Rooftop solar photo voltaic potential: Rand Water as case study

DI Makhathini

orcid.org/0000-0002-2317-7007

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Supervisor: Dr JF van Rensburg

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Student number: 26560720

Abstract

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Author: DI Makhathini

Supervisor: Dr JF van Rensburg

School: North-West University, Potchefstroom Campus

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South Africa has an abundance of coal reserves and about 85.7% of energy is generated from coal. However, the requirements of the United Nations Framework Convention on Climate Change, Kyoto Protocol, National Climate Change Response White Paper, Clean Development Mechanism, Integrated Resource Plan and National Electricity Plan emphasise the need for the use of renewable energy sources.

The purpose of this research is to study and identify the potential to save energy through the installation of rooftop solar photovoltaic (PV) systems at Rand Water buildings. The rooftop solar PV installation at Rand Water's head office is used as a case study and the information gathered from the case study is then used to analyse the potential for similar installations in other Rand Water buildings.

Solar PV potential is described as physical, geographical, technical, and economic potential. The characteristics of the location provide both physical and geographical potential, the type of equipment and controls selected for the PV system provide technical potential, economic potential provides financial benefits in terms of net present value, internal rate of return, levelised cost of energy and simple payback period. The reduction in greenhouse gas emissions is discussed extensively in literature but it is not included as environmental potential or greenhouse payback time.

This research proposes a methodology to analyse potential of a rooftop solar PV system installation with focus on the physical, geographical, technical and economic solar PV potential. The methodology indicates the importance of the geographical and meteorological data of the area identified as a potential location and the important variables to be considered in order to determine a suitable PV system size. Economic factors such as PV system cost, operation and maintenance cost, levelised cost of energy (in R/kWh) and simple payback period are discussed. It is evident that technical potential is the most extensive variable in determining solar PV potential.

The proposed methodology was used to determine the potential rooftop solar PV system installation at Rand Water's head office, which resulted in a 338kWp rooftop solar PV system. The actual energy production measurements showed a performance ratio of 80% for the 338 kWp system with an energy cost saving of about R550 000 per year. An additional 18 buildings were identified as potential buildings for a rollout of rooftop solar PV systems. Twelve of the 18 identified buildings showed potential for rooftop solar PV system installation with an estimated energy saving of 2 163 420 kWh/year, an energy cost saving of R1 794 492.64/year and a reduction in carbon emissions of 2 141 tons CO_2/year. The return on investment for these buildings is unattractive but there is potential to achieve a substantial reduction in energy, energy costs and carbon emissions.

Keywords: photovoltaic, PV, rooftop, solar, grid-tied, PV potential

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To my daughter, Ngolwethu, I thank God for you. I thank you for your unconditional love and for motivating me unknowingly because everything I do is for you.

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Nomenclature

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Symbol	**Description**	**Unit of measure**
A	current	Amp
Ah	capacity	amp hour
°C	temperature	degrees Celsius
c/kWh	tariff rate	cents per kilowatt hour
h	time	Hour
Hz	frequency	Hertz
kg	mass	Kilogram
km	distance	Kilometre
kW	power	Kilowatt
kWh	energy	kilowatt hour
kWp	peak power	kilowatt peak
kV	voltage	Kilovolt
kVA	apparent power	kilovolt ampere
m^2	area	square metre
ML	volume	Megalitre
mm^2	area	square millimetre
MVA	apparent power	megavolt ampere
MW	power	Megawatt
MW_{dc}	power	direct current megawatt
MWh	energy	megawatt hour
R	currency	Rand
V	voltage	Volt
W	power	Watt
Wh	energy	watt hour
Wp	power peak	watt peak
η	efficiency	conversion efficiency

Abbreviations

Symbol	**Description**
a-Si	amorphous silicon
AC	alternating current
CdTe	cadmium telluride
CIGS	copper indium gallium selenide
CSP	concentrated solar photovoltaic
DB	distribution board
DC	direct current
DoD	depth of discharge
EMS	Environmental Management System
FIT	feed-in tariff
GPS	Global Positioning System
IPP	independent power producer
IRR	internal rate of return
LCOE	levelised cost of energy
mil	Million
NERSA	National Energy Regulator of South Africa
NPV	net present value
O&M	operation and maintenance
PI	profitability index
PV	Photovoltaic
REIPPP	Renewable Energy Independent Power Producer Procurement
STC	Standard Test Conditions
USD	United States Dollar
VAT	value-added tax

CHAPTER 1: BACKGROUND


[1]

Available energy resources in South Africa.

[1] *Future energy mix in South Africa debated [Online]. Available: http://www.greenbusinessguide.co.za/future-energy-mix-south-africa-debated/*

1.1. Introduction

South Africa is a country that is rich in minerals and energy and solar maps show that the country has abundant levels of sun irradiation. The research focus is on the potential energy saving in Rand Water through the installation of rooftop solar photovoltaic (PV) systems.

This chapter provides an overview of the energy sources in South Africa and the background of the sole electricity provider, Eskom. The chapter further discusses the energy requirements within Rand Water's pumping stations and the strategic direction towards the use of solar energy. The requirements of the United Nations Framework Convention on Climate Change, Kyoto Protocol, National Climate Change Response White Paper, Clean Development Mechanism, Integrated Resource Plan and National Electricity Plan are highlighted to emphasise the need for the use of renewable energy sources.

Furthermore, the objectives and overview of this research are discussed in this chapter, a high-level description of each chapter within the dissertation is provided.

1.2. Overview of energy in South Africa

1.2.1. Energy sources

Coal

South Africa has an abundance of coal reserves, in the range of 60% to 70%, as reported in [1] and [2]. South Africa has the world's sixth-largest coal reserves – after China, the United States of America, India, Russia and Australia – at the following grades: export, steam coal and discards [3]. At the present production rate, there should be more than 50 years of coal supply left [1].

Eskom ranks first in the world as a steam coal user and seventh as an electricity generator; this shows the key role that coal reserves play in the South African economy. This excessive use of coal in electricity generation results in greenhouse gas emissions, which have a detrimental effect on the environment. However, South Africa is a signatory to the Kyoto Protocol, acceded to in 2002 [4], which commit the country to reducing its greenhouse gas emissions.

Figure 1 shows the percentage total primary energy supply, as reported by the South African Department of Energy, for the 2012 energy balances in South Africa [5]. In 2016, data from Statistics South Africa indicates a reduction from 90% to 85.7% in energy generated from coal.

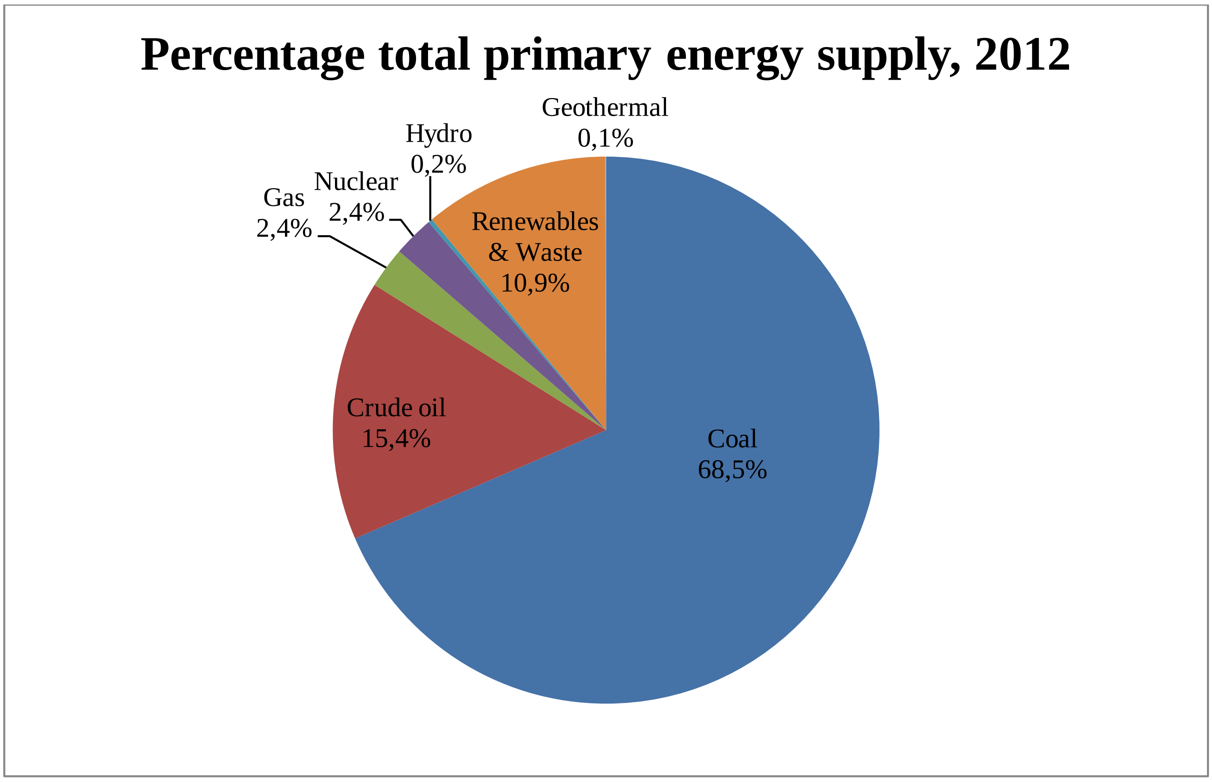

Figure 1: Percentage total primary energy supply in South Africa

Natural gas and oil

Natural gas is generally considered to be a 'cleaner' fuel as it produces lower greenhouse gas emissions when compared to coal and oil [6]. Natural gas is available in the west and south coasts of South Africa, but the bulk of natural gas is imported from neighbouring countries Namibia and Mozambique [3]. The Integrated Energy Plan [7] indicates that the energy content of the known gas reserves, including those of Namibia and Mozambique, are 0.5% of the known coal reserves. There is a project to bring gas from Angola to Secunda in Mpumalanga, which will join the existing pipeline that links Gauteng to Durban and Secunda [3].

There is potential for rapid expansion in the gas industry following the discovery of offshore gas reserves in South Africa in the Northern Cape coast [8], as well as shale gas and coal bed methane reserves in the Karoo [9] [10].

South Africa has very limited oil reserves, about 60% of its crude oil requirements are met by imports from the Middle East and Africa [1]. Refined petroleum products such as petrol, diesel, residual fuel oil, paraffin, jet fuel, aviation gasoline, liquified petroleum gas and refinery gas are produced using the following methods:

- Crude oil refining (oil refineries);
- Coal-to-liquid and gas-to-liquid fuels (Sasol); and
- Natural gas-to-liquid (PetroSA)

Uranium

Uranium is abundant in the Earth's crust and is used to generate nuclear energy using nuclear reactors. Uranium is a by-product of gold mining and is currently used at the Koeberg nuclear power station in Cape Town [3].

Biomass and landfill waste

Biomass such as sugar cane crop (bagasse or husks) is used mainly in industries such as sugar refineries, while round wood is used in the pulp and paper industries. Households use wood, dung and vegetable matter for domestic energy, particularly in rural areas [3]. Biofuels include biodiesel, ethanol, methanol and hydrogen [3]. Biodiesel is produced from oilseed rape, sunflower oil and jatropha, while bioethanol is produced from wheat, sugar beet and sweet sorghum. Methanol and hydrogen can be generated from biomass, but maize cannot be used in the production of biofuels due to the importance of maize for food security [1]. Other types of biomass source include organic components in municipal waste, industrial waste and landfill gas [6].

Hydropower

Energy from water can be generated from waves, tides, waterfalls and rivers. South Africa has only a few small rivers that are suitable for hydropower. However, some neighbouring countries have huge potential for generating hydropower which can be exported to South Africa [3].

South Africa has a mix of small hydropower stations and pumped-water storage schemes. Irrespective of the size of its installation, any hydropower development will require authorisation in terms of the National Water Act of 1998 [11].

The Integrated Resource Plan for the period 2010–2030 on electricity supply and demand shows that about 6.5% of the country's electricity requirements will be from hydro resources [1] [12].

Solar

Most areas in South Africa have an average of more than 2 500 hours of sunshine per year and an average daily solar radiation of between 4.5 kWh/m^2 and 6.5 kWh/m^2 [1]. Solar energy can be used to generate electricity to heat water; and to heat, cool and light buildings. For example, PV systems capture the energy in sunlight and convert it directly to electricity. Alternatively, sunlight can be collected and focused with mirrors to create a high-intensity heat source that can be used to generate electricity by means of a steam turbine or heat engine [6].

Concentrated solar photovoltaic (CSP) uses renewable solar resources to generate electricity while producing very low levels of greenhouse gas emissions. Thus, it has strong potential to be a key technology for mitigating climate change and the flexibility of CSP plants enhances energy security. Unlike solar PV technologies, CSP has an inherent capacity to store heat energy for short periods of time for later conversion to electricity. When combined with thermal storage capacity, CSP plants can continue to produce electricity even when clouds block the sun or after sunset [13].

Figure 2 shows the annual solar radiation (direct and diffuse) for South Africa – as published by Eskom, the Department of Minerals and Energy, and the Council for Scientific and Industrial Research – which reveals considerable solar resource potential for solar water heating applications, solar PV and solar thermal power generation [6].

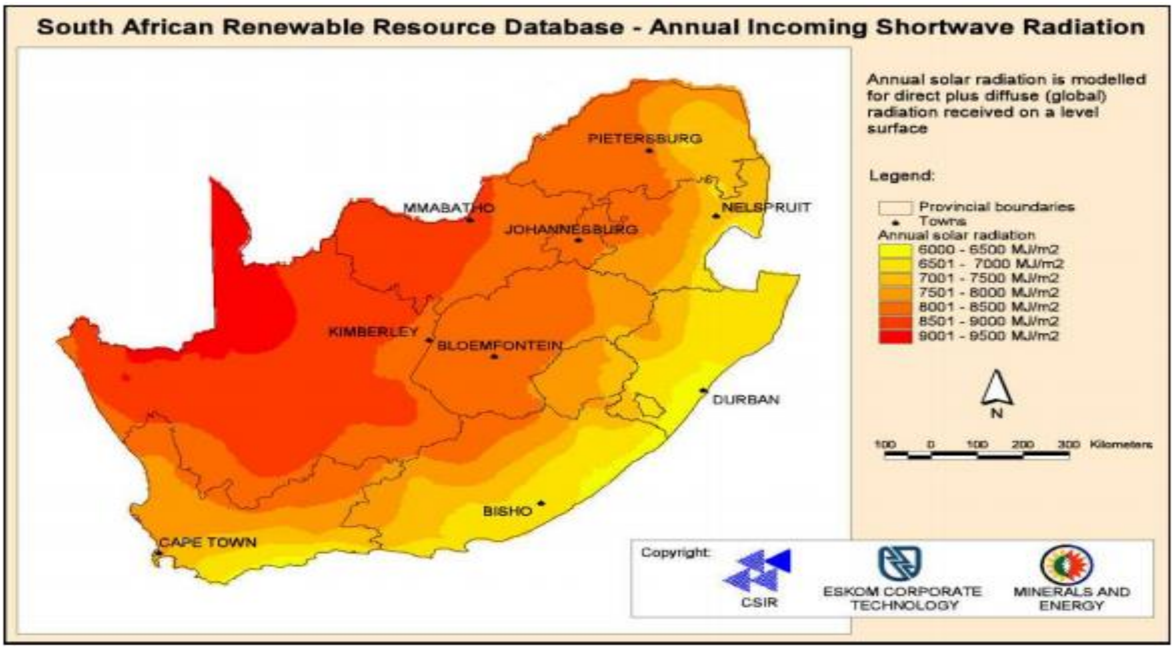

Figure 2: Annual direct and diffuse solar radiation applications [6]

The annual 24-hour solar radiation average for South Africa is 220 W/m^2 [1]. The interior of the country has an average insolation in excess of 5 000 Wh/m^2/day, with some areas in the Northern Cape with over 6 000 Wh/m^2/day [3].

Two large PV plants have been completed in the Northern Cape, namely the Jasper PV (96 MW$_{dc}$) and Lesedi PV (75 MW$_{dc}$) projects. Jasper will deliver about 180 000 MWh and Lesedi will deliver about 150 000 MWh of renewable electricity per year [1]. Furthermore, the Letsatsi PV (75 MW_{dc}) project, which is being developed in the Free State, will deliver 150 000 MWh.

There are five CSP plants located in the Northern Cape, namely Ilanga I (100 MW), Kathu Solar Park (100 MW), Kaxu Solar One (100 MW), Khi Solar One (50 MW) and Redstone Solar Thermal Power Plant (100 MW) [14].

Wind

Similar to solar, wind is a free resource that is readily available from nature. Wind as an energy source is practical in areas that have strong and steady wind, as is the case in coastal areas such as the Western and Eastern Cape.

Eskom constructed two wind farms in the Western Cape for demonstration, namely the Darling National Demonstration Wind Farm (5.2 MW) and Klipheuwel-Dassiefontein Wind Energy Farm (27 MW), which have been operating since 2008 and 2002 respectively. Nominal wind speeds required for full power operation at Klipheuwel-Dassiefontein vary between about 47 km/hour and 57 km/hour, with shutdown mechanisms operating at 90 km/h. They can start generating at between 11 km/hour and 15 km/hour [15].

The Sere Wind Farm is another wind energy farm that belongs to Eskom. It is located in the Western Cape and has a capacity of 100 MW [16]. It has been operating since 2014 and has an average annual energy production of about 233 000 MWh.

The Jeffreys Bay Wind Farm is a 138 MW wind farm which was built under the Renewable Energy Independent Power Producer Procurement (REIPPP) programme. The wind farm is one of the largest in Africa and will eventually generate about 300 MW of electricity [1].

1.2.2. South Africa's electricity supply system

In South Africa, electricity generation is dominated by state-owned utility Eskom, they provide about 91% of total electricity [3]. Eskom owns and operates the national electricity grid. Municipalities such as Cape Town, Bloemfontein, Tshwane and Johannesburg provide about 5.6% of electricity generated and industries that generate electricity for their own use provide about 3.1% [3].

Electricity is generated through coal power stations, nuclear power stations, gas turbines, hydropower and pumped storage. Coal power stations are located close to coal mines in Mpumalanga, Limpopo and Gauteng, while Koeberg is located 30 km north of Cape Town and assists with the stability of the grid in the Cape. Open-cycle gas turbines are owned by Eskom and municipalities; these are used for emergency power and to meet peak capacity. Future plans are to use combined-cycle gas turbines, whereby a gas turbine will be used with a steam boiler. Hydropower and pumped-storage power stations are used as peaking stations.

