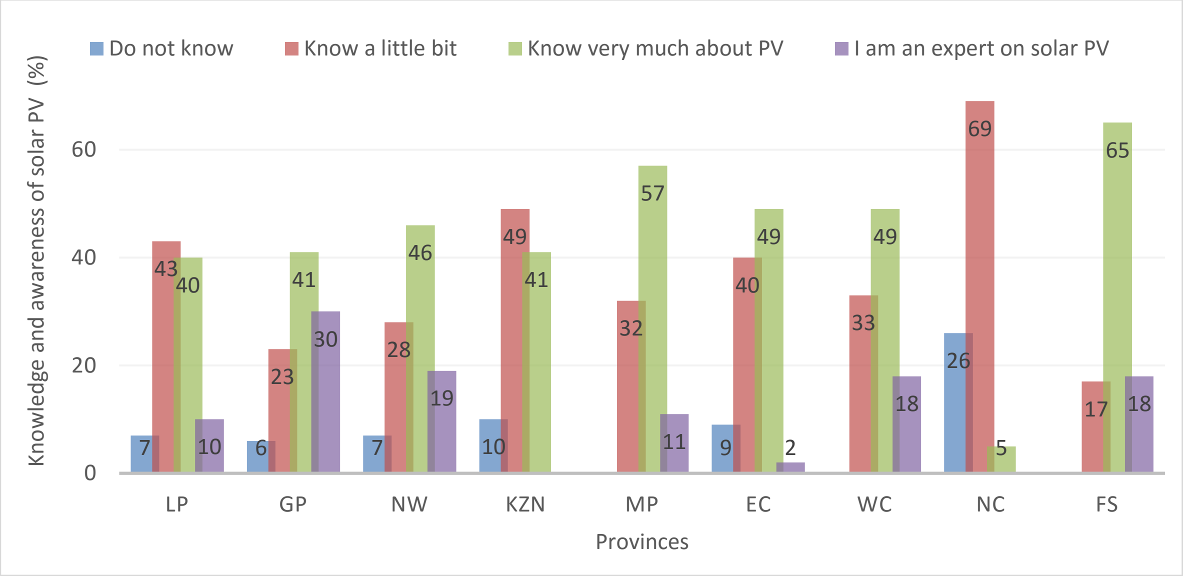


Figure 6.279: Knowledge and awareness of solar PV in the high income residents

Gauteng province has the greatest percentages of high income residents that are experts on solar PV; one of the reasons for such a high number is because of the solar PV businesses that are gaining momentum in the province. On average, less than 11% (with an exception of the Northern Cape Province) do not know solar PV in the high income group (Figure 6.29). Thus, the level of awareness of solar PV is much higher than in the middle and low income residents.

During the interviews, the high income residents demonstrated greater appreciation of solar PV technology if it were to be installed in their areas. All the reasons for the appreciation of solar PV technology mentioned in section 6.6.1 and 6.6.2 were cited with no concern except in Limpopo and Eastern Cape Provinces where the fact of dependency on sun, which fluctuates over time, was mentioned. However, the PV would be much appreciated. Thus, is anticipated, as this is a result of greater awareness and knowledge of solar PV.

There is substantial recognition of a green source as a basis for payment in the high income residents. On average, 43% of the high income category is willing to pay electricity based on green source (Figure 6.30). This is mainly in Limpopo, Gauteng, Mpumalanga, Western Cape and Free State Provinces (Figure 6.30). There is high percentage of members of the community that are willing to pay based on the source of electricity in these provinces. Once again, the awareness and knowledge of solar PV plays a crucial role in recognition of the impact of coal in electricity generation in South Africa. Where this recognition is low, e.g. in the Northern Cape Province, 90% of the high income residents are only willing to pay electricity based on cheapest source (Figure 6.30).

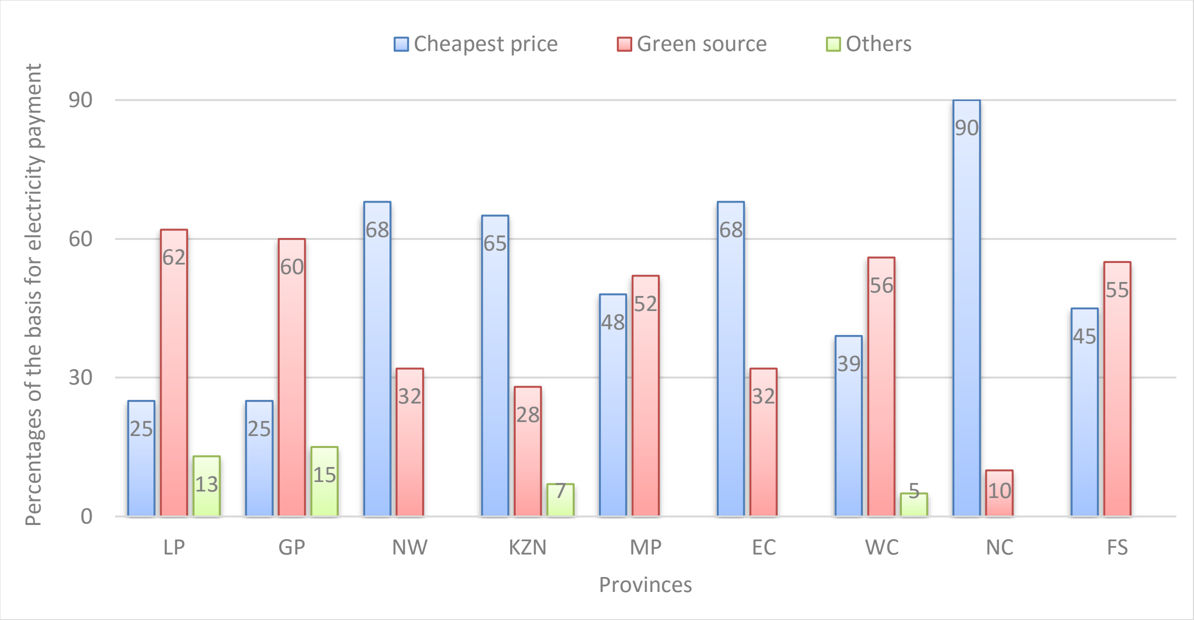


Figure 6.30: Basis for electricity payment in the high income residents

The trend in different income residents is that the awareness and knowledge of solar PV increases with the income group, that is low income residents have the least knowledge and awareness, the middle income group have high degree of awareness and knowledge of solar PV whilst the high income group have the highest level of solar PV awareness. Similarly, the same trend was realised in the basis for electricity payment where the low income prefers to pay electricity based on the cheapest price, whereas the high income prefer to pay electricity based on the generation source. The level of appreciation if solar PV is to be installed is anticipated to increase across the different income groups, but mostly in the middle and lower groups.

Just like in the middle income category, 43% of the high income group are interested to pay electricity based on green source. This group constitute 7.3% of the South African population. There is 16122000 number of households in South Africa (StatsSA, 2015). Therefore, the number of high income group households is approximately 1176906. Thus, 43% of the high income group spend over R1000 on their monthly electricity bill. This is an average of 500 kWh per month of electricity consumption, meaning 506069 (43% of the high income group) households consume over 500 kWh per month and are interested to pay the price of electricity based on green sources.

To determine the potential of high income households that are interested to pay electricity price based on the green source, the following calculations are made:

$$\mathbf{Potential = 43\%\ x\ kWh/month}$$

Where 43% refers to the high income group that is interested to pay the price of electricity based on the green source, kWh/month is the average electricity consumption by the high income group.

Potential =506069x500 kWh/month

= 253 GWh/month

= 3036 GWh/year

=3 TWh/year

Therefore, it is evident that 506069 households in South Africa that consume approximately 3 TWh/year is interested to pay electricity based on green source.

6.7 Convergence between Potential of solar PV *“Optioneering”* (Chapter 4) and Households energy consumption (Chapter 6)

The findings of the potential of solar PV (*Optioneering*) and households’ energy consumption lead to the same conclusion. Chapter 4 concluded that Gauteng and KZN provinces have good solar PV potential and are ideal for the construction of solar PV plants. These provinces have good solar irradiance and high electricity consumption, which solar PV could add value in the diversification of energy mix. Moreover, the rooftop solar PV installation would potentially increase if a renewable feed in tariff system is introduced and implemented in South Africa.

Chapter 6 found that 25% and 43% of the middle and high income households are willing to pay for electricity based on a green source. This therefore, means that such residents are willing to utilize electricity generated from solar PV plants which could be roof top PV installation or construction of solar PV plants. Moreover, high numbers of such middle and high income residents are based in Gauteng and KZN provinces (Figure 6.22). Gauteng alone has 45.5% and 28.6% of high income and middle income residents respectively. Furthermore, Gauteng has 60% of high income residents that are willing to pay electricity based on a green source as opposed to KZN with 28% (Figure 6.30).

Therefore, Gauteng Province has the best solar PV potential emanating from the findings of chapters 4 and 6. Furthermore, over 25% of electricity is consumed in Gauteng Province, hence this province is recommended for the construction of solar PV power plants and rooftop installation for the following reasons:

- Gauteng has good solar PV potential as concluded in chapter 4;
- It has high number of high and middle income households, of which 25% and 43% are interested to pay for electricity based on a green source, which is potentially 12 TWh/year;

- Construction of PV plants and rooftop solar PV would reduce electricity loss due to long distance transmission; and
- There is high consumption of electricity in this province

6.8 Conclusion and summary

The households' electricity consumption differs from one household income group to another. More than 90% of the low income households in Limpopo, Western Cape, Northern Cape, Eastern Cape and Gauteng Provinces spent less than R500 (US$35.76) per month on their electricity bill in 2015. This is equivalent to less than 300 kWh electricity consumption per month, which is an average of 8 kWh per day.

More than 90% of the low income category in South African population spend R500 or less on electricity on a monthly basis. Some low income residents use firewood and paraffin stoves as a source of energy, even though they are electrified, hence they consume less electricity. Some of the low income households spend just over R500 on a monthly electricity bill because there are business initiatives that they are pursuing, these include hair salons; welding business; *spaza* shop selling food items; and *shebeens* or pubs (informal liquor trading store).

An average of 50% of the middle income households spend between R500 and R1000 on their monthly electricity bill. Nonetheless, 30% spend less than R500 and 20% spend between R1000 to R1500 on their monthly electricity bill. Therefore, in 48.3% (middle income residents) of the South African population, 50% consume an average of 400 kWh of electricity per month, 40% consume less than 300 kWh per month and 10% consume over 400 kWh per month.

Similarly, 44% of the high income residents spend between R500-R1000 on their monthly electricity bill, moreover, 38% spend between R1000-R1500, and only 10% spend over R1500 on their monthly basis for electricity. It is worth noting that the high income group is 7.3% in South Africa, hence the power consumption at a household level is less on average compared to other income categories. The middle income category consumes most of the South African electricity, followed by low income taking into account that they form over 92% of the South African population.

The factors that influenced electricity consumption in the household sector are as follows:

- Households appliances;
- Households income;
- Weather pattern;
- Source of energy for cooking;
- Electricity theft and illegal connection;
- Provision of FBE;
- High unemployment rate; and
- Electricity price.

The low income category consumes less electricity, which is approximately 300 kWh per month, however, they constitute 44% of the South African population. Nonetheless, the middle income category consumes relatively more electricity with an expenditure on between R500-R1000 per month on electricity bill, which ranges from 350-450 kWh, this category is the highest in South Africa, which is 48%. The high income category consumes more than 500 kWh per month, nonetheless this category constitutes only 7% of the South African population, and hence the consumption impact is low for this category. Hence, the FIT mechanism may be beneficial in South Africa if the middle income category invests in such a mechanism.

There is a potential 2 million middle income households, which consume 9.6 TWh/year and are interested to pay for electricity based on green sources. South Africa has a technical potential of 7815 TWh/year. Therefore, there is substantial number of households that is interested in tapping into green source electricity, and South Africa should create an enabling environment and policies for such households.

Gauteng and KZN are the highest electricity consuming provinces. We found in Chapter 4 that solar radiation and electricity consumption are the key parameters, which concluded that these provinces have the greatest potential in the country. This is mainly because such provinces are dominated by the construction and manufacturing industries and have high population density. This chapter concludes that Gauteng has the greatest solar PV potential because there is high rate of middle and high income categories that is interested to pay electricity based on green source, which is potentially 12 TWh/year. Furthermore, this province is the highest electricity consumer, which solar PV construction could add value in the diversification of energy mix.

The size of the house and number of appliances determine the electricity consumption pattern. It was found that 66% of the low income residents occupy houses with 3 rooms or less, with 34% being the middle income residents. More than 70%of high income residents occupy houses with 7 or more rooms. With high income category of 7.3% in South Africa the size of the houses would not make significant impact in electricity consumption.

The number of inhabitants in the house has effect in electricity consumption pattern. 60% of the high income residents have 3 or less inhabitants in the household. Moreover, 73% of the middle income category has 7 or more inhabitants in the household. Therefore, electricity consumption would be relatively higher in the middle income category, specifically because this category is 48.3% of the South African population. In the low income category, 52% have 4-6 inhabitants, whilst 19% is 7 or more inhabitants in the households. The electricity consumption is deemed to be relatively low because of the quantity and type of electrical appliances in this category.

The awareness, education and perception of solar PV technology differs from one household income category to another. 43% of the low income category does not know solar PV technology, whilst 49.5% know a little bit about this technology. The low income category is 44.4% of the South African population, and hence the lack of knowledge in such high portion of the country’s population has an overall negative perception of solar PV technology. Similarly, 94% of the low income category would pay for electricity based on the cheapest price despite the source and implication of it. This makes sense because the residents have low income and could not afford high priced electricity based on its source.

The knowledge and awareness of solar PV technology in the middle income category is higher than in the low income. 55% know a little bit about solar PV and 31% know much about this technology. It is worth noting that 25% of the middle income category is willing to pay electricity based on green source rather than cheapest price. Some of the factors that contribute to this level of awareness is the level of education and the jobs that these income groups do. Thus, the FIT scheme is most likely be successful, increase and promote solar PV technology in South Africa because this category comprised of 48.3% of the South African population. The roof-top solar PV installation is probably going to increase based on the following factors in the middle income group:

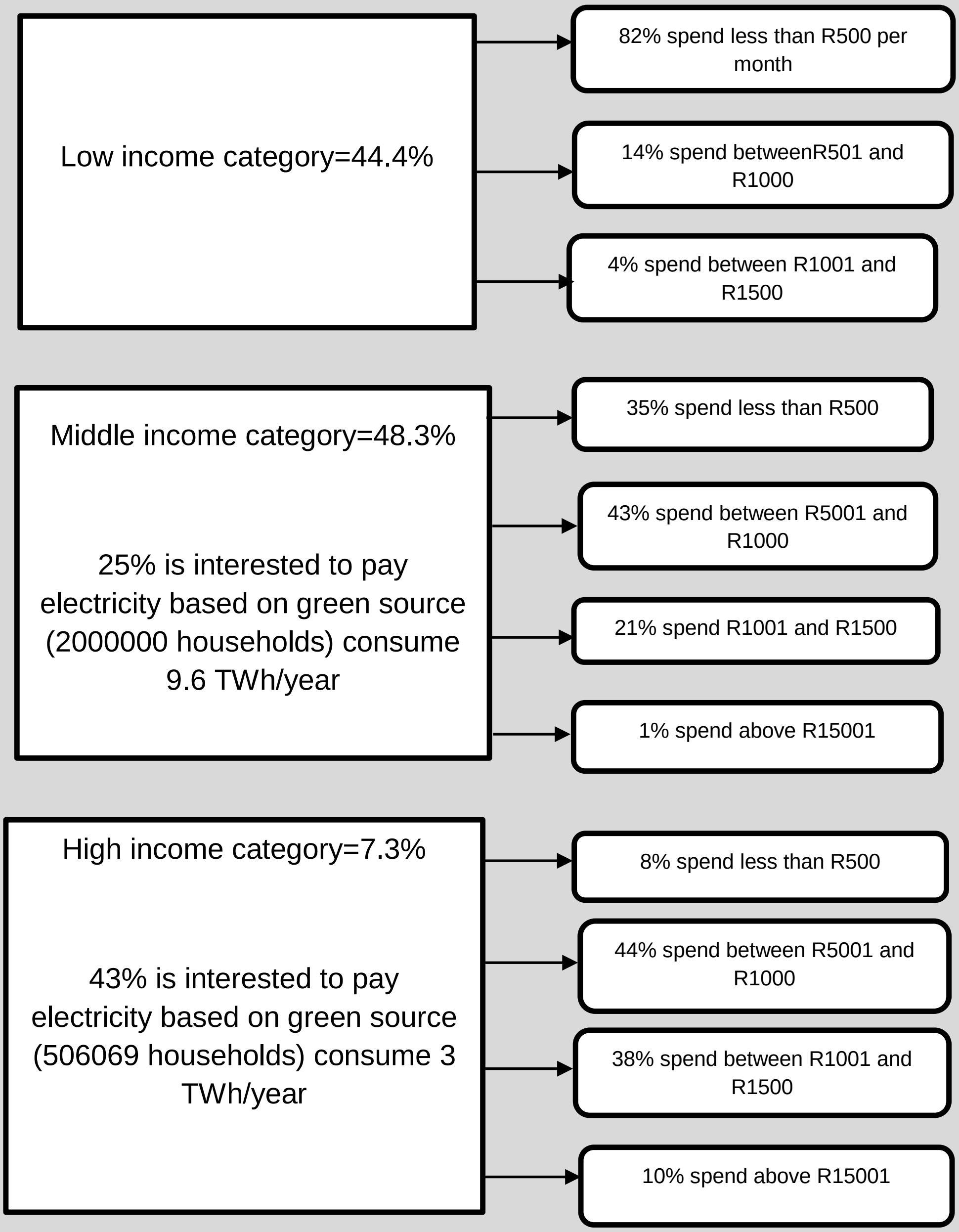
- Relatively higher income compared to low income group;
- Higher knowledge, appreciation and awareness on solar PV technology;
- High willingness to pay electricity based on source; and
- This is a target group for installers

Less than 10% of the high income category does not know solar PV technology, then the rest is aware of the technology. This is the case because 43% of the high income category is willing to pay electricity based on the green source rather than cheapest price. Nevertheless, 52% are willing to pay electricity based on cheapest price. Similarly, to the middle income category, the FIT scheme would be successful because there is substantial amount of population that is willing to pay electricity based on green source

This chapter is summarised as follows:

- South Africa comprised of 44.4% of low income, 48.3% of middle income and 7.3% of the high income households
- There is a potential 2 million middle income and 506069 high income households, which consume 9.6 TWh/year and 3 TWh/year respectively and are interested to pay for electricity based on green sources.
- 45.5% and 28.6% of high income and middle income categories are based in Gauteng province, therefore, this province has the greatest solar PV potential.
- Household income level determines electricity consumption. On average, approximately 82% of low income households spend less than R500 per month on their electricity bill, this translate to less than 300 kWh consumption per month
- 43% of the middle income households spend between R500-R1000 on their monthly electricity bill, whilst 35% spend less than R500 per month. In the high income households, 44% spend between R500-R1000, whilst 38% spend between R1000-R1500 on their monthly electricity bill

- The total electricity consumption is relatively high in the middle income category, specifically because this category is 48.3% of the South African population. In the low income category, 52% have 4-6 inhabitants, whilst 19% is 7 or more inhabitants in the households. The electricity consumption is deemed to be relatively lower because of the quantity and type of electrical appliances in this category.
- The electricity consumption per income categories and potential of solar PV is summarised as follows:



The average household electricity demand is as follows:

$$Electricity\ demand = Low\ (7158168^{16}) + Middle\ (7786926^{17}) + High\ income\ (1176906^{18})$$

= 300 KWh/month + 400 KWh/month + 500 KWh/month

= 2147 GWh/month + 3114GWh/month + 588 GWh/month

= 5849 GWh/month

= 70188 GWh/year

- 43% of the low income category do not know solar PV technology, whilst 49.5% know a little bit about this technology. The low income category is 44.4% of the South African population, and hence the lack of knowledge in such high portion of the country's population has negative perception on solar PV technology
- The knowledge and awareness on solar PV technology in the middle income category is higher than in the low income. 55% know a little bit about solar PV and 31% know very much about this technology.
- 25% and 43% of the middle income and high income categories respectively are willing to pay electricity based on green source rather than cheapest price.
- The FIT scheme is most likely be successful, increase and promote solar PV technology in South Africa because this category comprised of 48.3% of the middle income category in the South African population. The roof-top solar PV installation may probable be the best way of PV installation at a residential sector

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[16] Number of low income households

[17] Number of middle income households

[18] Number of high income households

CHAPTER 7: BARRIERS, RISKS AND OPPORTUNITIES IN THE SOLAR PV ENERGY IN SOUTH AFRICA

7.1 Introduction

The renewable energy sector has been identified as one of the strongest contenders to improve energy poverty among billions of people that do not have access to modern forms of energy across the world (Painuly, 2001). The supply of energy is critical in the socio-economic growth of societies across the world (Doner, 2007). In a society where communities do not have access to modern energy, even a small wind turbine, solar PV and battery storage system can make a substantial difference to the quality of people’s lives. Therefore, modern energy is a necessity that all citizens should have to advance their livelihood.

The international trend in utilisation of renewable energy resources such as solar PV, wind generation, small hydro and biomass generation for rural electrification remains low. Many factors cause the slow pace of rural electrification, such as the cost of grid extension to remote areas, a limited state budget for electrification and a high rate of population growth (Franz *et al.,* 2014). Among many renewable energy resources, solar energy systems are an ideal solution for rural electrification in view of abundant solar radiation and significant wind availability near many rural communities (Bekele and Tadesse, 2012). However, the generic major hurdles for the implementation and operation of the stand-alone, mini-grid solar PV energy system are factors related to socio-economic, policy, regulatory, economic and financial constraints (Franz *et al.,* 2014).

Despite substantial solar PV potential, technological development and economic viability in South Africa, as discussed in Chapters 4, only a small fraction of solar PV energy has been tapped thus far, and it has made an insignificant and minute contribution to transforming people’s lives. This is due to the existence of many barriers, ranging from technical, economic, social and technological ones to institutional arrangements. The need to enact policies and strategies to support renewable energy is often attributed to a variety of barriers or conditions that hamper investment (Beck and Martinot, 2004). The South African dependency on fossil fuel and importation of oil is an economic and security concern. Solar energy technology has faced significant challenges, though it has been anticipated to make a substantial contribution in the energy mix (Philibert, 2006).

7.2 Data collection approach

Solar PV technology comprises two types, namely grid-connected and off-grid. Some of the barriers and risks for these types may not be the same, mainly because the grid-connected projects are managed through competitive bidding for the IPPs by the government of South Africa, whereas the off-grid type is not led by the government, but rather the IPPs, mainly for own generation and/or private sale.

The data for the solar PV barriers was collected through questionnaires and interviews from the stakeholders' representatives including residents, government and generators (Appendix A, C and D). As discussed in section 3.3.1 (Primary data) of chapter 3. The data for the solar PV risks was collected from the generators through a questionnaire and interviews (Appendix D).

7.3 Barriers for solar PV energy

The solar PV sector (grid-connected and off-grid) has not yet developed to the extent that it should have been by now, especially taking into account the electrification backlog, lifespan of fossil fuels and environmental concerns across Africa in general, and South Africa in particular. This is evident taking into consideration the fact that South Africa generates more than 90% of its energy from fossil fuels. The challenges that hamper the growth and development of solar PV energy differ from one sector to another. The residential, generators, government and solar PV installers/suppliers sectors operate in the same space but fulfil different functions and roles in the solar PV industry.

7.3.1 Solar PV energy

This research found that South Africa faces barriers that are prevailing in different sectors within the solar PV industry. Nevertheless, some challenges cut across different sectors. Table 7.1 summarizes the solar PV barriers affecting different sectors.

Table 7.1: Barriers of the solar PV energy

Stakeholders	**Barriers**	**Barrier definition**
Generators Government	Financial	Lack of financial assistance for the Grid and off-grid IPPs as either loans, debt or equity. High capital cost for the off-grid is a barrier. Government REIPP procurement programme only caters the grid-connected, hence no financial support for the off-grid system
Residential Generators Government	Social, education and awareness	Lack of education and awareness about the solar PV potential. Vandalising of the solar PV infrastructure, unemployment and crime are major drivers for the social barrier. Reliability and stability due to seasonal fluctuation for the off-grid system is viewed as high risk.
Generators Installers Government	Technical and infrastructure	Lack of provision for access to the grid network for the IPPs operating outside the government REIPPP. Sufficient grid network infrastructure is required for the South African IPP programme.
Generators Installers Government	Variability and intermittency:	The fluctuation of solar radiation due to seasonal variation and daily cloud cover is a barrier for the off-grid solar PV. The variability and intermittency introduce problems around the voltage regulation, frequency regulation, reverse power flow, harmonics and under- and over-loading of the feeders
Government Residential Generators	Administrative and regulatory	The introduction of competitive bidding benefits the generators only and exclude other sectors such as residential, the absence of REFIT makes it almost impossible for the residential and other sectors to participate in the solar PV power generation sector as there is no government guarantees and PPA
Government Installers	Training and skills	Introduction of FETs and vocational studies to produce artisans and engineers, however lack of established institutions where the graduates can perform the in-service trainings

The challenges faced by the solar PV role players (PV installers, government, generators and residential sectors) in South Africa are as follows:

- **Administrative and regulatory barrier**

The government, residential and generator sectors expressed concern regarding the administrative and regulatory set-up in South Africa. The specific concern being the following:

  - Administrative barrier: The government and generators pointed out that the process of obtaining authorisations (Atmospheric emission license; water use license; waste license; and generation license) is lengthy and not properly coordinated. The residential sector expressed concern around the introduction of competitive bidding that benefits the generators only and excludes other sectors such as residential, which could potentially benefit through roof-top solar PV for power use as in Germany and the UK; and
  - Regulatory barrier: unavailability of the FIT came is the major barrier for the residential and generators sectors. As explained in Chapter 6 that there is a great potential for the middle and high income categories to tap into the solar PV market in South Africa should a suitable FIT mechanism be established.