In the 1970s, Eskom overestimated demand growth, which suggested a 7% to 8% growth in demand – meaning that generation capacity would have to be increased every decade [17] –and embarked on a massive investment programme to increase capacity through building new generation capacity [2]. In the 1980s, Eskom experienced excess capacity due to the lack of growth as a result of disinvestment in the country by foreign investors as a reaction to continued apartheid. Thus, between 1970 and 2000, electricity supply in South Africa exceeded demand, this led to the mothballing of several power stations in the late 1980s and early 1990s [18].

In the 1990s, Eskom ventured into the ‘Electricity for All’ initiative which saw an increase in the number of connections and electrification in areas that did not have electricity in the past [17]. Furthermore, the county’s electricity price ranked among the cheapest in the world [2].

In 2003, Camden, Grootvlei and Komati were returned to service to assist with alleviating anticipated electricity shortages. By 2004, as a result of the electrification drive, millions of South Africans were enjoying better lives but the reserve margins were dropping. In 2007, Eskom struggled to meet the electricity demand; the country experienced rolling blackouts in late 2007. Eskom was forced to implement load shedding in 2008 and again in 2014. In 2008, load shedding occurred as a result of inadequate generation capacity and a lack of new-build generation capacity. In 2014, load shedding occurred as a result of deferred maintenance, running equipment to failure, and delays on new-build generation capacity.

The Eskom New Build programme includes the Medupi and Kusile coal-fired power stations, each with a capacity of 4 800 MW, as well as the new 1 300 MW Ingula pumped-storage system. Construction commenced in May 2007 at Medupi and in August 2008 at Kusile. The first of six units in Medupi, Unit 6 at 794 MW, was synchronised into the national grid in March 2015 [19]. Eskom indicated that the first synchronisation of Kusile Unit 1 was scheduled for the first half of 2017, the first unit was synchronised in March 2017, with the 800 MW unit expected to enter commercial operation in the second half of 2017 [20]. Ingula comprises of four 333 MW generators and these were estimated to be fully operational by the end of 2016 [21]; all four units were reported to be fully operational in January 2017.

The price of electricity has been increasing drastically, putting a strain on Eskom’s customers and the economy. Eskom increased its electricity tariffs by an annual average of 16% for the year 2011/12 and by an annual average of 8% for the year 2013/14. In May 2015, Eskom requested an urgent 25.3% tariff increase for the 2015/16 to 2017/18 financial years, which the National Energy Regulator of South Africa (NERSA) declined pending a revised proposal. In February 2016, Eskom was granted an annual average price increase of 12.69% for 2015/16, which is made up of the 8% annual price increase approved in the original Multi-Year Price Determination 3 decision and an additional 4.69% as allowed through the revenue clearing account mechanism which forms part of the NERSA regulatory methodology [22]. A further 9.4% tariff increase was approved for the year 2016/17, 2.2% for the year 2017/18 and a recent 5.23% increase for the year 2018/19.

In 2003, Cabinet approved private-sector participation in the electricity industry and decided that future power generation capacity will be divided between Eskom (70%) and independent power producers (IPPs) (30%).

The Integrated Resource Plan 2010–2030 (hereinafter referred to as the National Electricity Plan), which was published in 2010 under the Electricity Regulation Act (2006); encourages the use of renewable energy sources in order to promote sustainable electricity supply, reduce carbon emissions and encourage energy efficiency in South Africa. In 2009, the government began exploring feed-in tariffs (FITs) for renewable energy but this was later rejected in favour of a competitive bidding process [2] called the REIPPP programme. The National Development Plan envisages adequate supply of electricity by 2030, with at least 95% of the population having access to grid and off-grid electricity.

The initial Request for Proposal under the REIPPP programme was issued in August 2011, resulting in the selection of 28 preferred bidders offering 1 416 MW for a total investment of USD 6-billion. By May 2014, a total of 64 projects had been awarded to the private sector under the REIPPP programme for a 3 922 MW renewable energy capacity at an investment of USD 14-billion [2]. In line with the national commitment to transition to a low-carbon economy, 20 000 MW of energy is expected to come from renewable energy sources beyond the year 2020 [1] of which 5 000 MW is expected to be operational by 2019 and a further 2 000 MW (i.e. combined 7 000 MW) operational by 2020 [23].

New capacity determinations include the following [23]:

- 13 225 MW of renewable energy, comprising of:

- solar PV: 4 725 MW,
- wind: 6 360 MW,
- CSP: 1 200 MW,
- small hydro: 195 MW,
- landfill gas: 25 MW,
- biomass: 210 MW,
- biogas: 110 MW and
- the small-scale renewable energy programme: 400 MW;

- 2 500 MW designated from coal-fired plants (excluding cross-border projects);
- 1 800 MW of cogeneration;
- 3 126 MW of gas-fired power plants; and
- 2 609 MW of imported hydro.

About 11 000 MW of Eskom's coal-based power stations will be decommissioned and close to 6 000 MW of new coal capacity will be contracted to IPPs and other Southern African countries [1]. This is aligned with the objective to meet the country's energy requirements by implementing an energy mix.

1.3. Need for rooftop solar PV systems

The process of generating electricity in a coal-based power station results in emissions such as carbon dioxide (CO_2), nitrous oxide (N_2O), sulphur dioxide (SO_2) and nitrogen oxide (NO_x). The energy sector has larger environmental impacts than most economic sectors, the associated greenhouse gas emissions are feared to be a major contributor to global warming. South Africa intends to play a constructive role in reducing environmental emissions as part of its commitments under the United Nations Framework Convention on Climate Change [24].

South Africa acceded to the Kyoto Protocol in March 2002. The Kyoto Protocol did not commit the non-Annex I or developing countries, like South Africa, to any quantified emission targets in the first commitment period between the years 2008 and 2012, nor was South Africa affected by international climate change regulations [4] [24].

Despite being classified as a non-Annex I country, South Africa committed at the Conference of the Parties in Copenhagen in 2010 to reduce its greenhouse gas emissions to 34% below current expected levels by 2020 and to 42% below current trends by 2025. This commitment is conditional upon reaching a fair, ambitious and effective international climate change agreement as well as provision of financial and technological support by developed countries [25]. Furthermore, the country's commitment is shown through the National Climate Change Response White Paper in which South Africa acknowledges its contribution to climate change, highlights mitigation strategies with reference to Articles 4, 5, 6 and 12 of the Kyoto Protocol and highlights initiatives such as the Clean Development Mechanism under Article 10 of the Kyoto Protocol.

The electricity pricing methodology used by Eskom and the price escalations implemented by municipalities, motivates a study on the use of renewable energy sources to reduce escalating electricity costs. The National Electricity Plan encourages the use of renewable energy sources in order to promote a sustainable electricity supply, reduce carbon emissions and encourage energy efficiency in South Africa.

Rooftop solar PV systems convert energy from the sun into electricity using semiconductor materials. The sun is a free renewable energy source which is available from nature. Although the production of the equipment that is used in PV systems poses risks to climate change from carbon and greenhouse gas emissions, the electricity generated from PV systems is free of emissions. Therefore, the benefit of using a solar PV system for climate change initiatives is defined as a reduction in kg/CO_2, in order to demonstrate the reduction in carbon emissions as a result of using a solar PV system as a source of electricity instead of conventional electricity supply from, for example, Eskom.

Three barriers exist with the use of solar energy - electricity generation is limited to daytime, it fluctuates and is intermittent over the year and it depends on the geographical location [26]. When compared to other energy sources, particularly those that are able to generate energy throughout the day, solar energy has a drawback because PV systems are only able to generate electricity for approximately 6 of the 24 hours. This is illustrated by the capacity factor in which solar PV systems have a capacity factor of under 20% while wind and hydro generation have capacity factors of up to 40% [27] [28].

In South Africa (in the year 2016) the average annual capacity factor of the solar PV, wind and CSP fleet was 26%, 35% and 31%, respectively [29]. The literature indicates that although solar power cannot be generated in the evening, solar power generation is more stable and the power is generated during peak sun hours as expected as compared to wind power which was unstable and generated power mostly in the evenings.

Literature indicates that, although it is still lower than other forms of generation, the capacity factor for solar PV systems has improved over the years. This is a result of improved technology in the form of tracking systems, installation of a larger PV array, increased installations in areas with high solar insolation and the use of battery storage [30] [31].

1.4. Rand Water energy requirements

The electricity supply within Rand Water is solely dependent on its respective electricity suppliers; namely, Eskom, the City of Johannesburg, the City of Tshwane, Metsimaholo, Emfuleni, Ekurhuleni, Midvaal, Mogale City, Rustenburg and Westonaria.

Rand Water pumping stations receive electricity from Eskom, Emfuleni, Metsimaholo, Ekurhuleni and the City of Johannesburg, as listed in Table 1. In 2015, the maximum demand for the entire Rand Water network was estimated at 317 MW at full pumping requirements, with a maximum pumping of 4 650 ML/day from both the Vereeniging and Zuikerbosch water treatment stations.

Table 1: Electricity supplier per pumping station

Electricity supplier	Pumping station	Smaller pumping station
Eskom	Zuikerbosch, Zwartkopjes, Palmiet	Daleside, Libanon, Lethabo, Trichardt, Bloemendal, Mamelodi, Cullinan, Townlands, Ironside, Zuurbekom
Emfuleni	Vereeniging	Houtkop
City of Johannesburg	Eikenhof	Roodepoort
Ekurhuleni	Mapleton	–
Metsimaholo	–	Sasolburg

The projected power requirement for 2035 is 437 MW, based on the water demand forecast and pumping requirements. Table 2 shows the estimated pumping load requirements at the water treatment plants, booster-pumping stations and smaller sites.

The Rand Water head office building (Rietvlei), which is situated in the south of Johannesburg, receives electricity supply from the City of Johannesburg at an annually escalated tariff rate.

Electricity was the third-highest operating expense in the business (following raw water and labour), but it has escalated to the second-highest operating expense since 2011.

Table 2: Estimated pumping load requirements at Rand Water sites

Rand Water site	System size	
	2015	2035
Zuikerbosch, Vereeniging, Lethabo	152 MW	216 MW
Eikenhof, Zwartkopjes, Palmiet, Mapleton	143 MW	184 MW
All smaller sites	22 MW	37 MW

1.5. Problem statement and objectives

The South African Country Studies Programme identified the health sector, maize production, plant and animal biodiversity, water resources and rangelands as areas of highest vulnerability to climate change; these areas need to be measured for their adaptation to climate change [32].

Rand Water is committed to participate in efforts to alleviate climate change through policies that aim to promote the implementation of energy efficiency and energy management strategies. Electricity prices have a direct impact on the water tariff and its annual escalation. The annually escalating electricity price and the water tariff, together with the organisation's strategic direction towards climate change awareness, motivates Rand Water to explore the option of renewable energy sources.

Due to the scale of energy demand at Rand Water pumping stations; solar energy alone will not be an adequate source of electricity. However, the objective of this research is to study and identify the potential to save energy through the installation of rooftop solar PV systems at Rand Water buildings. In order to achieve these objectives, the research aims to:

- Demonstrate the potential for reducing energy requirements and costs by investigating energy generation and use, investment variables and electricity tariff rates.
- Identify the buildings and sites in which rooftop solar PV installations are feasible within the organisation.

The study will look at the rooftop solar PV installation at the Rand Water head office as a case study and utilise the information gathered from the case study to analyse the potential for similar installations in other Rand Water buildings.

1.6. Overview of dissertation

The dissertation is structured as follows:

- Chapter 1: Background

The introductory chapter discusses the background to this research study, the problem statement and the research objectives.

- Chapter 2: Rooftop solar PV systems

This chapter provides the background and theory on rooftop solar PV systems. The solar irradiation, types of PV systems, components of the PV system, orientation and mounting of PV modules, solar PV economics, and solar PV performance are discussed.

- Chapter 3: Analysis of rooftop solar PV system potential

This chapter discusses the methodology followed to determine the feasibility of a rooftop solar PV system installation, as well as the different variables to be considered in order to determine a suitable PV system size. The economic factors are also discussed.

- Chapter 4: Case study

This chapter provides information about the rooftop solar PV system installation at the Rand Water head office. The installation costs, saving and payback period for the installation are discussed. The potential for similar installations in other Rand Water buildings is investigated and discussed.

- Chapter 5: Conclusion

This chapter highlights the conclusions reached from the investigation. The achievement of research objectives is discussed and recommendations for future research are provided.

CHAPTER 2: ROOFTOP SOLAR PV SYSTEMS

[2]

The two types of PV systems – grid-tied and stand-alone – are reviewed. The main components and balance of system components, economics and performance of PV systems are discussed. The chapter further discusses the estimation of rooftop solar PV systems in commercial buildings and the benefits thereof.

[2] *Commercial solar photovoltaic systems [Online]. Available: http://www.entersolar.com/commercial-solar-projects/croda-usa*

2.1. Introduction

The sun delivers energy in two main forms, namely light and heat. PV systems convert sunlight into electricity. PV modules are the main building blocks in a PV system and these modules can be arranged in an array to increase energy generation [33]. Research has shown that Africa has an abundant supply of solar energy.

This chapter provides the background and theory on rooftop solar PV systems. The solar irradiation, types of PV systems, components of the PV system, orientation and mounting of PV modules, solar PV economics and solar PV performance are discussed.

2.2. Solar irradiation

Solar irradiance or solar power is the sun's radiant power incident on a surface of unit area and it is expressed in kW/m^2 or W/m^2. The solar irradiation or solar insolation is the sun's radiant energy incident on a surface area and it is expressed in kWh/m^2 or Wh/m^2 [34]. Figure 3 shows the direct normal solar irradiation map of South Africa, Lesotho and Swaziland.

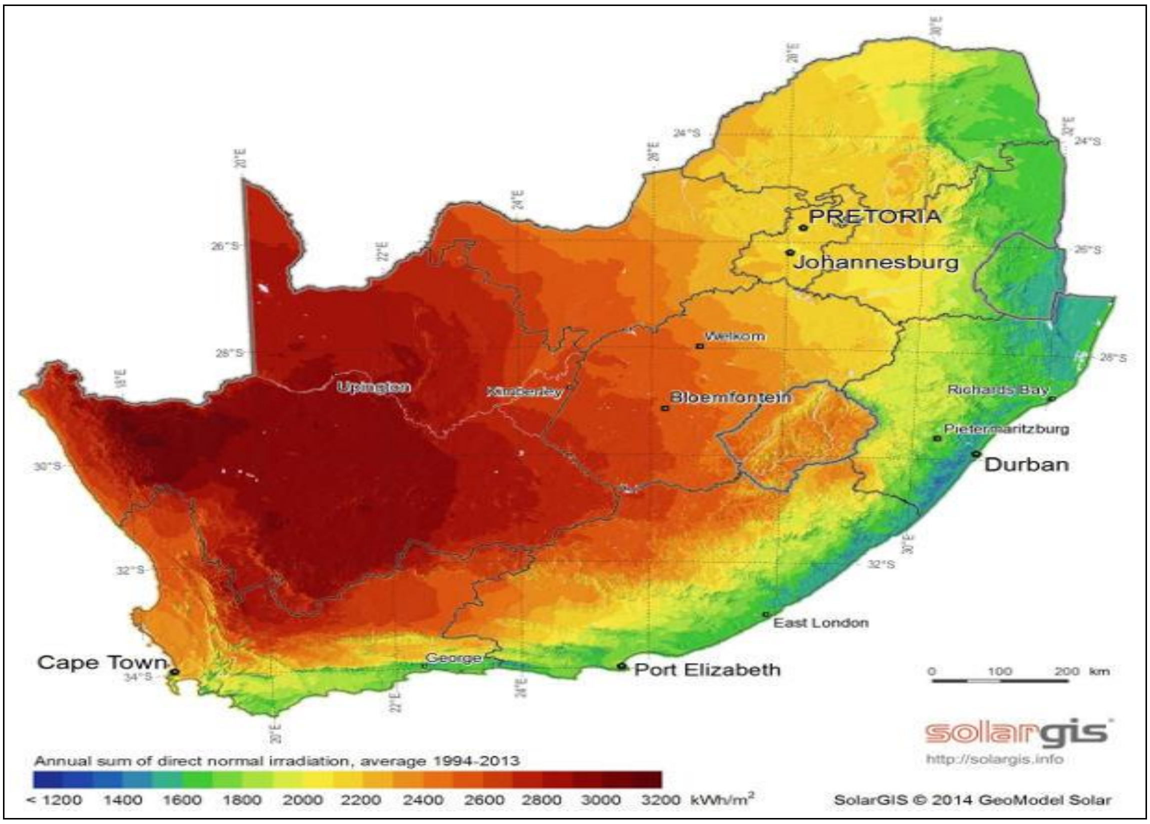

Figure 3: Direct normal solar irradiation map of South Africa, Lesotho and Swaziland [35]

Peak sun hours represent the number of hours in which the solar irradiance should remain at a peak level of 1 kW/m^2 to accumulate the total amount of daily energy received. PV modules are rated at 1 kW/m^2 solar irradiance (solar power); therefore, peak sun hours represent the number of hours in which the PV module will generate peak power output.

Figure 4 shows the relationship between solar irradiance (kW/m^2) and peak sun hours (h). It further shows that the area under the graph represents the solar energy or solar insolation in Wh/m^2.

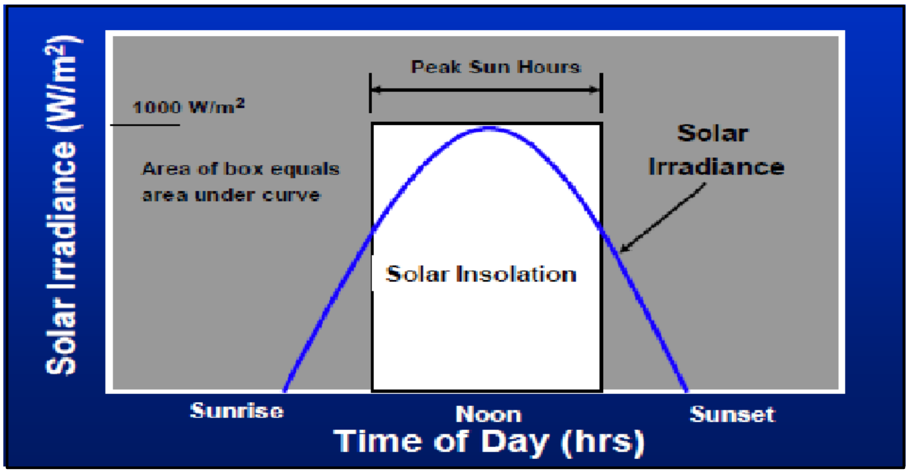

Figure 4: Solar irradiance vs time of day [34]

In South Africa, the average solar insolation levels range between 4.5 kWh/m^2/day and 6.5 kWh/m^2/day; this is equivalent to 4.5 to 6.5 hours of useful sunshine at Standard Test Conditions (STC) [36]. The average peak sun hours are 5.5 hours of useful sunshine; with reference to Figure 4, this means that peak solar insolation occurs between 09:00 and 15:00, with maximum peak generation at 12:00.