- **Social dimension, lack of education and awareness**

The government, generators and residential sectors pointed out social factors, the lack of education and awareness were significant barriers for solar PV energy development in South Africa. We found in Chapter 6 that some community members, especially the low income group are not interested in solar PV projects because of lack of education and awareness. The sectors are affected by social factors, lack of education and awareness barrier in the following ways:

  - The generators: social factors such as poverty and high unemployment results in community members vandalizing the solar PV infrastructure for various reasons such as selling stolen parts.

  - Residential: Lack of education and awareness on solar PV energy results in vandalizing of the solar PV projects. Addiction to drugs and alcohol result to different kinds of crime, including vandalising of properties, to make money in order to satisfy the addictions.
  - Government: Theft of the solar PV equipment especially in low income group due to lack of awareness and education as well as high rate of unemployment is a concern.

The Social dimension, lack of education and awareness challenge is common in Africa. Other African countries such as Nigeria have the same challenge, the level of solar energy awareness and education, especially in terms of socio-economic and environmental benefits, is low in Nigeria. The flow of information on the development, various applications, dissemination and diffusion of solar energy resources and technologies is inadequate. There is insufficient education and awareness of solar application among community members, for example about roof-top systems (Ohunakin *et al.,* 2014). This makes solar energy infrastructure vulnerable and prone to theft, vandalism and damage.

- **Skills, training and capacity building**

Both government and PV installers sectors are concerned by the fact that there is a limited number of qualified engineers/artisans that install solar PV systems at a reasonable cost in South Africa. Furthermore, there are other installers that inflate the labour cost for the solar PV installation, which makes solar PV generation unaffordable and unattractive to consumers, especially in the residential sector. The installation price is not regulated. Mulaudzi *et al.* (2012) found that there is a need for capacity building, training and skills development in South Africa. The country’s Further Education and Training (FET) institutions should train students and enhance skills development to produce qualified engineers and artisans. This will help the country to advance the solar PV sector in the near future.

- **Technical and infrastructural barriers**

This barrier affects the generator, government and PV installers sectors negatively in the following ways:

  - Government: the concern is that most of the successful IPP procurement bidders have sites in the Northern Cape and the Eastern Cape Provinces. This has an impact on grid network stability because the power generated would ultimately be fed into the utility grid network in a localized fashion far from where the users are. The Eskom Transmission Development Pan (TDP) intends to absorb electricity that is (to be) generated by private generators, IPPs and Eskom. Hence, the clustered IPPs in two provinces have the potential to cause grid instability and technical faults. This has huge implications for the upgrading of transmission lines and stabilisation of the grid capacity.

  - PV installers and generators: these sectors require a reliable grid network. Then, the transmission and distribution of electricity would require sufficient network infrastructure, such as reliable grid capacity and stability, reticulation, sub-stations or mini-substations to absorb power generated from any plant (solar PV included). This depends on many variables, such as the capacity of the grid network and the proximity and availability of the grid network in the area (Miller and Lumby, 2012). In many cases, mostly in developing countries, infrastructure barriers become a challenge in remote and small-scale grid-connected renewable energy installations such as solar PV projects because there is little demand and it is expensive to establish the network in remote areas (Ölz and Beerepoot, 2010).

Some grid networks in South Africa are not reliable, especially those used by some local municipalities, and this affects power transmission (Table 7.1). Some transmission and distribution network lines do not have sufficient capacity to handle power production of a particular MW amount from the IPPs. Some solar PV projects are located in isolated remote areas. The distance from the generation plant to the grid network is one of the key elements in the viability and success of a grid-connected solar PV project. The technical and infrastructure barrier has a negative impact on the generators/IPPs that are outside the South African procurement programme.

- **Financial barrier**

This barrier affects the generators and government sectors. It requires government decision regarding making a financial assistance mechanism available to the generators. The generators, especially smaller IPPs, are concerned about the financial barrier. The South African IPP procurement programme was implemented through a bidding process, with the successful bidders signing the PPA on access to the grid network with the government. The capital cost for the implementation of solar PV is high. Bigger international IPPs and smaller local IPPs are involved in the bidding process. The bigger IPPs out-competed the smaller ones during the bidding process because they were richer and bid at a lower tariff than the small ones. The big IPPs have higher competitive bidding prowess and create a barrier for smaller IPPs. Lack of financial assistance makes the IPP procurement programme favour bigger IPPs and it becomes unfavourable for smaller IPPs.

The South African government made an effort to accommodate smaller IPPs by establishing a bidding window specifically for capacity of less than 10 MW. This was to enable smaller local IPPs to participate in the renewable energy sector and contribute to the economic development of South Africa. Nonetheless, many more such efforts are needed to level the playing field and enable both smaller and bigger generators to fairly compete.

- **Variability and intermittency**

The government, generators and PV installers are concerned about the variability and intermittency at supply and demand. The concerns from specific sectors are as follows:

  - Generators and PV installers: the fluctuation of solar PV output power due to the variation in solar irradiance is one of the major problems for grid integration.

The seasonal variation of solar output, as discussed in Chapter 4, section 4.3.5 (Monthly and seasonal variation impact of solar PV output), could affect the grid power system negatively, especially on the distribution side. This is the case because the proliferation of PV power to the distribution system introduces problems with voltage regulation, frequency regulation, reverse power flow, harmonics and under- and over-loading of the feeders (Shah *et al.,* 2015). Consequently, the fluctuation and seasonal variation give an impression that solar PV is not a good power source.

- Government: solar energy is a variable resource and its availability varies and fluctuates over time throughout the day and in different seasons. Sunshine duration in South Africa ranges from 9-11 hours a day in summer to 7-9 hours a day in winter. Electricity output from off-grid/stand-alone solar PV power plants will consequently vary in accordance with the season and cloud cover during the day, while the demand does not follow a similar pattern. According to the government of South Africa, this is one of the barriers to meeting the power demand in a given location. The residential sector, especially low income group gets an impression that solar PV is not a reliable source of energy, which is exacerbated by lack of education and awareness.

- Generators: there are challenges on both the transmission (and sub-transmission) and the distribution level. The drastic change in PV output at a given time due to moving and thick clouds is one of the major problems in the secondary distribution system. However, on the transmission and sub-transmission level this is minimised by the natural averaging effect due to the installation of PV plants over a vast area (Shah *et al.,* 2015). Hence, as any drastic change in PV output affects power generation process badly, and contributes to low power output, there is an issue in the early stage of solar PV implementation as this averaging effect is not established. This provides an entry barrier for the technology into the energy market.

7.3.2 Mitigating measures for solar PV energy

There are mitigating measures to address the barriers identified in section 7.3.1. The introduction of such measures would aid to curb and eliminate the barriers. The recommended measures are as follows:

- **Introduction of renewable energy tariffs**

The government should introduce renewable energy tariffs to unlock the solar PV potential from IPPs that were not successful from the REIPP programme and the rooftop solar PV energy generation potential (mainly from residential and commercial sectors) in South Africa. The grid-connected solar PV potential is limited by the land space in some provinces such as Gauteng. However, the residential sector could significantly contribute through rooftop solar PV generation and sell the surplus power to the grid network. This study found that most of the middle and high income residential sectors are willing to venture into solar PV power generation for their own use and sell the surplus to the grid network. Moreover, 25% and 43% of the middle and high income groups are willing to pay for electricity based on its green source.

- **Streamline the process and duration of authorisations**

The time taken to obtain authorisations has contributed to the slow uptake of renewable energy technologies, especially for large-scale renewable energy projects. The government should find a way to prioritise and streamline the process of obtaining the required authorisations while ensuring that the environment is protected in such developments.

- **Intensive education and awareness**

Most of the social dimension challenges are due to lack of information, education and awareness of the benefits of solar PV projects. It has been established that when community members are not aware of the benefits to be derived from the solar PV projects they do not claim ownership and the project becomes vulnerable to theft and vandalism. Chapter 6 found that more than 50% of the low income category do not know anything about solar PV technology. This category constitutes 44.4% of the South African population. Education and awareness are crucial in ensuring that community members know of the benefits of solar PV projects and protect such infrastructure. Both government and other stakeholders should rollout intensive solar PV education and awareness, especially in the low income group.

- **Financial assistance**

Funding is key to the development and implementation of solar PV projects. The PV projects start with development, which includes various feasibility and baseline studies, as well as application for authorisations. The second phase is implementation, which includes engineering and construction work. These phases require intensive financial assistance with well-calculated risks. The government and private sectors should work together to fund solar PV energy projects, perhaps through grants or loan guarantees, or long term supply agreement at a favourable rate.

- **More radical and robust support to FET training (skills and capacity building)**

The government provides substantial financial support to the FET institutions, which produce artisans, electricians, engineers etc. Support in the form of bursaries helps to create capacity and skills that are crucial for the manufacturing, construction and maintenance of solar PV plants. More support in terms of bursaries (that would cover tuition, transport, accommodation and a monthly stipend) is crucial to attract more young scholars than is the case right now. However, government should consider bilateral and multilateral agreements with other countries that have good reputation on engineering, and fund students to study in those countries to acquire skills and expertise. For instance, the same arrangement that is happening on medical studies where the South African students are funded to study in in Cuban universities could be applied for solar PV with suitable partners.

- **Institutions for skills development (such as apprentice or job training)**

One of the barriers regarding the skills and capacity development by the FET institutions is that some learners complete the classroom work and do not get an opportunity to embark on an apprenticeship and job training for a sufficient period (one or two years) to become fully employable. Sometimes learners study in class rooms and do not get any opportunity to do practical or apprentice to get practical work experience. It is crucial for government and the private sector to adapt the education sector training authority to ensure the uptake of students who have completed class work at FET institutions into apprenticeships and job training in different firms and industries in order to enhance and improve their skills.

- **Initiatives to support off-grid projects (counter the REIPP procurement programme)**

The government has initiated an excellent programme of REIPP, which ensures that successful bidders/IPP secure PPAs at an agreed tariff for grid-connected renewable energy projects with access to transmission network. A similar initiative should be established for off-grid energy system, through which the IPPs could secure PPAs for the power to be generated. Such support is crucial to uplift and promote the IPPs that would like to embark on off-grid energy system projects in remote areas.

- **Local economic development and job creation**

Most of the social dimension challenges, such as crime related to drug addiction and alcohol abuse, which lead to a high rate of theft, are caused by the poor local economy that leads to poverty and a high rate of unemployment. To address the challenge of theft and vandalising of infrastructure, the local economy should grow to produce more economic and job opportunities. In part, this may come from the business opportunities raised by the installation and maintenance of solar PV systems. The encouragement of local business formation by the local government will be a critical part of this.

7.4 Risks for the solar PV energy

Solar PV, like any other infrastructural related projects, involves risk in one way or another. Renewable energy technologies in South Africa are fairly new and still in an infancy stage. They lack maturity and this leads to high volatility, posing a high risk associated with the development, implementation and growth of renewable energy technologies (Pegels, 2010). A risk refers to the magnitude of harm expected to occur at a given time consequent to a specific event such as an accident, fire, flood, hail damage, theft, vandalism and other activities affecting the solar PV component. Therefore, a risk is a situation where there is an adverse or severe deviation from the expected, planned or desired results (Vaughan, 1997). Hence, it is a combination of circumstances in the external environment where there is a possibility of loss.

The magnitude of risk is determined by the level of the likelihood of its occurrence and the impact it would have if and when the risk occurred (Vaughan, 1997). Statistically, the level of risk can be calculated as the product of the probability that harm will occur (e.g. that an accident will happen), multiplied by the severity of that harm (i.e. the average amount of harm or more conservatively the maximum credible amount of harm). In practice, the amount of risk is usually categorised into a small number of levels because neither the probability nor the severity of harm can typically be estimated with accuracy and precision.

Then, this is an uncertain condition; the risk may or may not occur. However, if it occurs, it will have either a negative effect on the solar PV energy projects (Chapman and Ward, 2003). Risk assessment is critical for the success of any project; it is a systematic, efficient and effective way of identifying risks and deriving the mitigating measures to prevent, reduce or manage them.

The probability of harm occurring in the solar PV is categorised into certain, likely, rare or unlikely. Similarly, the severity of the harm is classified as negligible, marginal, critical or catastrophic (Table 7.2). In this study, the risks are classified as low, medium, high and extreme.

The classification of risk corresponds to the impact and likelihood, e.g. low risk would be marginal in terms of its impact and unlikely in terms of occurrence. Similarly, the risk would be high if the impact is critical and probability is either rare or likely (Table 7.2).

Table 7.2: The risk matrix template

Probability\likelihood	**Severity/impact**				
		Negligible	**Marginal**	**Critical**	**Catastrophic**
	Unlikely	Low	Low	Medium	High
	Rare	Low	Medium	High	Extreme
	Likely	Low	Medium	High	Extreme
	Certain	Medium	High	Extreme	Extreme

The risk data was collected from generators taking into consideration their experience as far as the power generation projects are concerned. A risk template was developed which the generators were requested to complete (Appendix D). The categories of risks in the solar PV projects are as follows:

- Financial and business risk;
- Technical risk;
- Pre-completion risk;
- Post-completion risk; and
- Social and natural risks.

Based on the risk matrix for the development and implementation of solar PV project analysis, the solar PV projects are regarded as high-risk business because none of the risk factors is low or medium. In fact, they are mostly high and extreme, where the severity is critical and catastrophic and the probability for occurrence is not likely and rare (Table 7.3). The social and natural risk is more likely to occur and the severity is more marginal. The pre- and post-completion risks are regarded as critical and rare. Nonetheless, they remain high risk in the solar PV sector. Furthermore, the financial risk is high, because the impact is critical and is likely to occur consequent to volatile currency fluctuation and the fluctuation in the international oil price. The technical risk is regarded as extreme, hence the impact is catastrophic and the consequences are dire (Table 7.3). This is because any technical fault may result in failure to generate power and the reliability of the systems has not been demonstrated in the South African environment over the long term.

Table 7.3: The risk matrix for the development of solar PV energy power plants

		Severity/impact			
		Negligible	**Marginal**	**Critical**	**Catastrophic**
Probability\likelihood	**Unlikely**				
	Rare			Pre- & post completion risk	Technical risk
	Likely		Social and natural forces	Financial and business risk	
	Certain				

The afore-mentioned risk categories (depicted in table 7.3 above) are further sub-divided into various sub-risks and analysed taking into consideration the probability of their occurrence and possible level of impact (Table 7.4). The mitigation measures and risk techniques are shown in table 7.4 and equally discussed as follows:

7.4.1 Financial and business risk

- **Interest rates:** The interest rate fluctuates over time and is dependent on the international market variation, and this is the risk borne by an interest-bearing loan. The interest fluctuation can negatively affect the financial status of the generators. This risk is high, as the probability of occurrence is likely but the impact is marginal (Table 7.4).

- **Solar PV is a new business set-up:** The solar PV industry is new; few companies in South Africa have a long history of operating in this renewable energy sector. Therefore, there is no extensive operating experience of more than 20 years concerning projects of this nature. Hence, the probability of failure or persistent breakdown is likely. Similarly, this risk is high, the probability is likely and the impact is critical (Table 7.4).

7.4.2. Technical risks

The risk level of the technical sub-risks is depicted in table 7.4. The technical risk comprises the following components:

- **Solar module and efficiency:** There are various types of solar PV technology with different levels of quality. Some solar PV systems are more efficient than others; the efficiency of some ranges between 5 and 10% while that of others ranges between 12 and 20%. There is a risk of gradual reduced solar PV efficiency over time and this would negatively affect the project as discussed in detail in Chapter 4, section 4.4.6. The risk level is medium, it is critical and rare to occur (Table 7.4).

- **Inverters and cabling:** Over and above the module quality and efficiency, the overall system of the PV power plant should be designed correctly. This ensures that maximum power reaches the grid based on the gross irradiance reaching the modules. The technology and choice of manufacturer for the inverters are crucial to ensure trouble-free operation suitable for the environment and design of the PV plant. The system design is important as any error could result in significant power loss. This is a high risk in the solar PV project. Its impact is critical and it is likely to occur in some projects (Table 7.4). As experience in the technology increases, this risk will be reduced.

- **Technology failure:** The generation of electricity involves mechanical and electronic processes. Failure could occur in certain conditions, leading to loss of revenue and repair or replacement costs. The installation should be done correctly. This is extremely high risk because its impact is catastrophic should it occur.

- **Solar irradiation:** Changes in weather patterns and conditions, such as cloud cover, rainfall and heat waves, could reduce the expected energy output, and hence render the power plant financially unsustainable and a failure. This risk is high because it is likely to occur but its impact is marginal in the solar PV projects since such changes are short term or occur slowly.

- **Solar module degradation:** The efficiency of solar modules, as well as their degradation (loss of performance), has a direct effect on the performance of a solar PV plant. The supplier (usually less than 1% per year) normally indicates the degradation. The degradation rate can go up to 16% in a particular year of the project (Jordan and Kurtz, 2013). This is extreme risk because its impact is catastrophic but it is rare to happen. The risk is that if it happens it would severely affect productivity. Improving the long term efficiency of sola modules remains a research issue for the manufacturers.

- **Permits:** Various authorisations are required for the development and construction of solar PV power plants. The permits include an environmental impact assessment, water use license, waste license and generation license. Delays in obtaining these permits can be a serious risk. This is a high risk because the delay in obtaining the permits is likely to happen, and the project will not start before the authorizations are obtained.

7.4.3. Pre-completion risk

The pre-completion risk comprised of the following sub-risks:

- **Overspending (cost overrun):** The project budget usually comprised 10% contingency for any other items/materials that might not initially have been included or price increases for some unexpected reasons, e.g market related inflation. Yet, some projects do exceed the allocated budget. For example, the Medupi coal-fired power station in South Africa has exceeded the initial budget by more than 20%. Moreover, inflation and the country’s unstable currency may result in overspending. This risk is extremely high because it has a potential of stopping the project. Its impact is catastrophic and it could happen in any solar PV project.

- **Delays in completion (delivery of materials, employees' strikes etc):** The completion of many projects is delayed by aspects such as delays in the delivery of materials or employees embarking on industrial action for wage-related matters (this occurred at Medupi coal-fired power station). Many things could cause delays in the development and construction of solar PV projects. This is a high risk because it is critical and is likely to happen, as it did in Medupi coal fired power station.

- **Availability of stock/material:** Solar PV power station projects require materials to be available on site and stock to be available at all times, otherwise delays are likely. Materials being delivered late from the warehouse to the store or on-site delay many projects. In some cases, stock is brought to site as and when needed to prevent it from staying on site for long, as it stands a risk of theft. This is high risk because its impact is critical, however, it is rare to happen.

- **Employees' injuries on duty (IOD):** The development of power station projects is likely to cause some injuries. Occupational health and safety programmes and systems should be in place and strictly implemented to avoid injuries on duty, as this delays the completion of projects. This is high risk because there have been injuries and casualties in some power generation projects. In 2014/15 financial year, Eskom had 10 fatalities (employees and contractors) in different power stations. The main causes were vehicle accidents, electrical contact, caught between or under objects, struck by an object (Eskom, 2015). Therefore, solar PV systems roof-top installation can increase the risks of injury related to falls.

7.4.4. Post-completion risk

The post-completion risk comprises of the following sub-risks:

- **Market risk:** Changes in regulations may have adverse impact on the solar PV power plant. Changes in the renewable energy policy could reduce the forecast revenue and profits of new projects. Inflation may also affect the project badly financially. This is a high risk; it is rare to happen. South Africa initiated the REFIT is 2008, and changed to the competitive bidding in 2010. Therefore, market risk is high in South Africa.

- **Changes in legislation:** Though the IPP would have signed a 20 years PPA, a drastic change in legislation due to other factors, such as major financial and economic changes, can result in loss of value for the country's currency and the IPP may suffer serious loss of revenue. This is a high risk, its impact is critical and may affect the solar PV projects severely negative.

- **Operation and maintenance (O&M):** Every solar power station involves O&M, which is in most cases outsourced to contractors who have to carry out day-to-day maintenance. Inefficiencies in the operation and management of the project could reduce the energy output and cause loss of revenue. This is a high risk because it is likely to occur but its impact is marginal. The O&M risk is likely to affect the project negatively and interfere with the anticipated and projected production. This would reduce the revenues obtained from an operating solar PV system in a given year.

7.4.5. Social and natural risk

The social and natural risk comprised of the following sub-risks:

- **Theft and vandalising of infrastructure:** One of the lessons learnt from the pilot project on the hybrid energy system in South Africa was that it showed a high rate of theft and vandalising of the infrastructure. Vandalism and theft are high risks to solar PV and hybrid systems in South Africa as there is a resale value for the materials. This is a high risk, its impact is critical and is likely to occur as theft is one of the major problems in South Africa.

- **Floods:** A flood is an overflow of a large amount of water beyond its normal limits, especially over what is normally dry land. This situation has huge potential for sweeping everything away on land. In view of the weather pattern and climate change, where hailstorms have been experienced in South Africa, floods are likely to occur and would have the potential to cause severe and irreparable damage to solar power stations. Impact from hailstones would be similarly damaging (see the next section). Natural risks such as floods are rare; however, rainfall in 2015 in South Africa has resulted in flooding in some areas. The area/location where a plant is to be built should be on high land and in dry areas where rainfall is low. Peripheral and riparian zones should be avoided, as they are vulnerable to flooding. This is extreme risk, its impact is dire and catastrophic.

- **Hailstorms:** Hailstorms have been occurring in South Africa since 2014. Weather and climate records show that the last time severe hailstorms were experienced was over 50 years ago. The hailstorms have damaged people's properties, such as houses, vehicles and factories. This is a natural risk to solar power plants in South Africa.

  The recent weather pattern in South Africa has resulted in hailstorms that have caused severe damage. This risk is likely to occur any time in any area or location across the country. The consequences are critical, as the stones may break and damage solar PV panels and wind turbine blades. Therefore, the plant may stop operating, resulting in no power being generated, and major repairs may be required that need massive finance. This is a high risk because its impact is critical.

- **Fire:** Natural fire caused by lightning has been occurring in agricultural fields, nature reserves, national parks and mountainous areas, especially in the Drakensberg Mountains of the KZN Province and in the Western Cape Province. Natural fire in South Africa is influenced by heat waves and lightning. Other types of fire are man-made, where people start fires in livestock pasture that get out of control and damage infrastructure.

  Natural fire has caused severe damage to infrastructure in South Africa. It swept through a private nature reserve in Limpopo Province in 2015, where the shelters and vehicles were destroyed completely. Natural fire is likely to occur in many parts of South Africa, and the impact can be catastrophic, depending on the nature of the fire and the area where it burns. This is extreme risk, its impact is dire and catastrophic.

7.5 Techniques and strategies for managing risks

Section 7.4 illustrated various risks and sub-risks that solar PV is facing. The different level of risks was discussed. This section, however, discusses various risk techniques and strategies for managing the impacts and likelihood of the risks.

7.5.1 Risk avoidance

This technique avoids dealing with projects and activities that might result in the occurrence of risk. Hence, the technique encourages avoiding establishing projects in areas that are susceptible to risks; for example, the Eastern Cape Province has high probability of snow and hailstorms, and therefore it is advisable to avoid areas that are vulnerable to such natural risks in the province. Risk avoidance is a method that deals with risk in a more negative than positive way (Vaughan, 1997). If risk avoidance should be employed extensively in any solar PV energy projects, the power generation sector would be deprived of an opportunity to increase the contribution of renewable energy. This is the case because the solar PV projects can be established in risky areas, provided the design and construction is done in such a manner that prevents and/or reduces damage in case of the natural disasters.

The Northern Cape provinces is relatively dry compared to the coastal provinces. It is susceptible to natural fires and floods. The implementation of risk avoidance strategy involves avoiding the construction of projects in this province, if unavoidable, then establish measures to prevent or minimise the impact and severity of risks should they occur. However, in view of the solar potential it is almost impossible not to establish solar PV projects in this area, as it is viable and has substantial PV potential as described in chapter 4. Hence, it is advisable to establish the plants in areas that are not vulnerable to fire and floods. The Eastern Cape and KZN Province have relatively extensive low income areas, hence they are vulnerable to theft and other social risks. These provinces have good hybrid energy system potential. Thus, it is recommended that the projects be built in areas that have a lower theft rate and that security measures be strengthened.

The risk avoidance technique can be applied in the following risks and sub-risks:

- Technical risk (inverters and cabling, solar irradiance and permits sub-risks);
- Pre-completion risk (delay in completion and unavailability of stock sub-risks); and
- Social and natural risk (floods, hailstorms and fire sub-risks).

7.5.2 Risk reduction

Risk reduction is a technique that prevents the risk of loss of solar PV power, reduces the chances of such loss occurring and controls the severity of the loss if and when it occurs. Nevertheless, prevention is a priority and hence the best means of dealing with the risk (Vaughan, 1997). The pre-completion risk, which includes overspending, delays in completion of the plant, unavailability of materials and employees' IOD can be managed, minimised and prevented through risk reduction technique.

Overspending on the project can be reduced through cost savings and a stringent budget control mechanism. However, project development and implementation depend on many externalities. Delays in completing projects that may be caused by factors such as strikes should be managed carefully and reduced by addressing employees' needs upfront. The transportation and delivery of stock/materials to the site must be planned in such a manner that delay is eliminated.