2.3. Types of rooftop solar PV systems

A PV system is able to supply electric energy to a given load by directly converting solar energy to electrical energy through the PV effect. The main components in a PV system are the PV modules (which comprise of a number of cells) and the inverter(s). The PV effect occurs when sunrays strike the PV module and direct current (DC) is produced, this is electrical energy.

Sunlight is composed of photons or particles of solar energy, these photons contain various amounts of energy corresponding to different wavelengths on the solar spectrum [33]. When these photons strike the PV module; they are either reflected or absorbed, and only those photons that are absorbed generate electricity. The PV cell contains silicon material; the energy of the photons is transferred to the electron of the silicon atoms and the electron escapes from its normal position in the silicon atom to produce an electric field within a PV cell [33]. The electric current produced in a PV module is equivalent to the sum of the electric current produced by the cells in the PV module. Figure 5 shows the concept of electricity generation in solar technology.

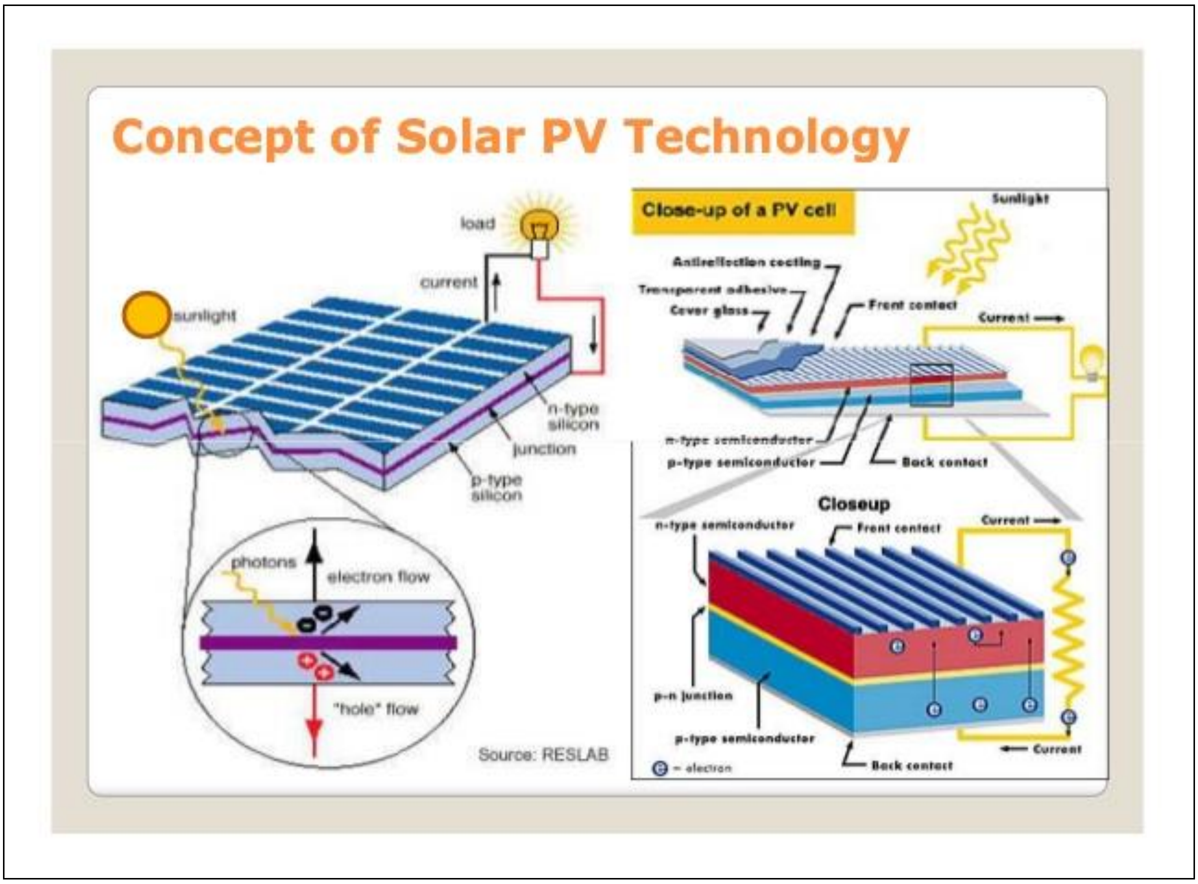

Figure 5: Concept of solar PV technology

A rooftop PV system is a PV system in which the PV modules are mounted on the roof. There are two main groups of PV systems, namely, stand-alone PV systems and grid-tied PV systems. The selection of the type of PV system depends on the end-use application of the technology [37].

2.3.1. Stand-alone PV system

A stand-alone PV system is isolated from the electrical distribution system. Figure 6 shows the configuration of a stand-alone PV system. These systems are ideal in areas which are isolated, do not have a power grid or are far from a power grid – such as rural areas or offshore islands [37]. The use of backup batteries is necessary to ensure that energy generated is stored in batteries such as lead-acid, nickel-cadmium or lithium-ion batteries. The stored energy is useful in conditions where the PV system generation is zero or minimal, for example during the night.

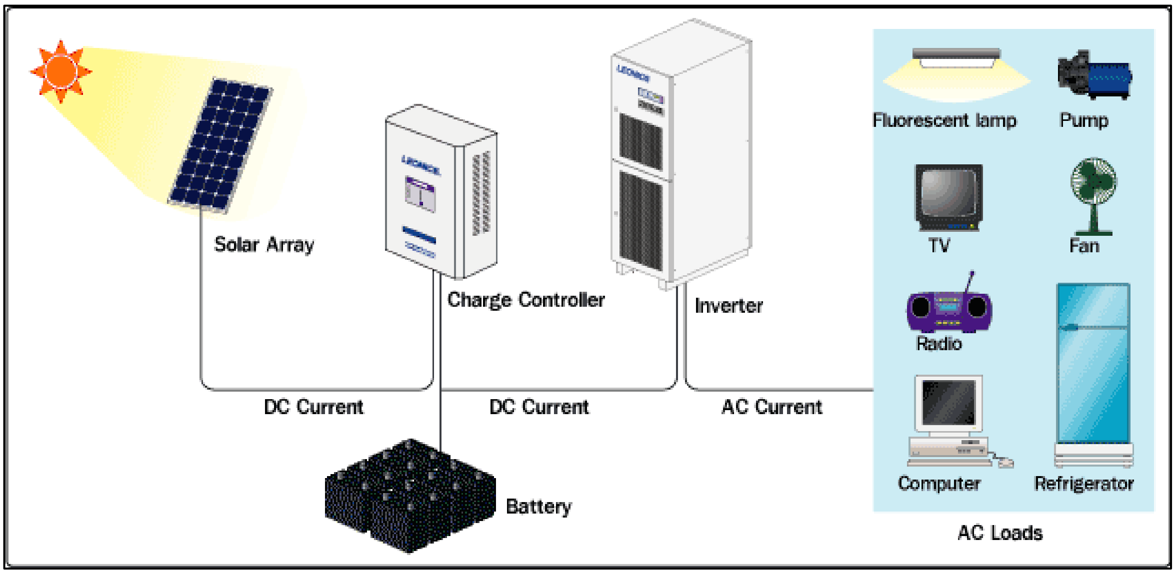

Figure 6: Configuration of a stand-alone PV system with battery backup [34]

2.3.2. Grid-tied PV system

A grid-tied PV system is connected to the electrical distribution system. Figure 7 shows the configuration of a grid-tied PV system. The power from the grid and the PV system is combined to supply the total load of the main alternating current (AC) distribution board (DB). The power grid and the electrical output from the PV system operate synchronously. The power grid has the capacity to supply power to the loads on days where the PV system is unable to produce electricity. Furthermore, it is possible to feed excess electricity produced by the PV system back into the power grid on days where excess electricity is produced.

2.4. Components of a solar PV system

The main components of a stand-alone and grid-tied PV system are the PV module and the inverter(s). A PV system with energy storage has additional components, namely, the charge controller and a battery bank.

PV module

PV modules are based on silicon and the common types that are available are mono-crystalline, poly-crystalline, thin-film and hybrid (a combination of mono-crystalline and ultra-thin film) silicon modules [33]. The important variables to consider when selecting a PV module are the PV module peak power output (Wp), its nominal operating temperature in degrees Celsius (°C) and the conversion efficiency (η).

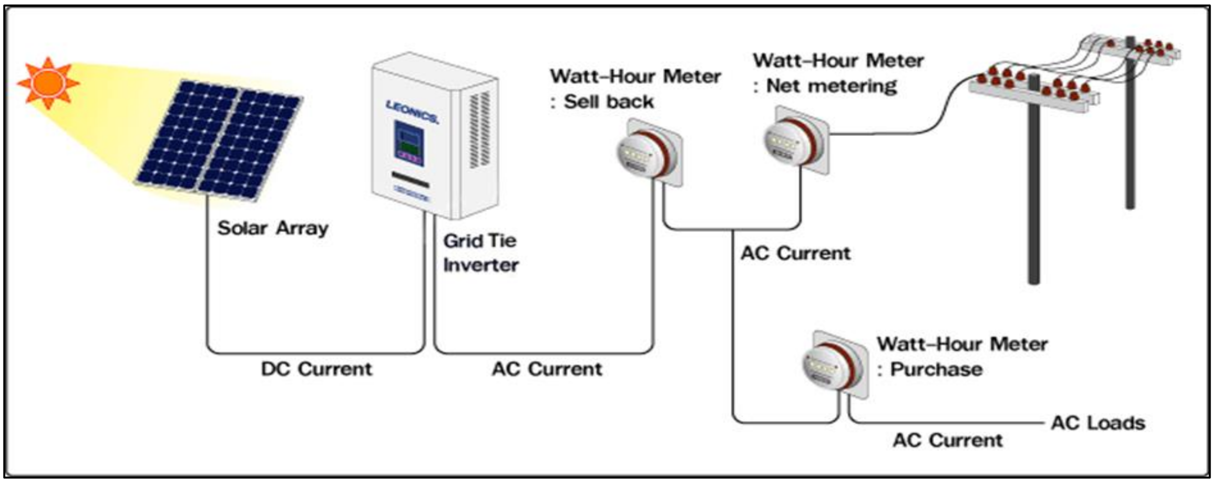

Figure 7: Configuration of a grid-tied PV system [34]

Efficiencies are reported based on STC, 1 000 W/m^2 at T = 25 °C of sunlight. It is important to note that theoretical efficiencies are reported to be as high as 30% for PV modules, while efficiencies from actual installations are closer to about 16% to 18% [38] [39].

Figure 8 shows a mono-crystalline, poly-crystalline and thin-film PV cell [33].

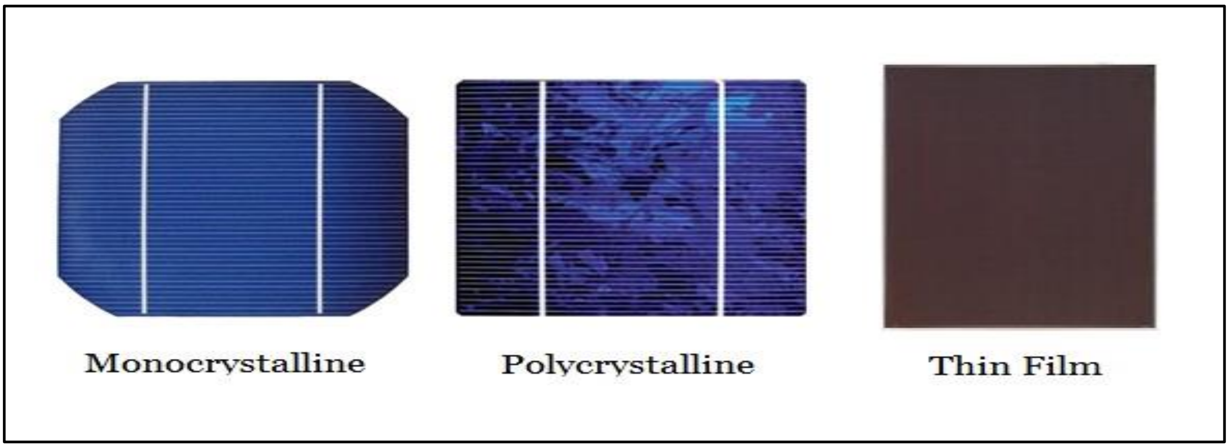

Figure 8: Mono-crystalline, poly-crystalline and thin-film PV cells [37]

Table 3 provides a comparison of the PV modules available in the market.

The cost of PV modules varies among suppliers and depends on the efficiency of the module; the higher the efficiency, the higher the cost. The hybrid PV system is the latest development in PV technology and it is also the most expensive. In 2015, the mono-crystalline and poly-crystalline modules were the most commercially available modules and accounted for 93% of PV modules sold globally in both small and large scale [40].

Table 3: Comparison of PV modules [33] [37] [38] [39]

PV cell type	Mono-crystalline	Poly-crystalline	Thin-film (all types considered)	Hybrid
Conversion efficiency	13–16%	11–15%	5–13% CIGS: 10–13% CdTe: 9–12% a-Si: 5–7%	>18%
Life expectancy	25–30 years	20–25 years	15–20 years	15–20 years
Cost (i.e. 100 Wp)	R10.79/Wp	R9.89/Wp	R8.99/Wp	R11.69/Wp

The mono-crystalline module is more expensive and efficient than the poly-crystalline module, but requires more time and solar energy to produce the same amount of electricity. Therefore, a mono-crystalline module can be used when a smaller surface area is available, while a poly-crystalline module can be used when a bigger surface area is available. The conversion efficiencies show that, for example at STC conditions, an a-Si thin-film PV array will need close to twice the space of a poly-crystalline silicon PV array because its module efficiency is halved [37].

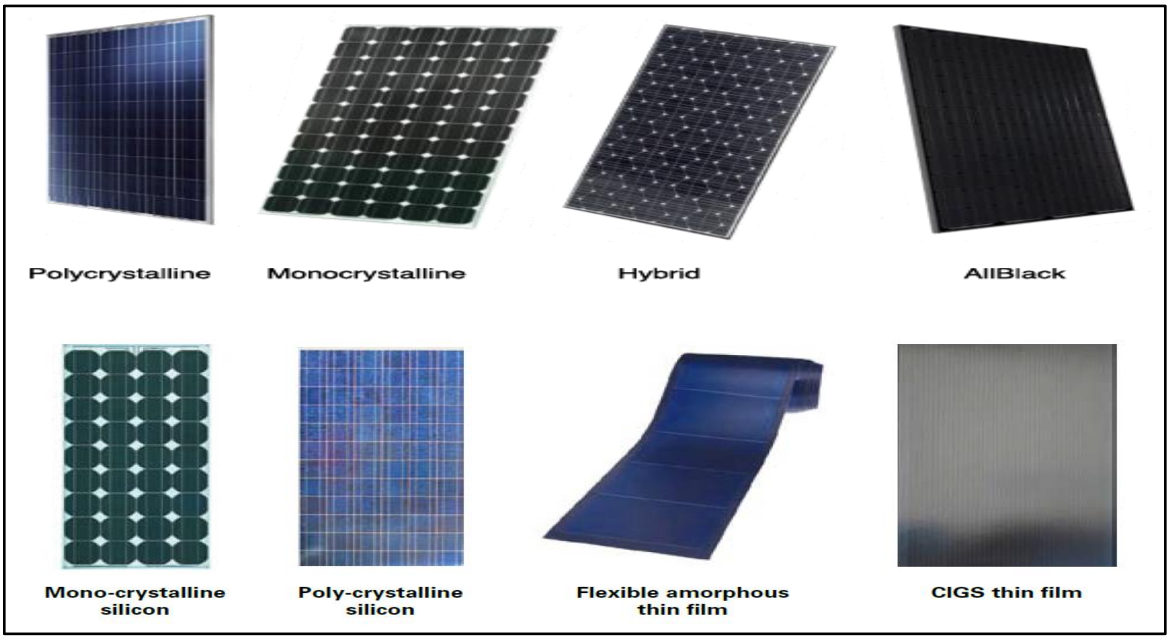

Figure 9: Poly-crystalline, mono-crystalline, hybrid and thin-film PV modules [37] [41]

Figure 9 shows the typical poly-crystalline, mono-crystalline, hybrid and thin-film PV modules. Some manufacturers produce modules with a black frame and black backing behind the cells instead of the traditional white and these are called all-black modules, as shown in Figure 9. The black backing on the cells is a disadvantage because the sunlight that hits the back of the cell is absorbed by the black surface instead of being reflected back to the cell [40].

The PV modules are connected in series to form a PV string and the PV strings are connected in parallel to form a PV array, as shown in Figure 10. The PV modules are designed to supply DC voltages of 12 V, 24 V or 48 V, and the current produced depends on the amount of sunlight that hits the module.

Figure 10: PV string and PV array [37]

Inverter

The inverter converts the DC power output from the PV system into AC power. In a grid-tied system; the AC output is connected to the existing electricity supply, as shown in Figure 7, such that the PV system offsets the electricity received from the existing supplier. In a stand-alone PV system; the AC output from the inverter is connected directly onto the load, as shown in Figure 6.