The risk reduction technique can be applied in the following risks and sub-risks:

- Technical risks (Solar PV efficiency and degradation, inverters and cabling, technology failure, solar radiation and permits sub-risks);
- Pre-completion risk (Over-spending and employees IOD sub-risks); and
- Post completion risk (O&M sub-risks)

7.5.3 Risk retention

The retention of risk occurs when risks are foreseen or known and ultimately not reduced or avoided for some reasons. In most cases, the risks are retained because there is no alternative way of dealing with them, or alternative ways of dealing with them may result in severe loss of power or severe consequences for the solar PV plant, therefore these risks are retained and the loss is managed.

The financial and business risk is well known and sometimes predictable. The interest rate fluctuates over time and the country's stability is key to maintain the value of the currency. It is known that if the South African rand's value goes down beyond a particular limit the country suffers, as the market struggles and loan repayments increase drastically. Consequently, the financial risk is known and definitely retained. Solar PV projects are subject to various risks, including the fact that they have not been proven to have operated for 20 years without a major breakdown. Then, this risk is known and retained.

The risk retention technique can be applied in the following risks and sub-risks:

- Financial and business risk (interest rates sub-risk);
- Technical risk (solar PV efficiency and degradation sub-risk);
- Pre-completion risk (employees IOD sub-risk);
- Post completion risk (market risk and changes in legislation, and O&M sub-risks); and
- Social and natural risks (theft and vandalising of infrastructure sub-risk)

7.5.4 Risk transfer and sharing

Risk transfer and sharing involve transferring risk from the generator to the financier and power distributor. This is usually done through contracts and agreements. The generator may transfer risks to the power distributor and transmission sectors in case if it rains for a month, no power generation as per agreement can occur and the community needs power. This is the most difficult risk management technique, because it involves transferring and sharing risk with another party through contractual obligation.

For the development and implementation of solar PV projects, risk strategy is key for the success of the project and also for securing funds. It is fundamental for the generator to avoid risk. Therefore, good site with minimal natural disaster potentially should be identified for these projects. Where risk cannot be avoided, then it should be reduced, risks such as over-spending, Medupi coal fired power station is a point in case in South Africa, and delays in completion should be reduced and minimised.

Some risks that are unavoidable such as financial forecast should be retained and managed effectively should they occur. Yet some risks such as rainy periods where it could be 100% cloud cover and raining the whole week, meaning that no or limited solar radiation and hence minimum power production, such risk should be transferred and shared with the insurance companies.

The risk transfer and sharing technique can be applied in the following risks and sub-risks:

- Financial and business risk (interest rates sub-risk);
- Technical risk (technology failure sub-risk)
- Post completion risk (market risk and changes in legislation sub-risk)
- Social and natural risk (theft and vandalising of infrastructure, floods, hailstorms and fire sub-risks)

Table 7.4: Risk categories, mitigation measures and risk techniques

Risk	**Sub-risks**	**Sub-risk probability and impact**	**Mitigation measure**	**Risk technique**
Financial and business	Interest rates	Probability is likely and impact is marginal=High risk	The government of South Africa has decided to introduce the competitive bidding as a policy instrument for the renewable energy sector. The problem with the competitive bidding is that it excludes other sectors such as residential to participate in the market. Therefore, a change of policy to REFIT is recommended.	Risk retention, risk sharing and transfer
	Solar PV is a new business set up	Probability is likely and impact is critical=High risk		
	Permit	Probability is likely and impact is marginal=Medium risk	Coordination by responsible organs of state in order to expedite the process of issuing authorizations	Risk avoidance and reduction
Technical	Solar PV efficiency and degradation	Probability is rare and impact is critical=Medium risk	The degradation of PV modules is not yet proven over a long period such as 20 years. The manufacturers should meet the international standards and norms when manufacturing solar PV modules	Risk reduction and retention

	Sub-risks	Sub-risks probability and impact	Mitigation measures	Risk technique
	Inverters and cabling	Probability is likely and impact is critical=High risk	Qualified artisans and engineers are needed. This is linked to training and skills barrier. The correctness of the configuration of solar PV plant and design.	Risk avoidance and reduction
	Technology failure	Probability is rare and impact is catastrophic=Extreme risk	The solar PV equipment must be procured from accredited manufacturer to ensure that equipment are made in accordance with the international standards and norms.	Risk reduction and transfer
	Solar irradiation	Probability is likely and impact is marginal=Medium risk	The changes in weather pattern related to climate change are a major threat. The mitigation factor for this is choice of site where the plant will be constructed should have good solar irradiance of above 6 kWh/m^2/day.	Risk avoidance and reduction
Pre-completion	Overspending	Probability is likely and impact is catastrophic=Extreme risk	Stringent and accurate project cost and time management should be in place.	Risk reduction
	Delays in completion	Probability is likely and impact is critical=High risk	Better planning and good project management are factors that could avoid this risk	Risk avoidable
	Availability of stock	Probability is rare and impact is critical=High risk	Better planning and good project management are factors that could avoid this risk	Risk avoidable
	Employees IOD	Probability is likely and impact is critical=High risk	Implementation of the Stringent occupational health and safety compliance	Risk reduction and retention
Post completion	Market risk and changes in legislation	Probability is rare and impact is critical=High risk	South Africa should retain its strong currency and export market	Risk transfer and sharing and retention
	O&M	Probability is likely and impact is marginal=Medium risk	Efficient and effective maintenance plan and strategy	Risk reduction and retention
Social and natural	Theft and vandalising of infrastructure	Probability is likely and impact is critical=High risk	Implement stringent safety measures and security system	Risk transfer, sharing and retention
	Floods	Probability is rare and impact is catastrophic=Extreme risk	The location for the project should be in areas that are not prone to torrential rainfall and floods	Risk avoidance, transfer and sharing

	Sub-risks	Sub-risks probability and impact	Mitigation measures	Risk technique
	Hailstorms	Probability is likely and impact is critical=High risk		Risk avoidance, transfer and sharing
	Fire	Probability is rare and impact is catastrophic=Extreme risk	The location for the project should be in areas that are not prone to wild fires	Risk avoidance, transfer and sharing

7.6 Opportunities for off-grid solar PV and hybrid renewable system

In the midst of all the identified barriers and risks that solar PV technology is facing, there is a wide range and variety of benefits from the PV technology in South Africa. These benefits have the potential to uplift and stimulate local economic development and growth in the locations that are not electrified in South Africa. Franz *et al.* (2014) discussed various benefits that off-grid and grid-connected solar PV systems offer. These benefits are, nonetheless common in many parts of developing countries. In South Africa the off-grid solar PV energy system has the potential to provide the following opportunities:

7.6.1 Socio-economic development (health, education and small business)

Electric lights alone bring about many benefits, such as extended hours for small business and education (i.e learners' ability to do schoolwork at night and better security due to visibility at night). Another socio-economic benefit is the development, improvement and enhancement of communication, which includes the ability to watch television, listen to local radio stations, use and charge mobile cellular phones, and the use of computers, including internet access in some parts of the rural areas that are not electrified in South Africa.

There are districts and municipalities, which have more than 30% electrification backlog such as Umkhanyakude, Sisonke and Umzinyathi, which could potentially benefit from the solar PV projects. It has been shown that the use of television, internet, radio and cellular phones leads to improved access to news, business information and distance education (Franz *et al.,* 2014). Off-grid and grid-connected solar PV energy systems provide high quality and reliable energy, which provides services such as lighting, heating, communication and education, better health and all-round improvement in the quality of life (Birol, 2014a).

Rural households in many African countries have a limited supply of electricity. The solar PV energy system can contribute to community facilities such as rural clinics and hospitals, as well as water pumping stations, which would enhance the welfare of people and rural development (Nema *et al.,* 2009). In Lesotho, Taele *et al.* (2012) found that the rural off-grid solution resulted in increased enrolment at school and an enhanced culture of learning and teaching with the use of modern technologies. Qualified teachers are attracted to schools with these technologies. Access to equipment such as overhead projectors, television sets, photocopiers and computers has enhanced the culture of teaching and learning in schools (Taele *et al.,* 2012). Then, the solar PV renewable energy system could have a significant role to play in the socio-economic development of many provinces in South Africa.

7.6.2 Communication

The use of television and radios in rural areas facilitates and promotes the ability of business advertisers to reach a wider audience. The Eastern Cape and KZN Provinces have a relatively high electrification backlog, and the off-grid solar PV renewable system would contribute significantly to the socio-economic development of the locations that are not electrified in these provinces.

Furthermore, the off-grid solar PV energy system in remote communities that are not electrified brings an opportunity for many things. The use of computers and the internet, which enable communities to be connected to the world, is vital in any community development. It makes computer businesses such as software development possible and viable.

The use of off-grid solar PV has made a significant contribution in some Asian communities with similar set up as in South African remote villages. Using off-grid solar PV renewable system to supply telecommunications such as radio stations is popular in Malaysia, because some radio stations are located in rural areas in mountainous regions. Small diesel generators already supply large numbers of these stations. The operational costs of these diesel generators are usually high because of high volatility in the fuel price, maintenance and transportation costs (Moghavvemi *et al.,* 2013). A solar PV stand-alone system that is entirely dependent on PV panels and a battery bank to supply such stations is also costly because of the large number of panels and battery units required for this system to cover station load demand in different climatic conditions. A combination of renewable energy sources, such as a hybrid energy system, is a sustainable and reliable solution for these radio stations (Moghavvemi *et al.,* 2013).

7.6.3 Service delivery to the general public

Off-grid solar PV provides significant transformation in the learning environment by providing access to electricity, and therefore results in a better learning environment, as discussed in section 7.6.1. Furthermore, electricity provision would improve people’s health, particularly in the residential sector, because the use of cow dung, charcoal and fuel wood produce emissions, which, in most cases, are the main causes of respiratory diseases. Off-grid electricity would also improve health care through the use of medical appliances such as refrigerators for vaccines.

7.6.4 Rural industrial development

Off-grid solar PV energy systems drive and improve economic development at community and household level. Community members are able to establish micro home enterprises and are able to sell materials that require refrigeration. Moreover, local community members are able to open small businesses such as welding concerns and to sell cold drinks and dairy products.

Shop owners in rural markets in Lesotho have shown significant interest in using small solar PV systems for various purposes, such as lighting their homes and charging mobile phones, which are stimulating rural economies, enabling grass-roots businesses to emerge, creating jobs and driving forward social change (Taele *et al.,* 2012). This leads to an improved standard of living in the community.

7.6.5 Employment opportunities

The solar PV energy system is made up of various components, parts and equipment. These parts are manufactured in the industrial sector. In the implementation and O&M phases of off-grid solar PV/hybrid renewable system projects, there are various role players and activities, which also involve direct and indirect job creation. The industrial sector for the manufacturing of solar PV panels requires inputs from a wide range of sectors such as mining, equipment supply, fabrication, energy supply, plastics, transport services and others (Cameron and Zwaan, 2015). Furthermore, job opportunities become available during the installation/development, operation and maintenance phases. Direct jobs are related to core activities, such as construction, site development, installation and O&M.

There are also indirect jobs that are created in the hybrid energy system sector, including jobs related to supply and support from the renewable energy industry at a secondary level. These jobs relate to the extraction and processing of raw materials, such as the production of copper and steel, marketing and selling, installation and work performed by regulatory bodies, consultancy firms and research organisations (Cameron and Zwaan, 2015). Various solar PV installing companies in South Africa have employed people, which resulted in significant job creation and skills transfer.

7.6.6 Environmental conservation

Most of the rural communities use fuel wood for space heating and cooking largely because they have no electricity and are poor. Rural communities need alternative energy sources to replace their heavy reliance on fuel wood as a primary source of domestic energy (Figure 1). In Lesotho, approximately 40% of the national biomass fuel consumption is wood for cooking (Taele *et al.,* 2012). The extraction of fuel wood is the main cause of deforestation and subsequent erosion. Deforestation destroys the habitat for wildlife species and may result in species extinction.

Figure 7.1: Fuel wood used as a domestic source of energy in Limpopo Province

There are many rural communities in the Eastern Cape and KZN Provinces where community members use fuel wood as a source of energy for domestic purposes. These community members, especially women, are vulnerable to indoor pollution, which causes respiratory diseases. Furthermore, the perpetual cutting down of trees is likely to result in desertification in many parts of South Africa.

7.7 Conclusion and summary

The solar PV technology (both off-grid & grid connected) systems are not only urgently needed to connect the vast number of people that do not have electricity, but are also most appropriate because of geographical constraints and the cost of grid extension in many isolated locations (Kempener *et al.,* 2015). Renewable energy sources for off-grid systems (mini-grid and stand-alone) in South Africa are abundant, including solar power and wind, although for a number of reasons solar off-grid system remains untapped thus far.

The solar PV stakeholders (government, residential, generators and PV installers) are facing different barriers in the energy space in South Africa. The generators and government sectors have the most barriers and urgent attention is needed to address such barriers in order to develop the solar PV technology in South Africa. The barriers that the stakeholders are facing are financial, social, educational regulatory, technical and infrastructure related.