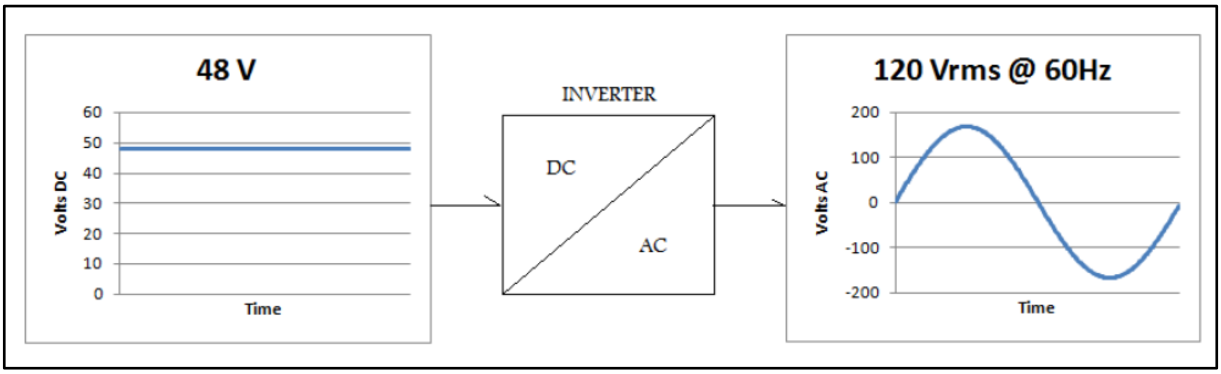

Figure 11: Representation of a DC-to-AC conversion [33]

Inverters are classified into stand-alone inverters and grid-tied inverters [33]. These inverters have efficiencies above 85% with a warranty of about 5 to 10 years [33]. Figure 11 shows a representation of a DC-to-AC conversion.

Stand-alone inverters require a battery bank that provides a constant DC input to the inverter. These inverters are classified into square-wave inverters, modified sine-wave inverters and sine-wave inverters (quasi-sine-wave inverters). The inverter is selected based on the type of load it will supply, i.e. a square-wave inverter for resistive load and a sine-wave inverter for a motor [33]. This inverter can be used as a grid-tied inverter or in combination with other renewable sources in a hybrid system.

The output from the grid-tied inverter is coupled to the electrical distribution and must produce a perfect sinusoidal AC output. The inverters in this group are classified into line-commutated inverters (which derive their switching signals from the line currents) and self-commutated inverters (which derive their switching signal from internal control units through monitoring grid conditions such as frequency and/or voltage) [33].

Self-commutated inverters are either voltage-source inverters or current-source inverters. In PV systems, voltage-source inverters are used because the PV system behaves as a voltage source. The voltage-source inverter can be further classified into voltage control and current control. Voltage control is used in applications where the grid reference is not available and the inverter operates as a voltage source, while in current control the inverter operates as a current source. Furthermore; current control voltage-source inverters use the utility voltage as a reference to provide the current available from the PV system and are not able to operate when the utility voltage is not available (or is zero) [33].

Batteries

Battery storage is used in grid-tied and stand-alone solar PV systems to store energy generated during the day at peak sun hours for use in the periods of zero solar energy production [42]. The battery capacity (kWh), power rating (kW), depth of discharge (DoD), round-trip efficiency, warranty and manufacturer are factors that are used to select a battery energy storage system for a solar PV system [42].

The battery capacity is the total amount of electricity that a solar battery can store and the power rating is the amount of electricity that a battery can deliver at one time. Therefore; a battery with a high capacity (kWh) and a low power rating (kW) would deliver a low amount of electricity (enough to run a few crucial appliances) for a long time, while a battery with a low capacity and a high-power rating could run your entire home but only for a few hours [42].

The depth of discharge (DoD) of a battery refers to the amount of battery capacity that has been used. A battery normally peaks at 90% DoD, for example you cannot use more than 90% or 9 kWh of a 10 kWh battery before recharging it [42]. The DC-AC conversion losses should be taken into consideration when sizing a battery storage system [43].

The performance of a battery degrades over time but most manufacturers will guarantee that the battery keeps a certain amount of its capacity over the course of the warranty [42]. The useful lifespan for a solar PV system battery is between 5 and 15 years with a guaranteed manufacturer warranty of a certain number of cycles and/or years of useful life. Thus, the batteries will have to be replaced at least once to match the 25-year lifespan of solar PV modules. The useful lifespan can be improved by ensuring that the batteries are maintained and protected from freezing or sweltering temperatures [42] [43].

The types of batteries used in solar PV systems are lead-acid, lithium-ion, sodium-sulphur, nickel-based, redox-flow and metal-air; with lead-acid being the oldest technology [42] [43] [44]. Table 4 below shows the comparison between lithium-ion and lead-acid batteries which are the leading battery technology at present.

Table 4 Comparison between lithium-ion and lead-acid batteries [42] [43] [44].

Lithium-ion batteries	**Lead-acid batteries**
• More expensive • Domestic grid-connected solar PV storage systems • Compact and lightweight • Require integrated controller, that manages charge / discharge • More efficient • Long lifespan • Perform better at low temperatures	• Cheaper • Off-grid properties where more storage is required • Heavier and larger • Require good charging/discharging to maintain battery health • Less efficient • Short lifespan • Perform poor at low temperatures

Similar to PV modules, batteries can be wired together to achieve the desired current, voltage, and power ratings [43] as shown in Figure 12. The addition of battery storage to a solar PV system is debatable because batteries are expensive and they have a shorter lifespan than PV modules.

The cost of batteries dropped by 14% on average, every year between 2007 and 2014, from $1,000/kWh down to $410/kWh with Tesla batteries reducing further down to about $300/kWh [44]. It is stated that by 2020, lithium-ion batteries are predicted to reach prices of $200/kWh without further technological improvements.

Figure 12 Battery bank [44].

Balance of system components

The balance of system components includes all the additional equipment required for the installation of a PV system and constitutes about 30% to 50% of the total cost of the PV system [33]. The balance of system components includes, but is not limited to, the following:

- Conductors, conduits and boxes,
- Fuses and breakers for overcurrent protection,
- Ground-fault protection,
- Mounting structures,
- Metering equipment,
- Maximum power point trackers,
- Charge controllers (battery backup),
- Battery enclosures, and
- Batteries.

2.5. Mounting and orientation of a PV system

The orientation of the PV system should ensure that the system performs optimally throughout the year. In order to achieve the best output from the PV system, the PV modules should be orientated towards the north and must have a clear view of the sun, i.e. unobstructed by trees, roof gables and surrounding landscape for most or all of the day. A PV module is made up of individual cells, as shown in Figures 8 and 9, which all produce a small amount of current and if one of the cells is shaded, this affects the entire module by dissipating power rather than producing it. Instruments such as solar path calculators can be used to assess shading at particular locations by analysing the sky view where the PV modules will be installed.

Roof-mounted PV systems can be mounted flat on the roof facing the sky or they can be mounted on frames that are tilted towards the north at an optimal angle. They are usually more expensive than ground-mounted systems. The amount of solar energy produced and the cost of producing the energy is influenced by, but not limited to, the type of roof material used and the orientation of the roof. For example, it is more expensive to install a PV system on a concrete roof than on a corrugated iron roof because of the reinforcement required for a concrete roof installation. Thus, factors to consider in mounting an array of PV modules include orientation, safety, structural integrity, local standards and local codes.

2.6. Solar PV economics

The cost of a solar PV system installation decreases as the size of the PV system increases, as shown in Table 5 [45].

Table 5: PV system sizes and costs

PV system size	Cost
0 kW–1 kW	R80/W–R100/W
1 kW–10 kW	R60/W–R80/W (grid-tied)
10 kW–100 kW	R50/W–R60/W (grid-tied)
100 kW–1 MW	R40/W–R50/W (grid-tied)

However, prices are falling as the market is growing. In 2013, suppliers and technical experts in the PV industry confirmed that the costs were R22/W to R28/W for a grid-tied system and R35/W to R40/W for a system with battery backup. Currently, costs have decreased to as low as R11/W and R9/W for a grid-tied PV system, depending on the installer.

The operation and maintenance (O&M) cost of PV systems varies and is reported to be in the range of 0.17% to 0.35% of the total installation cost for a fixed-tilt grid and single-axis tracking PV system, respectively [46]. In [47]; research was done with IPPs, solar companies, O&M providers, insurance providers and bankers to determine the O&M budget for solar PV systems and it was established that O&M typically accounts for 1% to 5% of the installation cost per year.

The performance warranty of the PV system components is as follows:

- A 25-year warranty for PV modules,
- A 5 to 10 year warranty for the inverter(s), which can be extended to 15 years at an extra cost, and
- A 6-year warranty for batteries.

2.7. Solar PV performance

Solar inverter power output varies and depends almost entirely on sunlight, but the current drops much faster until you reach very low light levels. PV modules will typically generate 16 V under very low light conditions but at very low current [48]. These variances in power produced are influenced primarily by the level of solar irradiance and ambient temperature, as shown in Figure 13.

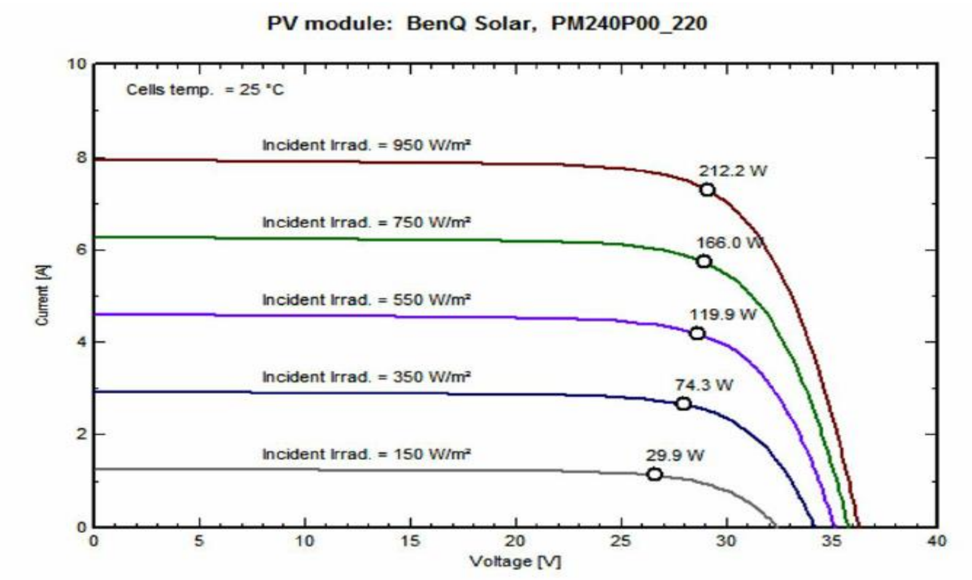

Figure 13: Voltage–current characteristic curves of a PV module [49]

The PV module performance is affected by the efficiency of the module and the temperature of the location in which the PV system is installed. It is stated that PV cell performance declines as cell temperature rises [37]. PV modules are rated at a specific temperature, and this is indicated as a temperature coefficient (%/°C) on the PV module datasheet.

Table 6 shows the temperature coefficient of various PV cell technologies. Thin-film technologies have a lower negative temperature coefficient, the ratio between the percentage drop in capacity and the increase in temperature in °C indicates that they tend to lose less of their rated capacity as temperature rises when compared to other PV cell technologies.

Table 6: Temperature coefficient of PV cell technologies [37]

Technology	Temperature coefficient (%/°C)
Poly/mono-crystalline silicon	–0.4 to –0.5
CIGS	–0.32 to –0.36
CdTe	–0.25
a-Si	–0.21

Figure 14 shows the effects of a negative temperature coefficient on the performance of the different types of PV modules.

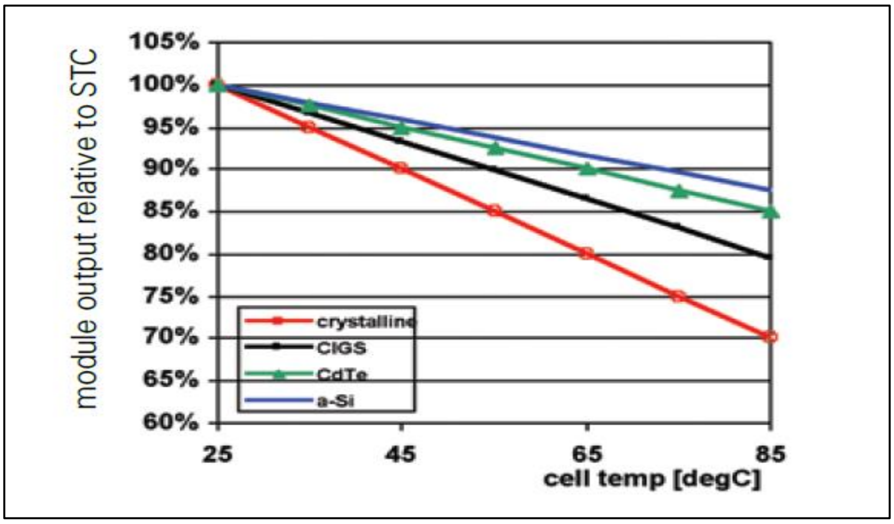

Figure 14: Effects of a negative temperature coefficient on PV module performance [37]

It shows that the temperature at STC is 25 °C and that the performance of the PV module drops as its temperature increases.

2.8. Estimation of rooftop solar PV potential

Solar PV potential can be defined as physical, geographical, technical and economic potential. Physical potential represents the amount of solar energy that can be received in a certain area, geographical potential is calculated by gradually excluding zones reserved for other uses while restricting the areas where solar can be gathered and technical potential considers the technical characteristics of the equipment used for converting solar energy into electrical energy [50].

In [51], Izquierdo et al investigate geographical, physical and technical potential in order to determine the available roof area for different geographical scales. The research indicates the limitations when determining the available roof area such as the orientation of the building, height of the building, number of buildings, inclination, location, shading, historical considerations and services located on the roof. The methodology is scalable and can be used on both a continental and regional scale.

In [52], Ntsoane investigates physical and geographical potential in the City of Johannesburg in order to determine the amount of usable rooftop area (in square metres) in the Johannesburg central business district. The estimation focused on a number of buildings in the city which led to a potential of 0.23% reduction in carbon emissions and a 0.31% reduction in electricity revenue. In South Africa, large-scale utilisation of solar energy took off as a result of the REIPPP programme in 2011. Therefore, there is minimal literature on the estimation of rooftop solar PV potential in South Africa.

Wang and Sueyoshi discuss the development of a methodology to investigate the performance and efficiencies of a number of commercial PV installations in California. The efficiency is determined with the use of physical, geographical and technical potential variables as input variables – i.e. solar irradiance, PV modules, total cost and temperature – while the output variables are capacity (kW) and electricity generation (kWh) [53].

In [54], Singh and Banerjee utilise the methodology in [51] to present the feasibility of a large-scale deployment of PV installations in Mumbai, India. Although the physical and geographical potential are described in the research, emphasis is placed on the technical potential to elaborate on the analysis and the results of the study.

Mewes et al examine the feasibility of installing PV systems at a university in Stockholm [55]. The research emphasises the need to improve energy efficiency in buildings prior to installing a PV system because it is cheaper to improve energy efficiency than to install a PV system. The methodology investigates physical potential by physical simulation to determine the solar irradiance and geographical potential by mapping available buildings within the campus and calculating the available rooftop area. The preferred buildings were selected based on a minimum available roof area as criteria i.e. the rooftop area must be 300 m^2 and above. PVsyst; a design and simulation software was utilised to model the potential solar energy generation from each of the buildings.

2.9. Economic benefits of rooftop solar PV systems

Energy saving and a reduction in carbon emissions are some of the benefits of using solar PV systems. Economic potential defines the benefits in monetary terms as a result of a reduction in the amount of energy demanded from the electricity supplier or complete independence from the electricity supplier.

Brahim and Jemni define economic potential in terms of energy saving potential, cost augmentation, estimated payback time, lifecycle cost saving and levelised cost of energy (LCOE). Environmental potential is described in terms of energy payback time, greenhouse payback time and their relevance on the energy and efficiencies of the PV system [56]. Shezan et al analyse the economic benefits of a hybrid plant with a focus on net present cost (USD), carbon emissions and the cost of energy (USD/kWh) [57]. The economic analysis conducted in [58] investigates the cash flows, net present value (NPV), internal rate of return (IRR) and tax incentives; the research shows that including tax incentives improved the IRR and NPV.

The aim of the research in [59] is to conduct a technical, environmental and economic feasibility study for a residential PV system. The lifecycle cost analysis is used to determine the economic potential which consists of the total fixed costs and operating costs over the lifespan of the PV system, expressed in present value. The research investigates the installation costs, O&M costs, NPV and LCOE. The environmental feasibility discussed in the research quantifies the reduction in carbon emissions. Furthermore, the study determined that the LCOE for a stand-alone PV system was higher than that of the conventional electricity supply to the residential sector in Cameroon.

Hammad et al aim to contribute to the research on fixed and tracking PV systems by comparing the economic benefits of the two systems instead of performing a technical comparison, as it was done by previous researchers [60]. The variables investigated are the capital cost, IRR, payback period, and the annual uniform payment or capital recovery factor for a project that is funded by a bank. The research shows that, although the tracking system generates more energy than the fixed system; the

IRR, payback period and electricity cost over 20 years are more attractive for a fixed PV system in Jordan and other countries with similar geographic characteristics.

In [61]; the NPV, NPV benefit-to-cost ratio and simple payback period are discussed to elaborate on the variables used to indicate the economic viability of a PV system. Economic viability is equivalent to a positive NPV, a high NPV benefit-to-cost ratio and a short simple payback period. In this research; the case study yields a positive NPV and a long simple payback period, of which the long simple payback period could be interpreted as financial unviability of the PV system. It is recommended that economic viability must be based on NPV analysis with the simple payback period as additional information.

Lukac et al investigate the economic and environmental benefits by focusing on NPV, return on investment using FITs, capital cost for the economic assessment, energy payback time and reduction in greenhouse gas emissions for the environmental assessment [62]. The study found that a higher NPV is achieved for PV systems installed on the most suitable roofs and surfaces. Furthermore, PV systems making use of a-Si modules have a fast EPBT but require longer operation for a positive NPV compared to p-Si and m-Si and the more efficient modules (p-Si and m-Si) have a slower EPBT but a higher GGER.

The economic analysis in [63] by Haegermark et al investigates the NPV and the profitability index (PI = NPV/Investment) to determine which projects use the money invested, efficiently. The scenarios investigated include tax rebate, investment subsidy and both tax rebate and investment subsidy. The study showed that tax rebate with an investment subsidy has an impact on profitability and the sizing of PV systems. Of the 108 buildings, 93% of the PV systems showed a positive NPV on tax rebate with an investment subsidy. A high PI was achieved on micro PV systems and supply points with high loads receiving an investment subsidy. The study further showed that the tax rebate supports relatively large installations and that the feasibility for a PV system is highly sensitive to roof characteristics, electricity demand and fuse size.

2.10. Conclusion

The selection of the type and size of the rooftop solar PV system is motivated by the electricity needs of the end user and the available budget. Research shows that the location (physical potential) at which the system will be installed provides an indication of the amount of solar energy that is available in the area. The orientation and mounting of the PV modules (geographical potential) allows the installer to maximise on the amount of solar irradiance absorbed by the PV modules for that specific location. The technical potential, represented by the type of equipment and the controls utilised for a PV system, is determined to ensure that the power requirements at desired efficiencies are met.

The economic potential in terms of NPV, IRR, LCOE and simple payback period provides an indication to decision-makers and investors of the financial benefits of a PV system. The capital cost of a PV system assists in budgetary provision and in determining the NPV, LCOE and simple payback period. The environmental potential, i.e. the reduction in greenhouse gases, is included in the economic analysis as a greenhouse payback time that indicates the reduction in carbon emissions in kg/CO_2.

CHAPTER 3: ANALYSIS OF ROOFTOP SOLAR PV SYSTEM POTENTIAL

[3]

The methodology to analyse the rooftop solar PV system potential is discussed.

[3] *D Makhathini, personal photograph. "Mounting structure for rooftop solar PV subsystem at the head office", South Africa, 2016.*

3.1. Introduction

This chapter discusses the methodology followed to determine the feasibility of a rooftop solar PV system installation, indicating in particular the importance of the geographical and meteorological data of the area identified as a potential location. The chapter further discusses the different variables to be considered in order to determine a suitable PV system size. Economic factors such as PV system cost, O&M cost, LCOE (in R/kWh) and simple payback period are discussed.

The methodology followed in this research focuses on the physical, geographical, technical and economic solar PV potential. Figure 15 indicates the methodology followed to analyse the potential for a rooftop solar PV system and from this figure it is evident that technical potential is the most extensive variable in determining solar PV potential.

3.2. Location of the potential site

The study location is the location where the rooftop solar PV system could possibly be installed. Solar PV systems should be installed in locations with a high solar irradiance to ensure that the system can produce solar energy for conversion into electrical energy.

In South Africa, the annual solar irradiance is available on the South African Renewable Energy Source Database and it provides an indication of the available solar irradiance on the South African map, as shown in Figure 2. For example; in Johannesburg, the annual solar irradiance is in the range of 2 084 kWh/m^2 to 2 222 kWh/m^2 (e_{sol}) with an average solar energy generation potential of 1 750 kWh/kWp (e_{elec}),

where,

- e_{sol} is the normalised solar energy that hits the front of the PV module within a certain time period (i.e. on the PV module plane) in kWh/m^2, and
- e_{elec} is the normalised electrical energy yield of the solar PV plant within a certain time period in kWh/kWp.

ftThe data required for a precise location are the latitude and longitude Global Positioning System (GPS) coordinates. The coordinates are inserted on Google Maps for a geographical layout of the site. The top view of the site provides the layout of the roof according to the geographical compass. This will provide an indication of the direction in which the PV modules should be mounted to ensure that solar energy generation occurs during peak sun hours, between sunrise and sunset.

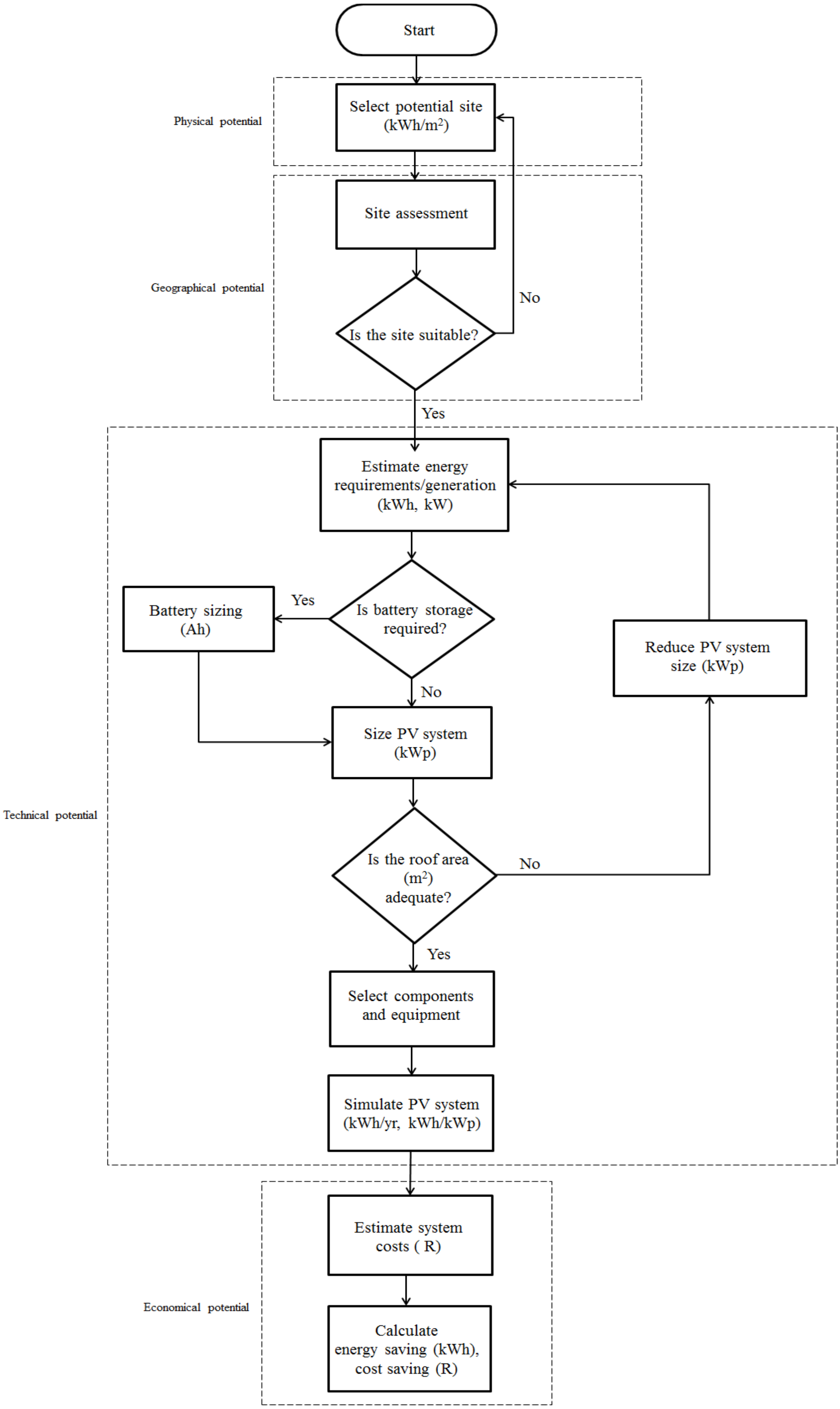

Figure 15: Methodology

Furthermore, the roof layout as seen on Google Maps provides an indication of the amount of space available on the roof on which the PV modules could be mounted. However, the site should be visited to measure the roof area (for example, using a measuring wheel) and to confirm any existing services on the roof. Existing services on the roof could reduce the amount of usable roof space due to shading – a phenomenon in which other existing structures on the roof cause shading on the PV modules as the sun moves from sunrise to sunset. In such cases, the PV modules must be mounted further from the shade to ensure that power production is not affected.

3.3. Selecting the type of PV system: Grid-tied or stand-alone

Organisations, companies and home-owners install PV systems for various reasons; for example, to reduce electricity consumption or costs, to reduce greenhouse gas emissions, or to provide power for their site. The abovementioned reasons provide guidance on selecting the type of PV system to install.

A grid-tied system is ideal in areas where there is an existing grid or electrical network. A grid-tied system without battery backup serves as an additional supply that is synchronised with the main supply, i.e. the Eskom supply. This means that the electricity supply is split between the PV system and Eskom, thus reducing the electricity consumed from Eskom and subsequently reducing the cost of electricity. Alternatively, the PV system could be the primary source of power with Eskom supply acting as backup during periods of low power generation.

A grid-tied system does not generate power when the main power supply is lost; this means that when the grid power is zero, the PV system will not supply any electrical power. The availability of electricity from the electricity supplier, grid voltage, serves as a control variable to determine the switching of the inverter. The main supply continues to supply electricity to the load in the early morning and evening when there is zero solar power generation. Emergency generators and uninterruptible power supplies are typically used as backup power in commercial buildings during a power failure or a power cut. A battery bank can be used to ensure that the PV system continues to supply power during power cuts or power failures. However, an economic benefit analysis must be done to select the preferred backup power technology as batteries and diesel are expensive.

A stand-alone system is ideal in remote areas without an existing grid or electrical network. Stand-alone systems are ideal as a main source of power and a battery bank is mandatory for a stand-alone system that is required for 24-hours of power supply because these systems do not have a grid or main supply as backup power. The PV system size must be big enough to feed the load and charge the battery during the day to ensure that power is available at night and in the early morning. These systems are generally more expensive than a grid-tied system without a battery bank; a battery bank increases the total cost of a PV system by approximately 50%.

In order to select a suitable type of PV system, the items listed below should be defined and discussed, as a minimum:

- Where is the site or building located and who is the main electricity supplier?
- What backup power is used, if any?
- Is the PV system the main source of electricity?
- Will excess energy be fed back into the grid?
- Is a battery bank needed?
- What is the budget?

3.4. Estimating power requirements

The size of the PV system is determined by the amount of power required by the site. Power requirements further assist in determining the type of PV system that should be installed; for example, power requirements may lead to the following system requirements:

1. A PV system that will provide the total daily electricity requirements for the site, or
2. A PV system that will provide the baseload electricity requirements during peak sun hours.

For the PV system to meet the total daily electricity requirements for the site; either a grid-tied or stand-alone PV system with battery storage can be utilised. The PV system must be sized such that excess power is generated during peak sun hours. This excess power is stored in batteries and used during periods of zero solar power generation, i.e. in the early morning and evening. Excess power can also be generated on days where the load is less than the power requirements for which the PV system was designed.

Baseload power is the minimum amount of energy required at the site; it is the same during weekdays and over the weekend. Similar to the previous discussion, either a grid-tied or a stand-alone PV system can be used and both systems will curtail the amount of electricity required from the electricity supplier – i.e. Eskom or the municipality – and will not produce excess power.

In South Africa, excess power generated from PV systems does not yield a financial benefit as the regulations and pricing pertaining to FITs have not been finalised. Therefore, it is important to avoid oversizing the PV system.

A PV system provides real power in watts (W); and the information needed to determine the required PV system size should be in W or kWh. In order to determine the power requirements in W or kWh, a site energy audit must be conducted as follows:

- An energy meter must be installed on the site for 15 to 30 days. The logged data must be used to determine the load profile and the behaviour of the load for a 24-hour profile.
- Alternatively, electricity billing accounts for 6 to 12 months can be used to determine the energy consumption trend of the site and the monthly (and daily) load requirements.
- For specific loads, a load list can be compiled. The operation philosophy for each load must be clear and understood in order to determine the 24-hour profile. It is important to ensure that each load or total load is considered when determining the size of the PV system.

3.5. Sizing the PV system

The size of the PV system is determined based on the type of PV system that is required and the estimated power requirements of the site. The PV system is sized in kilowatt peak (kWp) and this is defined as 1 000 W/m^2 at a STC temperature of 25 °C.

3.5.1. Power requirements in kWh

The annual solar irradiance is provided in kWh/m^2 for different geographical areas and it is provided in a range. The lower end or average of the two values can be used to calculate the e_{sol} per day in kWh/m^2/day, which can be read as hours/kWp/day at STC. Thus, the number of sun hours can be estimated from the solar irradiance.

The amount of power required from the PV system is determined as shown in (1).

$$P_{PV\_AC}\,(W) = \frac{E_{requirements}\,(kWh)}{t_{peak}\,(h) * n_{STC} * PR} \qquad (1)$$

where,

- P_{PV_AC} is the real AC power output from the PV system in W,
- $E_{requirements}$ is the estimated energy requirements in kWh,
- t_{peak} is the peak sun hours in h,
- η_{STC} is the efficiency of modules at STC in %,
- PR is the performance ratio of the PV system, which is defined as the actual energy generated against the anticipated energy generation at STC.

In order to ensure that the real AC power output from the PV system is the required amount of power, a DC-to-AC conversion loss ratio – which is between 1.1 and 1.15 – is used to increase the size of the PV array to cater for the conversion loss as shown in (2).

$$P_{PV\_DC}(W_p) = P_{PV\_AC} * Factor_{DC-AC} \qquad (2)$$

where,

- P_{PV_DC} is the real DC power output from the PV array in Wp,
- P_{PV_AC} is the real AC power output from the PV system in W, and
- $Factor_{DC-AC}$ is the DC-to-AC conversion factor.

Where the power requirements for a specific site are recorded in watts (W), the size of the PV system is determined as shown in (2), whereby the AC power requirement is PV_{PV_AC}.

3.6. Available roof space

It is stated in literature that the specific space requirement is in the range of 8 m^2/kWp to 10 m^2/kWp. The amount of roof space required can be calculated as shown in (3).

$$Area\ (m^2) = Factor_{specific\ \_space} * P_{PV\_DC} \qquad (3)$$

where,

- $Area$ is the roof area that is required to mount the PV modules, in m^2,
- $Factor_{specific_{space}}$ is the specific space requirement m^2/kWp,
- P_{PV_DC} is the real DC power output from the PV array in Wp.

The calculated roof space should be measured to ensure that there is adequate space on the roof for the specified PV system size.

3.7. Battery sizing

A battery storage system can be used for a grid-tied system or a stand-alone system. The costs associated with the use of batteries and their shorter lifespan when compared to the lifespan of PV modules discourages the use of batteries in PV systems. Assuming that the energy requirements for a PV system are known as $E_{requirements}$ in kWh; adding a battery storage system to ensure that power is available in the evening and/or on days of zero energy generation will require the solar PV system to generate more than $E_{requirements}$. The excess energy will ensure that the battery is fully recharged and that there is adequate supply of energy from the battery storage system when it is required.

The battery storage must be able to feed the energy requirements for a specific period of autonomy - a period in which the load can be fed from the solar PV system without recharging the battery- i.e. a few hours, a day or a number of days. The recommended number of days of autonomy for a stand-alone system is 5 days. The amount of battery storage capacity (Ah) required is determined as shown in (4).

$$Capacity_b(Ah) = E_{requirements} \times d_a \times T_{factor} \times \frac{1}{DoD} \times DM_{factor} \div V_b \quad (4)$$

where,

- $Capacity_b$ is the battery capacity in Amp-hour (Ah),
- $E_{requirements}$ is the estimated energy requirements in kWh per day,
- d_a is the days of autonomy in days,
- T_{factor} is the temperature correction factor and it is specific to the type of battery,
- DoD is the depth of discharge, normally in the range of 20% to 80%,
- DM_{factor} is the design margin factor, normally in the range 10% to 25% or 1-1.25, and
- V_b is the battery bank voltage; common voltages are 12V, 24V and 48V.

3.8. PV system simulation

The previous sections discuss theoretical calculations used to determine the size of the PV system for the site. A variety of simulation software for PV systems are available on the Internet, both as free trial versions and as full versions for purchase.

The simulation software requires the input variables indicated in Table 7 to calculate the projected monthly energy production for the simulated PV system. The annual projected energy production can be used to calculate the specific energy yield in kWh/kWp/year as shown in (5). The specific energy yield indicates the performance of the PV system according to the geographical location of the site.

$$E_{specific} = \frac{E_{projected}}{P_{PV\_DC}} \quad (5)$$

where,

- $E_{specific}$ is the specific energy yield in kWh/kWp/year,
- $E_{projected}$ is the simulated energy production per year, and
- P_{PV_DC} is the real DC power output from the PV array in Wp or kWp.

Table 7: Input parameters for projected energy production

Description	Input
PV system size	kWp or Wp
GPS coordinates	Latitude and longitude
Type of PV module	Manufacturer, Wp and silicon arrangement
Tilt angle*	Degrees
Azimuth angle of panels**	0 degrees, north
Array type	Fixed-tilt or tracking roof mount
Inverter efficiency	Percentage

* *The tilt angle is based on the latitude of the geographical location of the site.*
** *The azimuth angle is based on the continental location of the site, i.e. South Africa is in the Southern Hemisphere.*

3.9. Determining energy and cost savings

3.9.1. Energy savings

Grid-tied PV system

A grid-tied PV system is installed to curtail the energy consumed, at a specific tariff rate, from the main source of supply. Therefore, energy savings are defined as the reduction in energy consumption from the main source of supply. This saving is equivalent to the energy produced by the PV system. The energy generated by the PV system can be calculated as shown in (6).

$$E_{PV_{AC}} = P_{PV\_AC} * t_{peak} \qquad (6)$$

where,

- $E_{PV_{AC}}$ is the energy produced by the PV system in kWh,

- P_{PV_AC} is the real AC power output from the PV system in W, and
- t_{peak} is the peak sun hours in h.

The performance of the PV system must be monitored on a monthly basis in order to keep track of the amount of energy it produces and supplies. In the initial month of operation, the energy saving can be calculated as shown in (7).

$$E_s = E_{before} - E_{after} \qquad (7)$$

where,

- E_s is the energy saving achieved,
- E_{before} is the energy consumption at the site before the PV system was installed, and
- E_{after} is the energy consumption at the site after the PV system was installed.

The energy saving (as per the electricity bill) must be compared with the amount of energy produced by the PV system in that month to verify the impact of the PV system on the electricity bill. The energy reduction on the electricity bill should be compared to the PV system energy production on a monthly basis, not only to provide an indication of the monthly energy saving but also to confirm that the energy saving is achieved solely as a result of the energy produced by the PV system. This information must be further consolidated into an annual energy saving for the site.

PV modules have a design life of 20 to 25 years, depending on the manufacturer. The anticipated duration of guaranteed energy production is 20 to 25 years with a 10% degradation on the guaranteed PV power production after 10 years of operation. In the first year of operation, the guaranteed power production is above 90% of the PV module rating. Therefore, energy savings should be achieved for the design life and a slight reduction in energy saving is expected after 10 years of operation.