Various mitigating measures are imperative in order to remove the barriers. The introduction of the renewable energy tariff in a form of FIT is crucial, as it has been proven in other countries to be effective. It is therefore recommended that it would increase the penetration of solar PV in South Africa, taking into consideration the fact that residential sector will also tap into the rooftop solar PV. Other mechanisms such as streamlining the process of obtaining permits are key in the government and generator sectors. Financial assistance is needed for the generators to tap into the solar PV market, it is important for government to develop programmes with which the generators would get financial support for the development of solar PV projects.

The biggest threat in the development of solar PV projects is high perceived risk. Solar PV installations have mainly high and extreme risks as the technology is relatively new, especially in South African context. The technical risk is regarded as medium because it has not been proven to generate electricity for up to 20 years in South Africa. Moreover, it depends on solar module efficiency, inverters and cabling, technology failure, solar irradiation and module degradation, and permit sub-risks. The generators must find a balance in managing various risks that are high and extreme. The pre- & post completion risks are high, hence proper and careful planning is essential in the solar PV industry. The social and natural forces risk is medium, hence the generators must consider sharing and retaining such risk. These risks are both rare and likely to occur and the impacts range from marginal to critical and catastrophic.

Various techniques should be implemented in order to prevent or avoid the risks. These are risk retention, avoidance, sharing & transfer and reduction. Risks differ from one factor to another. Some risk requires retention such as social and natural forces, some require sharing and transfer such as financial and business risks. Solar PV projects are implemented on a case by case basis, and the risks and mitigation techniques would differ from one project to another. The generators must conduct strict and stringent risk analysis in order to determine which risk is prevailing and which technique measure to implement in order to prevent and/or minimize such risk. As the technology matures this will become easier but it is a barrier to early implementation.

The solar PV technology, grid and off-grid connected present various opportunities in the community. The opportunities come from the development, implementation and operation of the projects. The implementation of solar PV technology enhances education, health and small business in areas that were not previously electrified. The solar PV off-grid in particular enables the learners to do school work at night and people are able to use computers, the source of energy being the power generated from solar PV. The off-grid solar PV can generate power for rural clinics in order to operate some health care machines. Communication (e.g. the use of radio and television, and ability to charge cellular phones) is another opportunity that arises from the solar PV technology. The employment opportunity is a community benefit from the establishment of solar PV projects.

This chapter is summarised as follows:

- Solar PV stakeholders are faced with several barriers, with the government and generator sectors being the most affected.
- Financial, social, education and awareness, technical and infrastructure, variability and intermittency and administrative and regulatory issues are common barriers hindering the government and generators to advance the solar PV industry in South Africa
- Similarly, over and above the afore-mentioned barriers, the social, education and awareness and the lack of training and skills are the major barriers seen by the residential and installer stakeholders
- The mitigating measures for the above-mentioned barriers are the introduction of the FIT to enable smaller companies and the residential sector to participate in the market, streamlining the process and duration of obtaining authorisations, intensive education and awareness, financial assistance models and incentivising the off-grid and hybrid energy projects to counter the REIPPP
- The technical risk is extremely high, but the financial, pre- & post completion risks are high and the social and natural forces is medium.

- The technical risk is regarded as medium because it encompasses factors such as PV module degradation and technology failure. If these risks occur, the project is likely to collapse
- The social and natural forces risk is medium because it comprised of mainly the theft and vandalising of infrastructure, floods, fire and hailstorms, where the risk can be transferred, shared or retained, and effectively managed in a manner that will have minimal effect and impact on the project
- The technical risk can be avoided, reduced, retained, shared and transferred to a third party. Nonetheless, other risks such as financial and business can be retained, shared and transferred because solar PV systems is at an international market.
- There are various opportunities in the solar PV projects, especially in communities that did not have electricity before. The opportunities include socio-economic development (health, education and small business), communication, and rural industrial development and employment opportunities.

CHAPTER 8: CONCLUSION AND RECOMMENDATIONS

8.1: Introduction

South Africa has abundant potential renewable energy sources, notably solar and wind energy. Much of the potential remains untapped thus far. Various parameters were used to model the solar PV and hybrid potential. It was confirmed that South Africa has massive solar and wind energy potential, which is approximately 7815 TWh/year, mainly from crystalline PV modules. Furthermore, the coastal provinces, KZN and the Eastern Cape, in particular, have good potential to curb the electrification backlog and stimulate local economic development and growth through the implementation of a hybrid energy system, mainly in the remote rural communities that are far from the grid network infrastructure.

Renewable energy sources such as solar and wind energy can contribute to the electricity supply, but this contribution is limited to a maximum of 20% of the country's electricity required according to Ashby, 2015[19]. More than 20% contribution from these sources would require grid-scale storage because of the intermittency and fluctuation of the energy output (Ashby, 2015). This 20% technical upper limit is for the developed countries, however, in the developing economy like South Africa, the technical upper limit could be lower because of the inherent challenges on the grid network infrastructure. It is suggested that grid connected solar PV could contribute less than 8500 MW, which is below 20% of South Africa's power capacity. More than this contribution may result in an unreliable power supply because of intermittency and variability. This gives an opportunity to off-grid solar PV such as stand-alone PV, hybrid energy system and the roof-top PV for own generation.

One of the reasons that makes solar PV more competitive is continuous price reduction (Feldman *et al.,* 2014). In addition, the grid-connected electricity tariff increases annually by an average of 8% in South Africa (Eskom, 2015). Moreover, whilst the PV panels' price is decreasing, their efficiency is improving over time and

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[19] This upper limit relates to reference for an advanced economy grid infrastructure

solar PV generation reduces the environmental footprint of energy generation in the long run. Solar PV reduces the greenhouse gas emissions, and has the potential to aid South Africa to meet its emission reduction commitment agreed in the annual Conference of parties (COP), which is a legally binding agreement as discussed in Chapter 1 (section 1.2). The hybrid energy system would contribute in reducing emissions mainly in summer, because the solar radiation is higher than in winter. In the winter season the hybrid energy system generates more emission due to increased use of diesel generation, and the maintenance and fuel costs increase in the winter season.

8.2: Conclusion

The potential of solar PV and household energy consumption survey chapters concluded that Gauteng province has the greatest solar PV potential. This potential could be supplemented by the installation of rooftop PV; the middle and high income residents are willing to tap into such a market and consume electricity generated from the green source.

Chapter 4 concluded that Gauteng and KZN provinces have good solar PV potential and are ideal for the construction of solar PV plants. These provinces have good solar irradiance and high electricity consumption. Solar PV could add value in the diversification of energy mix.

Chapter 6 found that 25% and 43% of the middle and high income households are willing to pay for electricity based on a green source. This therefore, means that such residents are willing to utilize electricity generated from solar PV plants. Moreover, the greater number of such middle and high income households are in Gauteng and KZN provinces. Nevertheless, Gauteng alone has 45.5% and 28.6% of the high income and middle income categories respectively. Thus, Gauteng is recommended as the province with greatest solar PV potential taking into consideration the findings in chapters 4 and 6.

Over 25% of electricity in South Africa is consumed in Gauteng Province, hence this province is recommended for the construction of solar PV power plants and rooftop installation for the following reasons:

- Gauteng has good solar PV potential as concluded in chapter 4;
- It has high number of high and middle income households, of which 25% and 43% are interested to pay for electricity based on a green source, which is potentially 12 TWh/year;
- Construction of PV plants and rooftop solar PV would reduce electricity loss due to long distance transmission; and
- There is high consumption of electricity in this province

There is good renewable energy potential in South Africa. However, these technologies (renewable energy) will not replace fossil fuels soon. Fossil fuel, notably coal, will remain the main source of electricity for the foreseeable future, taking into consideration that South Africa is one of the two countries in the world that generate more than 90% of electricity from coal. Despite this, solar PV growth and development will continue, mainly stimulated by the price reduction over time and improved efficiency with a low degradation rate of more recent solar panels.

Reliance on coal resource continues in current and future energy systems across the world in general, and South Africa in particular. The options for South Africa are as follows:

- Continue using coal for power generation;
- At the same time, whilst utilizing coal, expand and increase the share of renewable energy in the total energy mix, both grid connected and off-grid;
- Prioritize Gauteng province for the establishment of solar PV plants and installation of rooftop PV;
- Implement mitigation measures as outlined in section 7.3.2 of chapter 7, and as concluded in Chapter 4;
- Review the regulations and introduce FIT in order to allow middle and high income groups to generate power through roof-top PV for own use; and
- South Africa should explore the replacement of electric geysers with boilers,

The hourly solar PV output does not match the load profile pattern in South Africa. The hours in which electricity consumption is high (early hours in the morning and later on in the afternoon) are hours where PV is not generating maximum power. Therefore, there is no match between hours the peak hours and PV maximum power generation hours. Similarly, there is significant mismatch in the seasonal power production and consumption. Solar power production declines in winter, yet the power consumption increases in winter. Clearly, there is a need to solar PV power generation storage in order to reduce the mismatch for the hourly and seasonal power consumption and production.

Solar PV power generation would contribute significantly to energy security, address environmental concerns and diversification of energy resources in South Africa. Moreover, solar PV technology has the ability to aid the country in meeting the greater part of its renewable energy target. Equally, solar PV would play a crucial role in enabling the country to meet its international obligation on emission reduction targets. Thin-film modules could generate up to 4884 TWh/year, while the crystalline modules could generate up to 7815 TWh/year (Chapter 4, section 4.4.1.1, and figure 4.10). This technical resource has massive potential to offset carbon footprint.

The fossil fuel lifespan remains the most significant energy threat and concern, especially in the South African energy profile, where the country is heavily reliant on such resources. Fossil fuel consumption is high with no indication of this declining (Figure 8.1). Nonetheless, South Africa should continue with the research and pilot projects on the Underground Coal Gasification (UCG). It could contribute to reducing the environmental impact while using the extensive coal reserves more effectively. It is estimated that the UCG could increase the country’s recoverable reserves by as much as an additional 45 billion tonnes (Sasol, 2012). Yet, this is another opportunity for South Africa to tap into the clean coal technology, which would extend the lifespan of coal while reducing GHG emission and pollution.

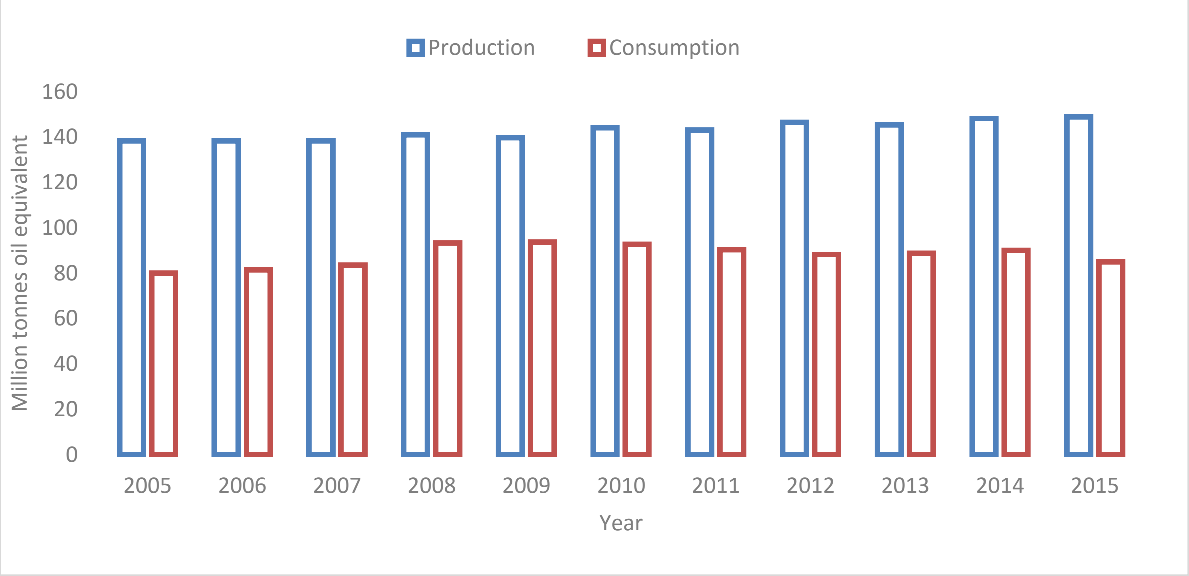

Figure 8.1: South African coal production and consumption (Source: Dudley, 2016)

In the residential sector, there are currently 2 million households, which consume approximately 10.8 TWh/year. These households are interested and willing in paying for electricity based on the green sources. South Africa has a solar PV technical potential of 7815 TWh/year. Therefore, this demand is a substantial number of households that are interested in tapping into green source electricity could easily be met. Nonetheless, South Africa should create an enabling environment and policies for such households to tap into the renewable energy market. The solar PV awareness and willingness to pay for electricity based on the green source is higher at the middle and high income groups, which constitute 56% of the South African population (StatsSA, 2015a). This group could make a substantial financial impact in the country meeting its renewable energy targets.