Assuming that the energy production is the same throughout the 25-year PV module lifespan, the anticipated energy production for the PV module design life is as shown in (8).

$$E_{PV_n} = \left(E_{PV_{AC}} * y_i * d * m\right) + (0.9E_{PV_{AC}} * y_{n-i} * d * m) \qquad (8)$$

where,

- E_{PV_n} is the amount of energy generated for the PV design life,
- $E_{PV_{AC}}$ is the guaranteed AC power production in the first 10 years,

- y_i is the initial years (i = 10 years), i.e. the first 10 years of the PV module design life,
- d is the number of days in a month,
- m is the number of months in a year,
- $0.9E_{PV_{AC}}$ is the guaranteed AC power production in the remaining life; i.e. years 11 to 25,
- y_{n-i} is the remaining life of the PV module, after year 10, and
- n is the design life of the PV module, i.e. n = 25 years.

Equation (8) is used to calculate the anticipated amount of energy savings for the duration of the PV module design life.

Stand-alone PV system

A stand-alone PV system is installed to provide electricity requirements to a load or site as a main source. The system is sized such that it is able to fulfil the complete load requirements of the site and to charge or recharge the backup batteries. The benefit of the system is achieved when the maximum expected power it produces is consumed at the load.

The energy capacity available from a stand-alone system is as shown in (9) and it is more than the energy requirements, $E_{requirements}$;

$$E_{stand-alone} = Capacity_b \times V_b \qquad (9)$$

where,

- $E_{stand-alone}$ is the capacity of the stand-alone PV system in kWh,
- $Capacity_b$ is the battery capacity in Amp-hour (Ah), and
- V_b is the battery bank voltage; common voltages are 12V, 24V and 48V.

The amount of power required from the PV system is determined as shown in (10).

$$P_{PV\_AC}\,(W) = \frac{E_{stand-alone}\,(kWh)}{t_{peak}\,(h) * n_{STC} * PR} \qquad (10)$$

where,

- P_{PV_AC} is the real AC power output from the PV system in W,
- $E_{stand-alone}$ is the capacity of the stand-alone PV system in kWh,
- t_{peak} is the peak sun hours in h,
- η_{STC} is the efficiency of modules at STC in %, and

- PR is the performance ratio of the PV system, which is defined as the actual energy generated against the anticipated energy generation at STC.

The size of the PV array is determined as shown in equation (2) and it will be much higher than the PV array for a grid-tied PV system. The energy saving is the guaranteed power produced by the PV system (as opposed to using the conventional power supplier for the site).

3.9.2. Cost savings and payback period

The total lifecycle cost of a PV system is as shown in (11).

$$PV_{total_{cost}} = PV_{system_{cost}} + \sum_{y=1}^{25} PV_{O\&M\_cost}(y) + \sum_{y=10,20} PV_{replacement_{cost}}(y) \quad (11)$$

where,

- $PV_{total_{cost}}$ is the total lifecycle cost of the PV system in Rands,
- $PV_{system_{cost}}$ is the installation cost of the PV system in Rands, including the procurement of components,
- y is represents the year,
- $PV_{O\&M\_cost}$ is the O&M cost of the PV system in Rands, and
- $PV_{replacement\_cost}$ is the cost for the replacement of inverters and/or batteries.

Assuming that the energy production is the same throughout the year, the energy cost saving per year is calculated as shown in (12).

$$C_s = (E_s * r_l * m_l) + (E_s * r_h * m_h) \quad (12)$$

where,

- C_s is the cost saving achieved in Rands,
- E_s is the energy saving achieved in Rands,
- r_l is the low season demand tariff rate in c/kWh for that year,
- m_l is the number of months in the low season demand,
- r_h is the high season demand tariff rate in c/kWh for that year, and
- m_h is the number of months in the high season demand.

The tariff rate in c/kWh increases every year, assuming that the energy production is the same in the first ten years, the annual increase in the tariff rate will result in a reduction in cost savings. A further reduction in the cost savings will be seen after ten years when the guaranteed energy production is reduced by 10%.

The total lifecycle cost savings can be quantified as shown in (13).

$$Total_{C_s} = \sum_{y=1}^{10} E_s([r_l(1 + t_{increase})^{y-1} \times m_l] + [r_h(1 + t_{increase})^{y-1} \times m_h]) \\ + \sum_{y=11}^{25} 0.9E_s(\, [r_l(1 + t_{increase})^{y-1} \times m_l] + [r_h(1 + t_{increase})^{y-1} \times m_h]) \quad (13)$$

where,

- $Total_{C_s}$ is the total cost saving achieved in Rands over a 25-year PV module design life,
- E_s is the energy saving achieved in Rands,
- r_l is the low season demand tariff rate in c/kWh for the first year of operation,
- m_l is the number of months in the low season demand,
- r_h is the high season demand tariff rate in c/kWh for the first year of operation,
- m_h is the number of months in the high season demand, and
- $t_{increase}$ is the tariff increase for the first year of operation.

The simple payback period is as shown in (14).

$$SPP = \frac{PV_{total_{cost}}}{C_s} \quad (14)$$

where,

- SPP is the simple payback period in years,
- $PV_{total_{cost}}$ is the total lifecycle cost of the PV system in Rands, and
- C_s is the cost saving achieved in the first year of operation, in Rands.

3.10. Conclusion

The methodology followed is a simple and generic methodology to analyse the potential for a rooftop solar PV system. The physical potential of the PV system is the initial consideration as this provides information on the solar irradiance in the area at which the site is located. The geographical potential indicates the suitability of the site for the installation of a rooftop solar PV system and the potential to harvest solar energy. The technical potential investigates and provides an indication of the PV system details such as the PV system size and battery size, the amount of roof area that is required, the balance of system components and the optimal tilt angle of the PV modules. The estimated and simulated energy production provides an indication of the technical potential for the rooftop solar PV system that is analysed.

Economic potential investigates the financial benefits in order to quantify the return on investment and the electricity cost saving. The LCOE is determined to indicate the benefits of the rooftop solar PV system in comparison to the existing electricity tariff for the site; a beneficial PV system yields an LCOE that is lower than the existing tariff for the site. A detailed financial model should be compiled to determine specific and detailed financial benefits; taking into consideration as a minimum (but not limited to) the lifespan of the equipment and the annual O&M costs.

CHAPTER 4: CASE STUDY


[4]

The rooftop solar PV system installation at the Rand Water head office (Rietvlei) is discussed.

[4] *Rand Water/NR Green photograph. "Rooftop solar PV system at Rand Water head office – aerial view", South Africa, 2017.*

4.1. Introduction

This chapter discusses the rooftop solar PV system installation at the Rand Water head office and the rooftop solar PV system potential at other Rand Water sites. The solar energy generation assessment, the energy requirements and the rooftop solar PV system options for the study location (Rand Water head office) are discussed. The chapter further discusses the preferred and selected option with an emphasis on the PV system size, simulation and design, cost, installation and savings.

4.2. Rooftop solar PV system at Rand Water head office

4.2.1. Study location

The Rand Water head office (Rietvlei) is situated in the south of Johannesburg, where the annual solar irradiance is in the range of 2 084 kWh/m^2 to 2 222 kWh/m^2 and the average solar energy generation potential is 1 750 kWh/kWp [34]. An accurate solar irradiance available in this location can be determined by specific simulation tools and measurement instruments.

Figure 16 shows the location of the Rand Water head office. The building has a flat concrete roof, and the PV modules can be mounted flat on the roof facing the sky or on frames tilted towards the north at an optimal angle.

The head office receives its electricity supply from the City of Johannesburg at 11 kV, three-phase voltage, on a low-voltage demand tariff. The electricity billing history for the financial years 2011/12 and 2012/13 shows an average electricity consumption of 456 886 kWh per month, with a maximum demand of 1.285 MVA and an average monthly cost of R653 289 (including VAT).

Four options were considered and the option to supply the baseload from the rooftop solar PV system was selected due to the available budget. A grid-tied PV system was selected as supply from the City of Johannesburg is available as an existing grid. As mentioned in the previous chapter, a grid-tied PV system does not generate power when the main supply power is lost. This means that when the grid voltage is zero, the PV system will not supply any electrical power. The building has backup power generation in the form of emergency generators to ensure that power supply for essential loads is maintained in cases of power cuts and load shedding.

Figure 16: Rand Water head office (Rietvlei)

4.2.2. Estimation of power and energy requirements at Rietvlei

An energy audit was conducted in April 2012 by Energy Resource Optimizers (ERO), the audit indicated that the average annual electricity consumption was 461 417 kWh and that the highest electricity demand occurs in the summer months due to an increased demand for cooling. This is also evident in the energy charges, as seen on the City of Johannesburg electricity bill in the summer months. Rand Water office hours are from 08:00 to 16:30, these office hours match the peak sun hours for PV energy generation.

An energy efficiency project was implemented in June 2014 and it was completed in December 2015. The scope of work entailed the following:

- Retrofitting of lights with energy-efficient lighting; both inside and outside the building, and
- Installation of heat pumps for water heating.

The heating, ventilation and air-conditioning system is the highest load at the head office but it system was not included in the scope of work as recommended by ERO.

The electricity bill for the year 2015/16 shows an average consumption of 449 561 kWh/month and an average demand charge of 974 kVA. Electricity consumption in the winter period remains lower compared to the summer period due to the increased use of air-conditioning in summer.

Table 8: Average seasonal loading in kW, 2011/12

	Average peak (kW)	Average load at 12:00 (kW)	Baseload (kW)
Winter profile	750 kW	700 kW	450 kW
Summer profile	900 kW	850 kW	500 kW
Holiday	900 kW	850 kW	500 kW

The City of Johannesburg uses estimated energy consumption (kWh) and reactive energy (kVA) to calculate electricity costs for the month, based on the consumption in previous months for a specific window period. A power-star energy meter was installed to investigate the actual saving achieved from the energy efficiency project. The average energy consumption for the periods 2014/15 and 2015/16 at Rietvlei was measured at 365 000 kWh/month.

Figure 17 shows the energy consumption profile of Rand Water's head office for the period July 2015 to August 2016. The reduction in energy consumption from the year 2015 to 2016 is due to the replacement of lighting with energy-efficient lighting and the use of heat pumps for water heating.

In September 2016, the kitchen experienced a challenge of inadequate hot water as a result of the topology of the water heating system. The heat pumps were bypassed to resolve the issue and were switched back on when the issue was resolved. This resulted in a slight increase in energy consumed at the head office in the month of September 2016, as seen in Figure 17.

4.2.3. Rooftop solar PV system size

The total roof space available was determined with the use of a measuring wheel as 7 802 m^2. The useful space available was assumed to be 80% of the available space (6 241 m^2) because of the shading that results from the manner in which the roof sections are arranged. This would also facilitate ease of walking around the installed PV system during maintenance.

The four options that were considered for the rooftop solar PV system for the main building are as follows:

1. a PV system that will feed the total daily electricity requirements for the building, 12637 kWh/day (2 906 kWp),

2. a PV system installed on the roof space that is available for use, 6 225 m^2 (778 kWp),
3. a PV system that will feed the baseload during peak sun hours, 450 kW (518 kWp), and
4. a PV system that will feed the average daily load that occurs at 12:00, 700 kW (805 kWp).

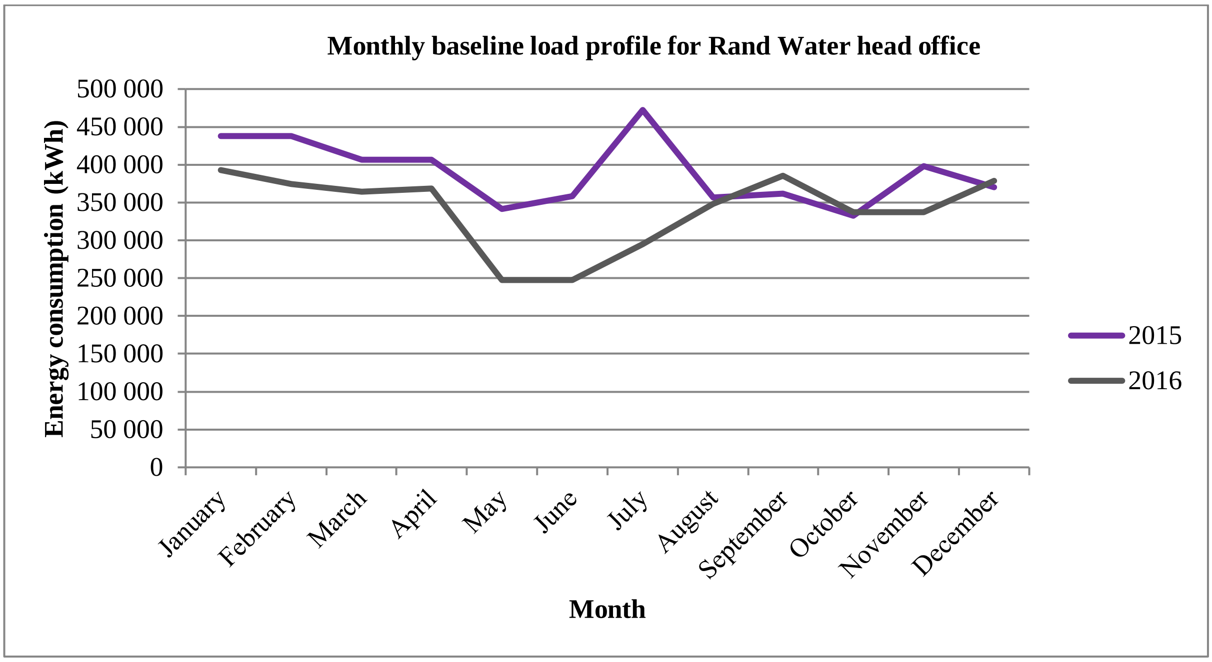

Figure 17: Energy consumption at Rand Water head office

Table 9 provides a summary of the four options that were considered for the rooftop solar PV installation at the main building. Each option is captured in terms of its PV system size in kWp. Appendix I shows detailed calculations for the four options that were considered, it was assumed that the energy yield is the same during peak sun hours and during each month in the year. The O&M cost was included for the 25-year period and the replacement cost for the replacement of inverters in year 10 and year 20 was excluded.

It is evident that the bigger the system; the higher the system cost, the higher the energy generated (kWh) and the higher the electricity cost saving.

The annual cost saving in R/year is a conservative annual saving for the 25-year period because each year the tariff increases, the cost saving increases. The cost saving in year 11 is reduced as a result of the anticipated 10% reduction in the guaranteed energy production. Each option shows that when the tariff increase is included on the cost savings, the investment begins to generate income on year 17 for all four options. This shows that the SPP formula utilised in this research does not give a good reflection of the payback period.

Table 9: PV system options considered for the Rietvlei main building

Option	PV system size (kWp)	Annual output (kWh/year)	PV system cost (R)	Annual cost saving (R/year)	Annual O&M (R/year)	LCOE (R/kWh)	Simple payback period*
1	2 906	4 765 524	87.18 mil	4 765 206	148 206	0.8115	19.07
2	778	1 220 400	23.4 mil	1 220 319	39 780	0.8509	20
3	518	810 000	15.54 mil	809 946	26 418	0.8511	20
4	805	1 260 000	24.15 mil	1 259 916	41 055	0.8503	20

* *Simple payback period does not include the year-on-year electricity cost increases, disposal costs, etc. It only considers the cost of the PV system and the annual electricity cost saving realised.*

Table 10 below shows the summary of the four options with the replacement cost included.

Table 10 PV system options for the main building including replacement costs.

Option	PV system size (kWp)	Annual output (kWh/year)	PV system cost (R)	Annual cost saving (R/year)	Annual O&M (R/year)	LCOE (R/kWh)	Simple payback period*
1	2 906	4 765 524	87.18 mil	4 765 206	148 206	27.507	646
2	778	1 220 400	23.4 mil	1 220 319	39 780	1.1799	27.72
3	518	810 000	15.54 mil	809 946	26 418	1.1799	27.73
4	805	1 260 000	24.15 mil	1 259 916	41 055	1.1788	27.7

The replacement costs is seen as an additional investment in year 10 and in year 20, this additional investment yields non-financially viable return on investment. However, there is potential to curtail the energy requirements from the City of Johannesburg and to reduce carbon emissions. The cost of generating electricity is higher than the tariff rate but this will change in the 3rd year of operation for the high-season tariff rate and in the 10th year for the low-season tariff rate within the 25-year lifespan of the PV system.

Option 3, a PV system size to feed baseload, was selected as the preferred option. This system was selected because it was the cheapest option and the business had committed to a budget of R10-million for this project.

A 16% energy saving from the energy efficiency project was assumed. The PV system size was reduced to 390 kWp (from 450 kW baseload) to incorporate the anticipated reduction in demand as a result of the energy efficiency project.

4.2.4. PV system simulations

The PV Watts Calculator [64] was used to determine the optimal tilt angle while ensuring that the specific energy yield is achieved (a minimum of 1 650 kWh/kWp). The optimal angle was determined to be 26°, which is equivalent to the latitude of an installation located in Johannesburg. The specific energy yield at 26° for a 390 kWp PV system showed a specific energy yield of 1 702 kWh/kWp/year but introduced inter-row shading and required the system size to be reduced to 292 kWp (75 kWp on the new wing and 217 kWp on the old wing).

A tilt angle of 15° was simulated and this resulted in a specific energy yield of 1 663 kWp/kWh/year. This is lower than the specific energy yield of 1 702 kWh/kWp/year but the reduced tilt angle does not have excessive inter-row shading and allows space for additional PV arrays to be installed.

Therefore, the rooftop solar PV system size was revised to 343 kWp – 75 kWp on the new wing at a tilt angle of 26° and 268 kWp on the old wing at a tilt angle of 15°.

4.2.5. Design

A turnkey contract was awarded for a 390 kWp rooftop grid-tied PV system without battery storage, which was revised to 343 kWp when simulated (as discussed in Section 4.2.4.). The structural integrity of the roof was conducted to determine its ability to carry the additional load from the PV system; this was done by analysing the roof slab at the head office. It was determined that the roof slab can sustain a load of 500 kg/m^2, the PV modules and the mounting structures are equivalent to a load of 140 kg/m^2. Therefore, it was concluded that the PV modules and mounting structures could be installed on the roof.

4.2.6. Installation

The rooftop solar PV system size was reduced further to 338 kWp as a result of the unavailability of 310 W PV modules and to maintain a standard use of 25 kW and 20 kW inverters. The PV system was installed on level 3, 4, 5 and 6 of the old wing and on level 6 of the new wing, as shown in Figure 18. This PV system comprises of the components detailed in Table 11. The DC combiner box combines the DC output from the PV arrays and this is the DC input to the 15 inverters.