Based on the high level of knowledge and awareness of solar PV in the middle and high income groups, the FIT scheme is most likely be a successful method to increase and promote solar PV technology in South Africa. The roof-top solar PV installation is probably going to increase based on the following factors in the middle income group:

- Relatively higher income compared to low income group;
- Higher knowledge, appreciation and awareness on solar PV technology;
- High willingness to pay for electricity based on source; and
- Ownership of location where solar PV is installed.

8.2.1 Solar PV

There is massive solar PV potential in Gauteng, KZN, Eastern Cape and Northern Cape Provinces. Equally, the Gauteng province are ideal for solar PV plants and could mainly reduce electricity demand, whilst minimising transmission and distribution power loss. It is the highest power consumption province in the country and has significant number of middle and high income residents that are willing to pay electricity based on green source.

The Northern Cape and Eastern Cape Provinces have equally important solar PV potential. These provinces are ideal for large-scale solar PV projects. This would involve transmission of power from one province to another. Yet, these provinces have the lowest power consumption and highest available land area, which makes them more feasible for large-scale solar PV plants.

8.2.2 Hybrid energy system

The Eastern Cape and KZN Provinces are ideal for hybrid energy systems. These provinces have the highest electrification backlog, good solar, and wind energy resources. The Western Cape and Northern Cape Provinces have equally good solar and wind resources; however, they have the lowest electrification backlog and hence do not need a hybrid energy system plant. The Northern Cape Province has less than 5% of South African power consumption with 2.3% of the population, therefore, the hybrid energy system is not ideal in this province.

The Eastern Cape, KZN and Western Cape Provinces have similar patterns and trends, with substantial potential for hybrid energy system application. Nevertheless, scenario 1 (in chapter 5) presents different dynamics from the other two scenarios in the same chapter, with the Northern Cape Province having the highest potential, despite its low population and electricity consumption (Chapter 5, section 5.3.3, figure 5.5). The overall results for the three coastal provinces proved that the Eastern Cape, KZN and Western Cape Provinces have fairly good hybrid energy system potential, which warrants consideration of the establishment of hybrid systems in order to curb the electrification backlog, while providing a sustainable electricity supply.

The Eastern Cape and KZN provinces are ideal for the hybrid energy system taking into consideration that they have high electrification backlog, good wind and solar irradiance. The hybrid energy system project may not need vast land as compared to grid connected solar PV. Further study is recommended for the identified districts in the Eastern Cape and KZN provinces in order to identify sites where the hybrid energy projects could be implemented.

The percentage of households that are connected to the electricity supply has increased from 77% in 2002 to 85% in 2014 in South Africa (StatsSA, 2015; Department of Planning, Monitoring and Evaluation, 2014). The Eastern Cape and KZN provinces have high electrification backlog of over 20% (StatsSA, 2015). This is an opportunity for hybrid energy systems to make significant contribution in providing sustainable energy. Complete electrification backlog eradication is almost impossible because of population growth and expansion of households’ over time.

8.2.3 Barriers hampering the development of solar PV and hybrid energy systems

The development and implementation of solar PV and hybrid energy systems are hampered by numerous challenges and impediments. It is important to establish mechanisms and measures to promote the implementation of solar PV and hybrid energy systems in South Africa. The impediments include insufficient finances to support the development and implementation of the projects, social issues, education and awareness, technical and infrastructure barriers, variability and intermittency, regulatory and training restrictions, skills and capacity building.

The financial assistance, social, education and awareness, technical and infrastructure, variability and intermittency and administrative and regulatory are common barriers hindering the government and generator sectors to advance the solar PV industry. Similarly, over and above the afore-mentioned barriers, the social, education and awareness & the training and skills deficit are barriers facing the residential and installer sectors. The mitigating measures for the above-mentioned barriers are the introduction of the FIT to enable smaller companies and the residential sector to participate in the market, streamlining the process and duration of obtaining authorisations, intensive education and awareness raising, financial support and incentivising the off-grid and hybrid energy project to counter the REIPPP.

Solar PV and hybrid energy systems are subject to various risks that may occur at any stage during the development and implementation of the project. The development and implementation of solar PV projects is a high-risk business because none of the risk factors is low or medium, they are rather high and extreme, which the severity is critical and catastrophic and the probability for occurrence is likely even if rare (Table 8.1). The social and natural risk is likely to occur and the severity is marginal. The pre- and post-completion risks are regarded as critical and rare. However, they remain high risk in the solar PV sector. Furthermore, the financial risk is high, because the impact is critical and is likely to occur consequent to volatile currency fluctuation and the international oil price. The technical risk is extreme, hence the impact is catastrophic and the consequences are dire. This is because any technical fault may result in failure to generate power and repair may not be feasible untimely.

Table 8.1: Risk matrix for the development of solar PV energy power plant

Probability/likelihood	**Severity/impact**				
		Negligible	**Marginal**	**Critical**	**Catastrophic**
	Unlikely				
	Rare			Pre- & post completion risk	Technical risk
	Likely		Social and natural forces	Financial and business risk	
	Certain				

Despite the barriers and risks that solar PV technology is facing, there is a wide range and variety of benefits from the PV technology in South Africa. The opportunities include socio-economic development including health, education and small business enterprises, communication (cellular phones, radio, and televisions), rural industrial development and job creation.

8.3: Recommendations

The following recommendations are made:

8.3.1 Solar PV potential

- Solar PV plants be constructed in Gauteng province as it has greatest potential taking into consideration the technical potential and the household energy consumption (willingness to pay electricity based on green source); and high rate of electricity consumption in this province.
- Reasonable consideration should be extended to KZN province because it has relatively good solar PV potential. Moreover, it saves power where the generation is closer to consumption point.
- South Africa should introduce the regulations for the renewable energy tariff such as FIT for the residential sector, amongst others, to generate power from roof-top PV for own use and sell the surplus to the grid. There is reasonably high interest from the middle and high income groups to generate power from the roof-top PV for own use.
- South Africa should consider the replacement of electric geysers with boilers in certain sectors, such as the residential sector. This initiative should be subsidised.

8.3.2 Hybrid energy system

- The Eastern Cape and KZN Provinces have good hybrid energy potential. It is therefore, recommended that hybrid energy system projects be established in these provinces, as they have a low electrification rate.
- Most parts of the rural communities in the Eastern Cape are not electrified, they are mountainous with terrain not conducive for grid-connected electricity, and the population is sparsely distributed in some parts of these provinces. The Eastern Cape has low electricity consumption, and is thus ideal for off-grid hybrid energy system project

8.3.3 Future studies

In the process of data analysis, research findings and discussion on the potential of solar PV and hybrid energy, barriers, risks and opportunities of solar PV, households' energy consumption pattern and conclusion, it was discovered that there are areas that need further research. Therefore, this research recommends that the following should be researched and investigated further:

- Investigate the feasibility of replacing electric geysers with boilers, and determine the potential power savings at the residential and commercial sectors;
- Investigate the PV efficiency and degradation rate taking into account South African weather condition and pattern, as this is critical for investors;
- Identification of sites suitable for hybrid energy system projects in the coastal provinces (Eastern Cape and KZN) using the HOMERGIS software; and
- Investigate the power loss through long distance transmission such as power production from the large scale solar PV in the Northern Cape and Eastern Cape to other Provinces

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APPENDICES

APPENDIX A: RESIDENTIAL SECTOR

1. CONSUMERS (COMMUNITY MEMBERS)

- Name (Optional):____
- Town:____
- Province:____

1.1 ELECTRICITY SUPPLY QUESTIONS

- How much do you pay for your electricity per month? Please tick the appropriate box:

Less than R500	
Between R500 and R1000	
Between R1000 and R1500	
Over R1500	

- How big is the house and family members? Please fill in the box below:

Number of rooms	
Number of family members	

- What are the electricity appliances do you use? Please tick an appropriate box below:

Kettle	
Stove	
Refrigerator	
Geyser	
Others, please specify	

- How much has your electricity bill gone up over the past 5 years? Please select an appropriate box below:

Less than R200 per year	
Between R200 & R500 per year	
Over R500 per year	
Other, please explain	

- What would be the base of your electricity payment? Please tick an appropriate box below:

Cheapest price	
Green source (solar, wind)	
Other, please explain	

1.2 SOLAR PHOTOVOLTAIC (PV) QUESTIONS

Electricity is generated from different sources such as coal, oil, nuclear, wind, solar etc. Solar photovoltaic is a panel of solar arrays that converts solar radiation directly into electricity. Hence electricity generated from solar can be used anywhere, anytime and anyhow.

- Given the above explanation, what is your level of knowledge about electricity generated from solar? Please tick an appropriate box below:

I do not know solar at all	
I know a little bit about solar	
I know very much about solar	
I am an expert of solar	

- If a solar PV plant is to be set up in your area, would you and your community appreciate it? Yes/no, and why?

Yes, explain:	
No, explain:	
Not sure, explain	

- If a solar PV plant is to be set up in your area, do you think there will be a need for security to look after the infrastructure?

Yes, explain:	

No, explain:	
Not sure, explain	

- Some solar PV plants are often vandalised or stolen, what do you think are the causes of such vandalism or theft?

____

____

- Who is your electricity supplier? Please fill in the box below:

Eskom	
Municipality	
Private generator	
Do not have electricity	

2. ADDITIONAL DATA COLLECTION

2.1 What influenced you to install the solar PV system?

2.2 When did you install it and how much did it cost you?

2.3 What are the challenges for your solar PV system?

2.4 Have you had to service or clean up the PV system?

2.5 Would you encourage other residence to install it?

APPENDIX B: SOLAR PV INSTALLERS AND SUPPLIERS SECTOR

1) QUESTIONNAIRE FOR THE INSTALLERS

- How much is the whole set (e.g 1 kW solar panel, battery charger and DC/AC) of solar PV plant?

Item	**Cost**	**Installation cost**				
		1m^2	**2m^2**	**5m^2**	**10m^2**	**15m^2**
Module						
Installation						
Battery						
Inverter						
Cooling fan						
Equipment						
Annual maintenance						
Total						

- Who are your customers and the percentages of sale? Please fill in the box below:

Customers	**Percentages of sale**
Residential	
Commercial	
Government	
Mining	
Manufacturing	
Industries	
Other, specify	

- What are the barriers for the market penetration in the solar PV industry?

____

____

2) ADDITIONAL DATA COLLECTION

2.1) What is the driving force for the different sectors (Residential, agriculture, commercial) to install solar PV?

2.2) What is the typical kW capacity installation in the residential sector?

2.3) How much is the 10 kW solar PV system for the residential sectors?

2.4) How long would it take to install PV system for a typical residential household?

2.5) Do we have the capacity (in South Africa) to install the solar PV, say in the Gauteng Province residential sector?

2.6) Are the materials locally made or import, and are they readily available?

2.7) Do you have any monitoring system to quantify the power production?

3) COMPANIES INTERVIEWED

Company	Address	Province
Airco (Pty) Ltd	39 Webber Street, Selby, Johannesburg	Gauteng
APS Solar (Pty) Ltd	230 Battery Street, Silverton Lynnwood Ridge	Gauteng
Rhino energy	Johannesburg	Gauteng
Ellies (Pty) Ltd	94 Eloff Street Ext, Johannesburg	Gauteng
Green Zone Energy (Pty) Ltd	Shop 12 Laritza Commercial Park,	Mpumalanga
Bright black solar	609 Lanseria Corporate Estate, Falcon Lane, Lanseria Ext26, Johannesburg	Gauteng
Hajira Bibi Osman t/a Universal Solar & Eco-Lighting	7 Stanhope Place, Briardene, Durban 4001	Kwazulu Natal
Solar Charge (Pty) Ltd	14 Kyalami blvd, Midrand	Gauteng
Solar Century	Hampton Office Park, Bryanston 2060	Gauteng
Solar Con	51 Brunton Circle, Founders View, Modderfontein	Gauteng
Solarsun Solutions (Pty) Ltd	19 Springside Road,Hillcrest,3650	Kwazulu Natal
Green Habitat	Johannesburg	Gauteng

Solsqr (Pty) Ltd	Unit 3, Venturi Cresent, Hennopspark, Centurion, 0157	Gauteng
altEnergy (Pty) Ltd	Adderley Street 03,	Western Cape
Solaray	53 Alexander Road, Durban	Kwazulu Natal
APS Solar (Pty) Ltd	230 Battery Street, Silverton Lynnwood Ridge	Gauteng
Indicel Solar	25 Bakersfield	Gauteng
Solareff	620 Kudu St, Constantia Kloof Office Estate, Johannesburg	Gauteng
Inti Solar Corporation	White Hills Close, Fourways, Johannesburg, 2055	Gauteng
Solar Academy of Sub Saharan Africa	15 Cleveland Rd15 Cleveland Road, Johannesburg, Gauteng	Gauteng
Solarsun Solutions (Pty) Ltd	19 Springside Road,Hillcrest,3650	Kwazulu Natal
Solarvest	22 Kyalami Park	Kwazulu Natal
Solarworld Africa (Pty) Ltd	24th Floor Thibault Square No 1	Western Cape
Solsqr (Pty) Ltd	Unit 3, Venturi Cresent, Hennopspark, Centurion, 0157	Gauteng
Sun Electricity	165 Van Rensburg Street, Mayville	Gauteng
Green Zone Energy (Pty) Ltd	Shop 12 Laritza Commercial Park	Mpumalanga
Indicel Solar	25 Bakersfield	Gauteng
Solareff (Pty) Ltd	165 Van Rensburg Street, Mayville	Gauteng

APPENDIX C: GOVERNMENT SECTOR

1) Questions

- What determines electricity price increase?
- What determines the electricity supply? (e.g demand, available capacity, excess capacity etc)
- How are you intending to increase the share of renewable energy (solar PV in particular) in the total energy mix? What are the mechanisms and tools in place to boost solar PV increase?
- What are your renewable energy (solar PV in particular) targets?
- Is solar PV part of the Government plan? If so how much capacity and what are the timelines?
- What are the programmes in place to ensure that the targets are achieved?
- What are the financial mechanisms and schemes available to promote renewable energy use (solar PV in particular)?
- What are the barriers for the development of solar PV in RSA?