Figures 16 and Figure 18 show an aerial view of the building/roof and the different subsystems on the roof respectively. The main DB is located on the south end of the building, close to level 4, and the PV subsystems close to the main DB are located on levels 4 and 5 (see Figure 18).

The PV subsystems located on level 6 and on the new wing will pose cable-routing challenges to the main DB; longer cables will have to be used to integrate the power output from these subsystems into the main DB which will result in increase in losses due to the use of longer cables.

Each level has a designated DB assigned to that particular level and its zone segments. Seven DBs were identified to alleviate the abovementioned challenges and to ease integration between the supply from the City of Johannesburg and the electrical energy produced by the rooftop solar PV system.

The 15 outputs from the inverters were aggregated using AC combiner boxes and integrated into the DBs, as shown in Table 12. Therefore, seven AC combiner boxes were utilised, as stated in Table 11.

Table 11: 338 kWp rooftop PV system components

PV system component	Size	Number	Total
PV module	305 W	1 108	337.94 kW
Inverter	20 kW	4	50 kW
	25 kW	11	300 kW
AC combiner box	–	7	–
DC combiner box	–	15	–

Table 13 provides details on the selection of the DC and AC cables used for the PV system. Both the DC and AC cable selection datasheets were used to select the best suitable cable size.

4.2.7. Challenges in this project

Waterproofing

The roof at the Rand Water head office is concrete and it is painted with waterproof paint. The waterproofing was assessed for quality and deterioration prior to the installation of the mounting structure to ensure that it was adequate.

The waterproof was assessed and accepted as adequate during the site assessment. However, the subcontractor responsible for the installation discovered that the condition of the waterproofing in some areas of the roof was poor. The waterproofing was redone on levels 3, 4, 5 and 6 of the old wing; this delayed the project by about three weeks.

Bird droppings

Rand Water head office is located in a nature reserve which is home to a number of animals, particularly birds and doves. A challenge was experienced with bird nests under and between the mounting structures, as well as bird droppings on the PV modules.

In order to achieve the best production from a PV module, the PV cells must be free from any obstructions such as dust or shading which might prevent full electrical solar energy production. Bird droppings on the PV modules have a potential to reduce the solar power produced by the module.

The solution was to install bird-control devices (in the form of mirrors) on different points of the roof to deter birds and flocking every three months was included in this solution.

Tie-in AC cables heating up

The system was commissioned in two phases, namely open-circuit and closed-circuit conditions. The open-circuit condition tests were done on the DC side of the PV system up to the AC tie-in point; this was done on all seven DBs after the continuity tests were concluded.

The closed-circuit tests were also done on each tie-in point or DB and the PV system was switched on for about two hours before measurements were taken. It was discovered that some main circuit breakers and AC cables from the PV system were heating up; there was a notable temperature difference when the PV system was switched on and off.

Power quality analysis was conducted by an external contractor, in which the focus was on harmonics and temperature analysis. The study investigated the changes in the harmonics and temperature when the PV system was switched on and when switched off. It was observed that, when the PV system was on with a low power production, the harmonics were high and the power factor was low.

Table 12: Details per DB

<table>
<tr><th rowspan="2">DB</th><th colspan="4">Inverters</th><th colspan="2">Circuit breaker (A)</th></tr>
<tr><th>Power output (kW)</th><th>Quantity</th><th>Total (kW)</th><th>Output current per phase (A)</th><th>PV system</th><th>CoJ*</th></tr>
<tr><td>DB L3-N-Z3&Z4</td><td>24.4</td><td>2</td><td>48.8</td><td>74.2</td><td>80</td><td>100</td></tr>
<tr><td>DB L4-N-Z2</td><td>24.4</td><td>1</td><td>24.4</td><td>37.1</td><td>40</td><td>63</td></tr>
<tr><td rowspan="2">DB L4-S-Z2</td><td>24.4</td><td>1</td><td rowspan="2">59.2</td><td rowspan="2">90.1</td><td rowspan="2">100</td><td rowspan="2">100</td></tr>
<tr><td>17.4</td><td>2</td></tr>
<tr><td>DB L5-S-Z1</td><td>24.4</td><td>2</td><td>48.8</td><td>74.2</td><td>80</td><td>100</td></tr>
<tr><td rowspan="2">DB L5-N-Z1</td><td>24.4</td><td>1</td><td rowspan="2">41.8</td><td rowspan="2">63.6</td><td rowspan="2">80</td><td rowspan="2">100</td></tr>
<tr><td>17.4</td><td>1</td></tr>
<tr><td>DB L4-N-Z1</td><td>24.4</td><td>1</td><td>24.4</td><td>37.1</td><td>40</td><td>63</td></tr>
<tr><td rowspan="2">DB R1</td><td>24.4</td><td>3</td><td rowspan="2">90.6</td><td rowspan="2">137.8</td><td rowspan="2">160</td><td rowspan="2">160</td></tr>
<tr><td>17.4</td><td>1</td></tr>
</table>

* *City of Johannesburg*

Thermal imaging was used to investigate the increase in temperature in order to quantify the temperature increase and to confirm whether the temperature increase was a threat to the circuit-breaker device and any other equipment. A temperature rise was evident around the Fuchs breakers during PV production, particularly on higher loads and high PV production, and a temperature rise was evident on the AC cables that were tied into the Fuchs breakers.

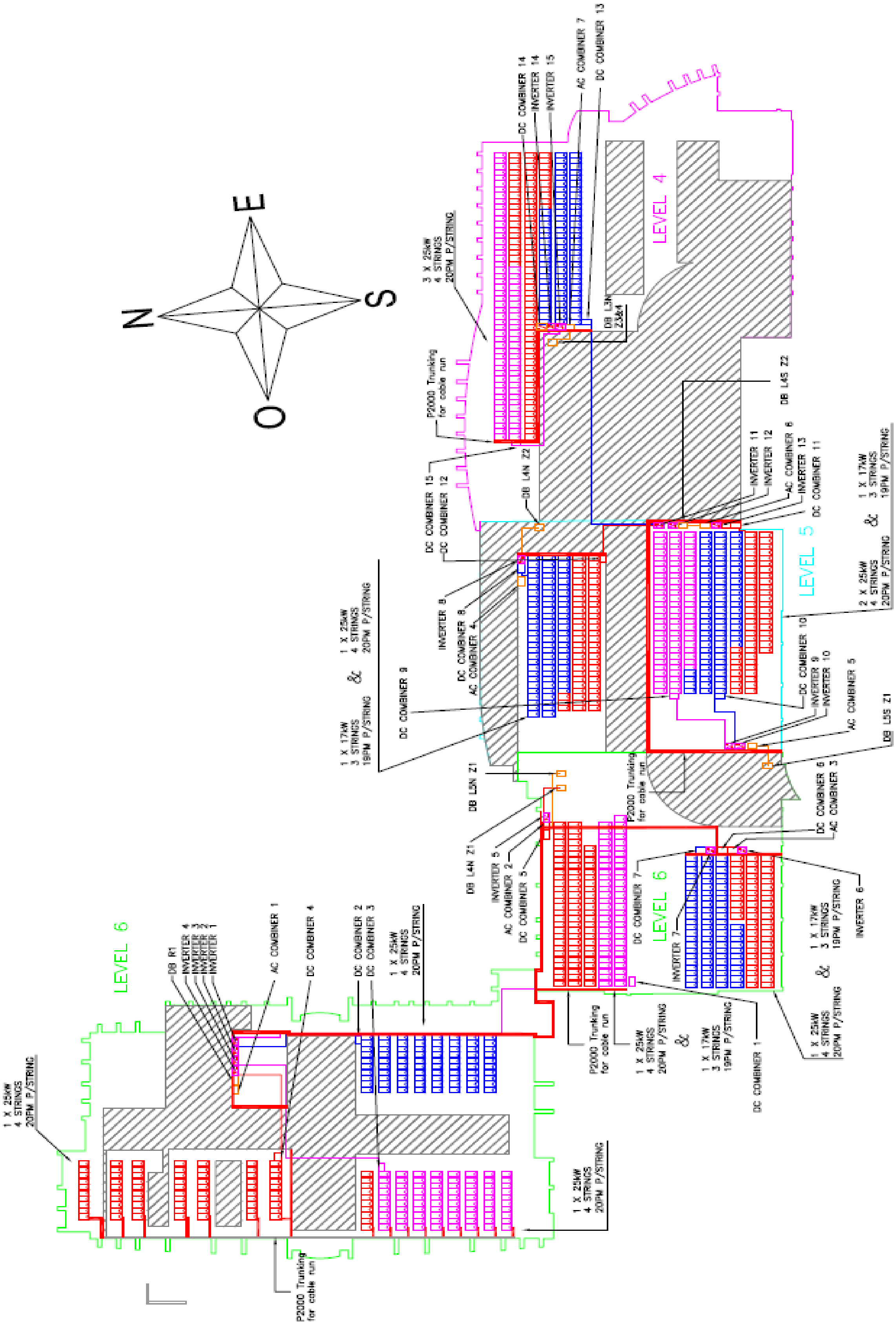

Figure 18: Rooftop solar PV system layout at Rietvlei

The Fuchs breakers were replaced and thermal imaging was done on the new breakers and existing cables. The results showed a reduction in the rise in temperature. There will always be a temperature

Table 13: DC and AC cable selection

DC cables			
Subsystem	**Output current (A)**	**Cable rating (A)**	**Cable size (mm^2)**
PV array	8.33	70	6
DC combiner box: 20 kW	25	70	6
DC combiner box: 25 kW	33.32	70	6
AC cables			
Inverters	**Peak current (A)**	**Cable size (mm^2)**	**Current rating ducts (A)**
25 kW	37	10	58
20 kW	26.4	10	58
DB	**Peak current (A)**	**Cable size (mm^2)**	**Current rating ducts (A)**
DB L3-N-Z3&Z4	74.2	25	22
DB L4-N-Z2	37.1	10	27
DB L4-S-Z2	90.1	35	20
DB L5-S-Z1	74.2	25	10
DB L5-N-Z1	63.6	25	56
DB L4-N-Z1	37.1	10	25
DB R1	137.8	70	10

increase as current is flowing but the increase should not exceed certain limits in order to avoid catastrophe on the tie-in points.

Integrating seven tie-in points

The 338 kWp system is made up of seven subsystems, as shown in Table 14. The system was designed in this manner because of the topology of the building (with different roof levels for the different sections of the roof), inadequate space in the main DB and long distances between the main DB and other PV subsystems.

A cluster controller was installed to integrate the power production from the seven subsystems in order to obtain the overall impact of the amount of power produced by the rooftop solar PV system. Fibre optics was used to link the cluster controller and the 15 inverters, for communication and data logging.

The challenge with the subsystem topology is that instead of uploading data from one location, the overall PV data production from the subsystems is integrated in the cluster and only then can it be extracted or downloaded.

Table 14: 338 kWp power output per subsystem

DB	Power output fed into DB (kW)
DB L3-N-Z3&Z4	48.8
DB L4-N-Z2	24.4
DB L4-S-Z2	59.2
DB L5-S-Z1	48.8
DB L5-N-Z1	41.8
DB L4-N-Z1	24.4
DB R1	90.6

Another challenge was the communication failure between the cluster and one or more inverter(s); this was seen on power production data downloaded from the cluster controller, where data was missing on some days.

Data extraction

Power production data for each individual inverter can be extracted from the inverter and then integrated (for example, on an Excel spread sheet) to provide an overall view of the power production of the PV system.

As mentioned previously, data extracted from the cluster controller was missing in some intervals. The following inverters were identified as problematic inverters since the system was commissioned in May 2017:

- Inverter 7 was off until March 2018 due to a technical issue,
- Inverter 8, the communication module was faulty and the inverter was replaced in October 2017,
- Inverter 12 was on but had a technical issue that caused the signal light; in a green state, to flicker, and
- Inverter 13 also experienced technical issues.

4.2.8. PV energy production

The simulated energy production for the rooftop solar PV system was estimated at an average of 46 937 kWh/month with a specific energy yield of 1 798 kWh/kWp/year. The commissioning of the system commenced in January 2017 and the various tests that were performed highlighted power quality issues which had to be addressed prior to putting the system into operation. The power quality analysis was concluded in May 2017 and the system was put into full operation in July 2017.

Energy production data can be retrieved from each of the 15 inverters and the integrated energy production from the cluster controller. The performance assessment of the rooftop solar PV system was done for the period May 2017 to May 2018. The inverter records the total daily energy production for the number of days in a month and the cluster controller records both the energy production in kWh and power production in W on a 5-minute interval.

Table 15 provides a comparison between the simulated energy production and the actual energy produced. Note that Table 15 shows the inverters in which the recorded data was missing for that particular month. The missing data was a result of technical challenges experienced with inverters 7, 8, 12, 13; the energy production data from these inverters was included as and when the technical issues were resolved.

The missing data influences the total energy production recorded on a monthly basis. Table 15 shows that the energy produced and fed through inverter 8 is recorded and available as of October 2017, this is evident with an increase in the total energy produced in October. Another significant increase in the actual energy production is seen in January 2018 when the energy produced and fed through inverter 13 is included.

Table 15: Simulated energy production vs actual energy production in kWh

	Actual energy production (kWh)		Simulated energy production (kWh)	Inverters excluded
Month	**Cluster**	**Inverter**	**Simulation**	
May 2017	31 141	30 147	44 371	7, 8, 12
June 2017	35 969	26 784	41 727	7, 8, 12
July 2017	34 313	30 490	45 241	7, 8, 12, 13
August 2017	40 004	40 814	48 967	7, 8, 12, 13
September 2017	52 484	41 737	48 101	7, 8, 12, 13
October 2017	30 552	45 163	50 767	7, 12, 13
November 2017	25 663	46 582	47 994	7, 12, 13
December 2017	20 912	45 333	51 565	7, 12, 13
January 2018	38 022	49 862	49 022	7, 12
February 2018	20 510	35 747	43 288	7, 12
March 2018	29 099	40 765	47 941	12
April 2018	26 665	45 150	44 262	12 (first five days)
May 2018	35 839	41 104	44 371	NONE
Specific energy yield (kWh/kWp/year)	1 246	1 538	1 798	N/A

The actual energy production is very close to the simulated energy production and in some instances the energy produced in a month is higher than the simulated energy production, this is seen in January and April 2018.

Table 16 shows the power production in Watts. The data shows that the maximum peak power produced from May 2017 to May 2018 is 294 kW at 11:30 on 10 April 2018. It also shows that the peak power production occurs a bit later in winter months compared to summer months, i.e. peak power production in colder months occurs at 12:00 and after 12:00, while in warmer months the peak power production takes place before 12:00.

Table 16: Power production in watts

Month	Average (kW)	Time	Maximum (kW)	Time
May 2017	129	12:10	–	–
June 2017	127	11:35	208	12:50
July 2017	197	12:25	213	11:45
August 2017	209	11:50	252	12:20
September 2017	201	12:15	234	11:55
October 2017	150	11:15	246	11:45
November 2017	126	10:50	151	10:50
December 2017	87	11:50	146	10:15
January 2018	88	12:15	149	10:55
February 2018	103	11:30	161	11:30
March 2018	146	10:40	272	12:05
April 2018	203	11:40	294	11:30
May 2018	215	11:30	286	11:55

Figure 19 shows the power production profile for January 2018; this is a typical daily solar power production profile for the period May 2017 to May 2018. This follows the solar energy production profile as illustrated in Figure 3, Section 2.2, where the peak sun hours are discussed.

The average daily power production shows that the period of power production is from 05:25 to 19:20. The average power production is recorded as 0 W at 05:25 at a frequency of 50 Hz and an average phase voltage of 231 V; and as 0 W at 19:20 at a frequency of 50 Hz and an average phase voltage of 232 V. The frequency during production averages at 50 Hz and the voltage at 233 V. The average peak production is 88.338 kW at 12:15 and the maximum peak production of 149.715 kW is recorded on 8 January 2018 at 10:55.

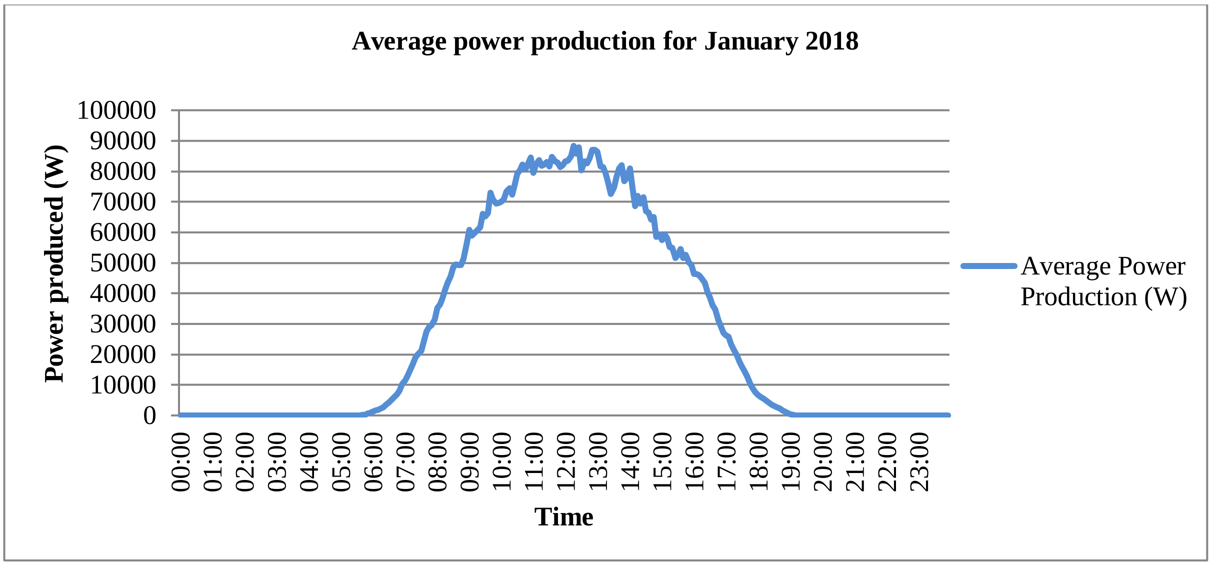

Figure 19: Power production profile for January 2018

4.2.9. Cost savings and payback time

The financial analysis for the 338 kWp rooftop PV system was concluded for the period May 2017 to May 2018 and the results are as shown in Table 17. The City of Johannesburg uses estimated data for billing on a monthly basis. The low season energy tariff for the period May 2017 to May 2018 was R1.1431/kWh in 2017 and R1.1691/kWh in 2018, while the high season tariff effective for both 2017 and 2018 was R1.3695/kWh. A saving of R559 926 was realised for the period May 2017 to May 2018.