2) Government departments interviewed

Department	**Province based**	**Website**
Department of Energy	Gauteng	www.energy.gov.za
Department of Science and Technology	Gauteng	www.dst.gov.za
Department of Trade and Industry	Gauteng	www.dti.gov.za
National Energy Regulator of South Africa	Gauteng	www.nersa.org

APPENDIX D: ELECTRICITY GENERATORS/IPP SECTOR

1. SUPPLIER/GENERATOR (ESKOM, MUNICIPALITIES, PRIVATELY OWNED GENERATORS)

1.1 ELECTRICITY RELATED QUESTIONS

- What percentages (%) of electricity do you supply to the following customers:

Municipalities	
Mining	
Residential	
Industries	
Manufacturing	
Other, specify	

- What are the sources of electricity and production/capacity for your power station(s)? please complete the box below:

Source	Capacity/production (MW/MWh)
Coal	
Nuclear	
Gas	
Hydro	
Solar PV	

Solar CSP	
Biomass	
Other, specify	

- How much of your electricity (MWh/GWh) do you sell to the domestic customers?________
- What is your electricity tariff for your following customers:

Customer	Tariff (c/kWh)
Municipalities	
Mining	
Residential	
Industries	
Manufacturing	
Other, specify	

1.2 SOLAR PV QUESTIONS

- Are you considering setting up solar PV/wind energy plant?
    - If yes, where, what capacity and when?

____

____

____

____

____

- If no, why not?

____

- Where in South Africa do you think there is good solar potential?

____

- How much do you think solar PV (1 kW) cost?______________________________

1.3 GENERAL QUESTIONS

- How much (percentages) annual electricity price increase was for the past five years? Please fill in the box below:

Year	Price increase (Rand)
2012	
2011	
2010	
2009	
2008	

- What are the barriers for the establishment of solar PV plant?

ADDITIONAL DATA COLLECTED

1) What are the challenges in the solar PV and why?

2) What could be the mitigating measures?

3) What are the risks associated with solar PV?

4) Rank the risks using the risk matrix below:

Probability\likelihood		Severity/impact			
		Negligible	**Marginal**	**Critical**	**Catastrophic**
	Unlikely	Low	Low	Medium	High
	Rare	Low	Medium	High	Extreme
	Likely	Low	Medium	High	Extreme
	Certain	Medium	High	Extreme	Extreme

APPENDIX E: SOUTH AFRICAN EXPERIENCE ON HYBRID ENERGY PROJECTS

The hybrid energy system project was established in Hluleka and Lucingweni locations in the eastern part of the Eastern Cape Province. The purpose of the project was to assess and evaluate the viability of the hybrid energy system in South Africa with a view to replicate the project to other areas. This project was implemented in two different sites for different purposes. Hluleka hybrid project was meant to provide power to a game reserve (Figure E.1), while Lucingweni hybrid project was meant to supply power to the community members of Lucingweni village, which was not electrified (Figure E.2).

The Hluleka hybrid project comprised 5 kW (2 x 2.5kW) wind generators, 5.6 kW (56 x 100 watts) solar PV panels, a single 5 kVa diesel generator for backup power and 140 kWh (30 cells of 2,360 Ah @ 2V each) batteries for power storage (DME, feasibility study, 2006; Scholle and Afrane-Okese, 2007). It was located in a mountainous area of windy grassland with tall trees that could cast shade over the solar PV panels and interrupt power generation (Figure 5.9). Extension of the grid to this area would be expensive because of the terrain in the area, hence a hybrid energy system becomes a better, affordable and sustainable energy solution.

The hybrid project operated for a period of six months and collapsed in response to many challenges, including poor management and perpetually unsolved technical errors. Unfortunately, the system was never repaired or maintained to generate power again. The game reserve continued to use a diesel generator, as it had done before the project.

Figure E.1: The wind generator and PV panels in Hluleka hybrid energy system

The Lucingweni hybrid energy system project consisted of 36 kW (6 x 6kW) wind generators mounted on 6-metre tall masts, 56 kW (560 x 100 watts) solar PV panels mounted on a steel structure (Figure E.2) and 2.2 MWh (2 x 110 cells of 5,030 Ah @ 2V each) batteries for power storage. The power was reticulated to 220 households, small shops, a community hall, street lights and water services in the form of pumping water from a borehole in Lucingweni village (Department of Minerals and Energy, 2007).

Just like many other villages in the Eastern Cape Province, the Lucingweni village was not electrified prior to an electrification project. Like Hluleka hybrid energy project, Lucingweni hybrid energy project operated for a short time and collapsed in less than a year after being commissioned. It was never repaired or maintained to re-generate power for the community members, and hence it became redundant and its materials became obsolete for a number of reasons as mentioned in the next section. Theft became prominent and the plant was completely stripped and could never be resuscitated again.

Figure E.2: The PV panels and wind generators in Lucingweni

Lessons learnt from hybrid energy system projects in South Africa

The Hluleka hybrid energy system project was technically well designed and professionally installed (Scholle and Afrane-Okese, 2007). However, the management of the project seemed to have been poorly executed; it was found that the operation of the system faced a number of challenges a few months after commissioning. According to Scholle and Afrane-Okese (2007), the following challenges faced the Hluleka hybrid energy system project:

- The Hluleka nature reserve management's understanding of the system operating concept, its capabilities and limitations was poor.
- The design of the demand limitation devices was faulty and allowed guests in the nature reserve accommodation facilities to by-pass the current-limiting devices, which resulted in power being over-used or over-drawn.
- There was over-booking of guests at the Hluleka nature reserve accommodation facility, which led to over-use of power generated by the hybrid energy project.
- The management of the hybrid energy project on-site regarding energy management and basic maintenance was poor. The problem was exacerbated by staff turn-over and poor hand-over from one operating staff member to the next.

- The Hluleka nature reserve authorities did not take effective ownership of the hybrid energy project by properly assuming responsibility for operator training support, awareness creation, professional maintenance and other administrative tasks.
- The hybrid energy project was installed at a good wind site. However, this was at a distance of about 1 km from the buildings in the nature reserve. This resulted in less monitoring of the project performance and provided little security, which resulted in theft and vandalising of the infrastructure. Some of the solar PV panels were vandalised and stolen.

Lucingweni hybrid energy project operated as intended for only a few months after being commissioned before the first complications occurred (Scholle and Afrane-Okese, 2007). The reasons for these problems are not attributed to a single cause, but were rather the result of a variety of issues, such as:

- In the integrated service delivery approach taken in the Lucingweni hybrid project, the design concept was based on providing integrated energy services, which included thermal services for cooking (liquefied petroleum gas) and potable water provision from boreholes that were intended to be powered by the hybrid energy project. However, neither of the services was rendered and this led to dissatisfaction in the community and resulted in users (community members) connecting hotplates to the hybrid energy project by by-passing circuit breakers. The increased load and energy demand contributed to system overload.
- The project was designed to provide power for each household at 2 amps (to allow for lighting, radio/TV and cellular phone charging only). However, it was mistakenly installed at 20 amps per household. Therefore, one household could draw all the available power at the same time. An effective current limitation system through the means of circuit breakers or an equivalent system was not installed. The intention was that such a system would limit power to each household and in the event of an overload trip the circuit as close as possible to the source of the overload instead of bringing down the whole system (cascading).
- There was no provision for energy metering and possibly an energy dispensing concept in order to limit the daily energy budget per user.

- Energy was not monitored at distribution points (e.g. per ten households) to ensure that no illegal connections were being made.
- One of the key aspects of a successful operational phase for the project was to charge revenue for metered consumption. However, the Lucingweni hybrid energy system was switched on before a revenue collection system was in place. Therefore, community members would not have been able to pay for the service.

APPENDIX F: LETTERS FOR DATA COLLECTION FROM NEWCASTLE UNIVERSITY

LETTER 1

School of Chemical Engineering

and Advanced Materials

Newcastle University

Merz Court

Newcastle upon Tyne

NE1 7RU

Professor Steve Bull MA PhD CEng

02 December 2013

TO WHOM IT MAY CONCERN

DATA COLLECTION BY SILAS MULAUDZI (S130603719) PHD STUDENT IN THE SCHOOL OF CHEMICAL ENGINEERING AND ADVANCED MATERIALS, NEWCASTLE UNIVERSITY

Dear Sir / Madam

Mr Silas Mulaudzi (student number 130603719) is a Doctoral student at the Newcastle University in the School of Chemical Engineering and Advanced Materials, United Kingdom. His research area is on the assessment of the viability of Solar Photovoltaic (PV) and potential of hybrid application in South Africa

Mr Mulaudzi will be collecting data for the completion of his thesis and your organization was identified relevant for data collection. I would therefore like to request you to provide him with the data that he needs either through completing a questionnaire or at an interview.

The data will be solely used for the fulfillment of his studies in the study area indicated in the first paragraph. Moreover, the data will be handled as strictly confidential and under no circumstance will it be used for any other purpose except the fulfillment of the study and it will not be divulged to any other institution or individual.

Your cooperation and support in this request would be highly appreciated.

Yours faithfully,

SJBull

Professor Steve Bull

Cookson Group Chair of Engineering Materials

E-mail: steve.bull@ncl.ac.uk

Phone: +44 191 208 7913

LETTER 2

School of Chemical Engineering
and Advanced Materials

Newcastle University

Merz Court

Newcastle upon Tyne

NE1 7RU, UK

Professor Steve Bull MA PhD

11 June 2015

TO WHOM IT MAY CONCERN

DATA COLLECTION FOR SILAS MULAUDZI (S130603719) PhD STUDENT IN THE SCHOOL OF CHEMICAL ENGINEERING AND ADVANCED MATERIALS, NEWCASTLE UNIVERSITY.

Dear Sir / Madam

Mr Silas Mulaudzi (student number 130603719) is a Doctoral student at the Newcastle University in the School of Chemical Engineering and Advanced Materials, United Kingdom. His research area is on the assessment of the potential of Solar Photovoltaic (PV) and hybrid renewable application in South Africa.

Mr Mulaudzi will be collecting data from July to December 2015 for his studies. I would like to request your support and assistance in providing him with the data he needs either through completing a questionnaire or an interview. The data will be solely used for his studies only, and will be handled as strictly confidential. Under no circumstance the data will be used for any other purpose except for the fulfillment of his study.

Your cooperation and support in this request is be highly appreciated.

Yours faithfully,

SJBull

Professor Steve Bull

Cookson Group Chair of Engineering Materials

E-mail: steve.bull@ncl.ac.uk

Phone: +44 191 222 7913

APPENDIX G: SOUTH AFRICAN UNIVERSITIES

University	Province and Town
Cape Peninsula University of Technology	Western Cape, Cape Town
Central University of Technology	Free State, Bloemfontein
Durban University of Technology	Kwazulu Natal, Durban
Mangosuthu University of Technology	Kwazulu Natal, Durban
Nelson Mandela Metropolitan University	Eastern Cape, Port Elizabeth
North-West University	North West, Potchefstroom
Rhodes University	Eastern Cape, Grahamstown
Tshwane University of Technology	Gauteng, Pretoria
Stellenbosch University	Western Cape, Stellenbosch
University of the Free State	Free State, Bloemfontein
University of Cape Town	Western Cape, Cape Town
University of Fort Hare	Eastern Cape, Alice
University of Johannesburg	Gauteng, Johannesburg
University of Kwazulu Natal	Kwazulu Natal, Durban
University of Limpopo	Limpopo, Polokwane
University of Pretoria	Gauteng, Pretoria
University of South Africa	Gauteng, Pretoria
University of the Western Cape	Western Cape, Bellville
University of the Witwatersrand	Gauteng, Johannesburg
University of Venda	Limpopo, Venda
University of Zululand	Kwazulu Natal, Kwadlangezwa
Vaal University of Technology	Gauteng, Vanderbijlpark
Walter Sisulu University	Eastern Cape, Mthatha