Using the conversion factor 0.99 $kgCO_2/kWh$, the equivalent reduction in carbon emissions for an average energy saving of 40 000 kWh/month is 39.6 tons of CO_2 on a monthly basis.

Table 17: Cost saving of the 338 kWp rooftop PV system

Month	Simulations	City of Johannesburg	Actual measurements
Energy saving (kWh/month)	46 740	41 875	39 976
Rand energy saving (R/year)	R849 138.03	R559 926.89	R549 710.00
Payback period (years)	16	N/A	21
LCOE	R0.67/kWh	N/A	R0.78/kWh

The PV modules, the most expensive component of the PV system, have a lifespan of 25 years and a guaranteed power production of 95% down to 80% for 25 years. The inverter has a lifespan of 10 years. Although the payback period is not attractive, the system can pay itself off before the end of its lifespan if the inverters are not replaced after 10 years.

Table 18 below shows the cost saving of the 338 kWp rooftop PV system when the replacement cost is included.

Table 18 :Cost saving of the 338 kWp rooftop PV system including replacement costs

Month	Simulations	City of Johannesburg	Actual measurements
Energy saving (kWh/month)	46 740	41 875	39 976
Rand energy saving (R/year)	R849 138.03	R559 926.89	R549 710.00
Payback period (years)	25	N/A	Not achieved before end of lifecycle
LCOE	R0.89/kWh	N/A	R1.05/kWh

The results show that the energy saving in kWh and energy cost saving in Rands is achieved. The cost of generating electricity is higher than the tariff rate but this will change in the 2nd year of operation for the high-season tariff rate and the 6th year for the low-season tariff rate; within the 25-year lifecycle of the PV system.

The return on investment is not realised within the lifecycle of the PV system. It is important to note that PV system prices have dropped, with some prices as low as R9/W to R11/W. This reduction in the investment cost will improve the return on investment and payback period for similar installations in the future.

4.3. Rooftop solar PV potential within Rand Water buildings

The focus of the investigation into the potential of installing similar rooftop solar PV systems was on Rand Water administration buildings. This was motivated by the solar energy production profile or peak sun hours which are between 09:00 and 15:00, i.e. typical office hours.

Table 18 provides details of the identified buildings which are administration buildings at Rand Water operational sites.

Appendix II shows the geographical layout of the buildings listed in Table 18 which was used to assess the orientation of the buildings. Buildings that are orientated towards the northeast are preferred because this is where maximum power production is achieved. A gabled and/or hipped roof prescribes the orientation of the PV modules and the angle at which they can be tilted. Depending on the orientation of the gabled/hipped roof, only one side of the gabled roof or two sides of the hipped roof show potential to mount PV modules for maximum power production. However, simulations show that the modules can be mounted at a specific tilt angle and orientation to achieve power production on a gabled and/or hipped roof.

The orientation of the buildings listed below is not desirable for maximum power production:

- Zwartkopjes (HR Administration Building),
- Libanon,
- Zuurbekom,
- Krugersdorp, and
- Brakpan.

Table 19: Identified administration buildings

Site	Electricity supplier	Tariff	Location	Building name
Zuikerbosch	Eskom	Megaflex	Vereeniging	Administration Building, Risk Building, Maintenance Offices
Vereeniging	Emfuleni	Tariff 7.2	Vereeniging	Administration Building, Process Technology
Libanon	Eskom	Miniflex	Westonaria	Administration Building
Krugersdorp	City of Johannesburg	Seasonal	Krugersdorp	Administration Building
Germiston	Ekurhuleni	Tariff B	Germiston	Administration Building
Zuurbekom	Eskom	Miniflex	Lenasia	Administration Building
Brakpan	Ekurhuleni	Tariff B	Brakpan	Administration Building
Esselen Park	Ekurhuleni	Tariff B	Kempton Park	Administration Building
Zwartkopjes	Eskom	Megaflex	Johannesburg South	Administration Building, HR Administration Building, Maintenance Offices, Conference Centre, EMS, Emhlangeni Workshop, Emhlangeni Administration Building

Table 19 shows the estimated power requirements for the identified buildings. The PV system size must be slightly larger than the load values listed in Table 19 to ensure that the losses incurred during DC-to-AC conversion do not compromise the power available to feed the load. Typically, a conversion factor of between 1.1 and 1.15 is used.

Helioscope, a simple and fast simulation software, was used to simulate the potential PV system size for all the identified buildings. Appendix III shows the layout of the maximum PV system potential for each of the identified buildings.

Table 20: Estimated power requirements at identified buildings

Site	Building name	Load (kW)
Zuikerbosch	Administration Building	161
	Risk Building	41
	Maintenance Offices	80
Vereeniging	Administration Building	130
	Process Technology	170
Libanon	Administration Building	8
Krugersdorp	Administration Building	10
Germiston	Administration Building	18
Zuurbekom	Administration Building	9
Brakpan	Administration Building	12
Esselen Park	Administration Building	15
Zwartkopjes	Administration Building	122
	HR Administration Building	84
	Maintenance Offices	46
	Conference Centre	35
	EMS	44
	Emhlangeni Workshop	0
	Emhlangeni Administration Building	38
Total		**1 023**

The simulations confirmed that the installation of a rooftop PV system at Krugersdorp is not feasible and that smaller rooftop PV systems (less than 3 kW) are feasible at the some of the sites which are listed above as orientated towards an undesirable direction.

The potential rooftop PV system size, total lifecycle cost, energy cost saving, simple payback period and LCOE were determined for each of the identified buildings, using equation (3) to (10); the summary of the calculations is as shown in Appendix IV. The total potential rooftop solar PV system amounts to 1274 kW (excluding Zuurbekom with a potential of 0.96 kW and Krugersdorp at 0 kW). This is equivalent to an estimated energy saving of 2 293 128 kWh/year and an estimated cost saving of R1 904 116.44/year.

The simple payback period ranges from a minimum of 9.41 to a maximum of 23.11. The replacement cost for the inverter in year 10 and year 20 doubles the simple payback period, the bigger systems have a longer simple payback period because the replacement cost for those systems is higher. The LCOE ranges from a minimum of R0.6367/kWh to a maximum of R0.7107/kWh. The LCOE is slightly higher than the tariff rate at each of the identified buildings in the first year of operation except at the smaller sites (Libanon, Brakpan and Esselen Park), in which the low season tariff rate is lower than the cost of generating solar energy. This is expected to improve in the 6^{th} year of operation when the tariff rate increase results in a tariff rate that is higher than the cost of generating solar energy.

The load requirements at the Vereeniging (Administration Building), Libanon, Germiston, Zuurbekom, Brakpan and Emhlangeni Administration Buildings are much higher than the potential PV system size at each of the sites. A combined rooftop solar PV potential at these sites is estimated at a load curtailment of 40.92 kW, compared to the 1 233.08 kW of the combined potential at Zuikerbosch (Administration Building, Risk Building, Maintenance Offices), Vereeniging (Process Technology), Esselen Park and Zwartkopjes (Administration Building, HR Administration Building, EMS, Emhlangeni Workshop and Conference Centre).

Zuikerbosch (Administration Building), Vereeniging (Process Technology) and Zwartkopjes (Administration Building, Maintenance Offices and Emhlangeni Workshop) show a potential energy cost saving of about R100 000 and more; per year from each site. It is important to note that these buildings are buildings on which larger rooftop PV systems can be installed, thus the energy production and energy cost saving is high. The potential rooftop PV system at the Zwartkopjes Maintenance Offices makes use of the roof space of both the Maintenance Offices and the Maintenance Workshop.

Emhlangeni Workshop is not utilised at the moment but it will be used as an office space in the near future; the largest rooftop solar PV system (of about 618 kWp) can be mounted on this roof. This is equivalent to the combined rooftop PV system potential of the 17 identified buildings. The combined estimated cost saving, excluding Emhlangeni Workshop, is equivalent to R921 024.95/year.

4.4. Conclusion

The feasibility study, with informed assumptions, provides an indication of the potential PV system size that can be installed at a site. The system size is refined using a solar PV simulation software and it is further optimised by studying the motion of the sun on the designated roof area.

The PV system size required to supply the baseload at the head office was reduced as a result of the energy efficiency initiatives that were implemented prior to the installation of the PV system, thus reducing the investment cost of the PV system. However, due to the cost of the PV systems at the time, the case study installation yielded an unattractive investment benefit in terms of payback period and return on investment.

Although the payback period is unattractive; this PV system yielded a performance ratio of 80% in its first year of operation, above the anticipated 75%. The performance of the simulated and installed system was comparable and in some summer months the installed system yielded higher energy production when compared to the simulated energy production.

The methodology discussed in Chapter 3 was followed to investigate the rooftop solar PV system potential for 18 identified buildings. These buildings are located at Rand Water operational sites and are much smaller than the head office – except for Emhlangeni Workshop, which has a potential PV system of about 618 kWp. The total potential rooftop solar PV system amounts to 1 274 kW, which is equivalent to an estimated energy saving of 2 293 128 kWh/year and an estimated cost saving of R1 904 116.44/year.

The replacement cost for the inverters increases the simple payback period because a new investment cost is introduced in year 10 and year 20 when the inverters reach their end of useful life. The payback period is reduced when the annual tariff increase is used to determine annual cost savings for each year in the 25-year period. The increase in the tariff rate results in a lower cost of generating electricity over the 25-year lifecycle of the PV system.

In order to realise the benefits of solar PV systems and considering the power requirements for Rand Water, rooftop solar PV system installations should be considered at the buildings with higher energy savings and energy cost savings potential. The following buildings provide physical, geographical technical and economic rooftop solar PV potential from which Rand Water will realise energy savings and energy cost savings:

- Zuikerbosch (Administration Building, Risk Building, Maintenance Offices),
- Vereeniging (Administration Building, Process Technology),
- Esselen Park, and
- Zwartkopjes (Administration Building, HR Administration Building, Maintenance Offices, Conference Centre, EMS and Emhlangeni Workshop).

This is equivalent to an estimated energy saving of 2 163 420 kWh/year, an energy cost saving of R1 794 492.64/year and a reduction in carbon emissions of 2 141 tons CO_2/year. The return on investment is unattractive but there is a substantial reduction in energy, energy costs and carbon emissions that can be realised.

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CHAPTER 5: CONCLUSION


[5]

Summary of the research work.

[5] *D Makhathini, personal photograph. "PV array mounted on level 4 at the head office", South Africa, 2016.*

5.1. Summary

The current electricity supply crisis and annually escalating electricity prices motivate the use of renewable energy sources. The National Electricity Plan encourages the use of renewable energy sources in order to promote a sustainable electricity supply, reduce carbon emissions and encourage energy efficiency in South Africa. Electricity prices have a direct impact on the water tariff and its annual escalation. The annually escalating electricity prices, the water tariff, and Rand Water's strategic direction towards climate change awareness motivate the organisation to explore the option of renewable energy sources.

The objective of this research was to demonstrate the potential to reduce energy and energy cost at various Rand Water buildings by installing rooftop solar PV systems. The completed installation of a 338 kWp rooftop solar PV system at the Rand Water head office was used as a case study. The methodology to analyse the potential for a rooftop solar PV installation, which is proposed in this research, was followed to determine the potential of the rooftop solar PV system installed at the head office. The load requirements (kW), space area required (m^2), PV system size (kW), solar energy production (kWh), energy cost saving (R), simple payback period and LCOE were determined for the 338 kWp installation.

The physical and geographical potential is determined at inception phase, the technical potential is defined at inception phase and it is refined during design and installation, the economic potential is defined at inception phase and refined during the performance assessment phase (during which the energy cost savings and payback period are assessed).

The load profile provides a substantial indication of the PV system size that is required and the simulation study provides an indication of the feasibility to install a specific system size on that particular roof. A physical site visit provides a pictorial view of the feasibility, the motion of the sun on the area in which the solar modules will be mounted is assessed to ensure that the tilt angle and layout of PV modules will yield the desired PV system output.

The average monthly power production for the 343 kWp system was simulated on PVsyst simulation software. The PV system was further reduced to 338 kWp as a result of unavailability of the 310 W PV modules and to maintain a standard use of 25 kW and 20 kW inverters. The simulated energy production for the 343 kWp was estimated to an average of 46 937 kWh/month which is equivalent to a specific energy yield of 1 798 kWh/kWp/year.

Although commissioning commenced in May 2017, the system was only put into commercial operation in July 2017 as tests highlighted power quality issues that had to be addressed prior to putting the system into operation. The performance assessment for a year, May 2017 to May 2018, of full operation was completed for the 338 kWp PV system regardless of the inconsistency in the energy production data.

The actual energy production measurements showed a good performance ratio of 80% for the 338 kWp system. The energy saving is shown by a reduction in energy costs on the electricity bill from the City of Johannesburg, with a cost saving of about R550 000 per year (about 11% of the total electricity bill). A comparison between the actual energy production in kWh and the reduction in the energy reading on the electricity bill was carried out and the difference between the two was minimal. Thus, it could be concluded that the reduction on the electricity bill was as a result of the energy supply from the PV system. The costs for PV systems have reduced since 2015 when the contract was awarded; the 338 kWp PV system was priced at a high cost and yielded an unattractive payback period. The cost of generating electricity is higher than the tariff rate but this will change in the 2nd year of operation for the high-season demand rate and 6th year for the low-season demand rate; this is within the 25-year lifecycle of the PV system.

Eighteen (18) additional buildings were identified as potential buildings for a rollout of rooftop solar PV systems. The methodology proposed in this research was used to analyse the rooftop solar PV potential for these buildings but only 12 of the 18 identified buildings showed potential for a rooftop solar PV system installation. The buildings located at the following sites provide physical, geographical, technical and economic rooftop solar PV potential; from which Rand Water will realise energy and energy cost savings:

- Zuikerbosch (Administration Building, Risk Building, Maintenance Offices),
- Vereeniging (Administration Building, Process Technology),
- Esselen Park, and
- Zwartkopjes (Administration Building, HR Administration Building, Maintenance Offices, Conference Centre, EMS and Emhlangeni Workshop).

The replacement cost for the inverters increases the simple payback period because a new investment cost is introduced in year 10 and year 20 when the inverters reach their end of useful life. The payback period is reduced when the annual tariff increase is included in determining the annual cost savings for the 25-year period. The increase in the tariff rate results in a lower cost of generating electricity over the 25-year lifecycle of the PV system.

The potential rooftop solar PV rollout is equivalent to an estimated energy saving of 2 163 420 kWh/year, an energy cost saving of R1 794 492.64/year and a reduction in carbon emissions of 2 141 tons CO_2/year. The return on investment is unattractive but there is a substantial reduction in energy, energy costs and carbon emissions that can be realised.

The challenges experienced and the lessons learnt on the installation of the 338 kWp rooftop PV system will provide guidance for future installations. The following recommendations must be considered for the identified buildings:

- The type of roof, including waterproofing conditions and requirements, must be assessed to ensure that the waterproofing is adequate prior to installing the PV mounting structure and modules.
- The AC tie-in point must be identified and selected. A single tie-in point is preferable as it allows for easier troubleshooting, performance assessment and data logging.
- If there is more than one tie-in point, it is important to ensure that the integration of the energy produced by the different subsystems is reliable, consistent and of good quality.
- Provisions must be made for independent metering, if necessary, to monitor the energy fed into the distribution network by the PV system.
- Inverters with an LCD display showing the inverter’s power production profile should be used.
- The method through which data will be extracted from the PV system must be finalised prior to the installation, to ensure that the application protocol is selected and agreed upon before the system is put into operation.
- The bidding price in Rand/Watt must be determined before the bid is issued to the market. This will ensure that the return on investment is realised, assuming that the design and installation is of good quality.
- A maintenance strategy must be put in place by adapting the O&M manual submitted by the installer/contractor to ensure that the PV system is maintained. The full benefit of the PV system will only be realised with frequent and proper maintenance.

The methodology followed in this research provides a basic method to investigate or analyse the potential for a rooftop solar PV system at any specific site or building. The potential PV system can be refined during design and installation such that the maximum power production is yielded.

5.2. Recommendations for future work

The load requirement for Rand Water administration buildings is small compared to the load requirement for pumping. The additional buildings have a total load of 1.023 MW of maximum power production and a maximum power production potential of 1.274MW; this is small compared to the 320 MW power required for Rand Water operations.

The methodology proposed in this research is a simple and basic method to analyse and determine the potential for rooftop solar PV installation. The PV system size and design are optimised and refined during the design and installation phases. It is recommended that an optimisation model based on this methodology should be investigated to ensure that the proposed system is an optimal solution in terms of physical, geographical, technical and economic potential.

A substantial reduction in energy consumption and cost can be achieved with the use of alternative energy resources, particularly renewable energy, to power pumping load. Solar PV technology on its own is not adequate to meet the power requirements at Rand Water operations. It is recommended that the use of hybrid power systems, inclusive of solar energy, should be considered for future work in order to reduce escalating electricity costs, operating costs and (by extension) the water tariff. The hybrid system will inform the PV system size and the amount of space required for the PV system, while also ensuring that motor power requirements are met.

The impact of investing in renewable and/or alternative energy – in other words, the capital expenditure required, and the impact of reducing energy costs and/or operating costs – should be investigated to determine the influence of such energy sources on the determination and escalation of the water tariff.

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APPENDIX I

Rooftop solar PV potential at Rietvlei

Option 1: A PV system that will feed the total daily electricity requirements for the building, 12 637 kWh/day

The assumptions for this option are as follows:

- The average electricity consumption for 2011/12 and 2012/13 is 456 886 kWh/month.
- Electricity saving after implementation of the energy efficiency project is 76 294 kWh/month.
- The electricity requirement for the building is 397 127 kWh/month or 12 637 kWh/day.
- Electricity costs are R4 549 016/year or R379 084/month.
- Efficiency of the PV module at STC is 16%.
- The performance ratio is 0.8; this is a coefficient of all the losses in a PV system. The performance ratio describes the relationship between the actual and theoretical energy outputs of the PV system.
- Solar irradiation energy is 5 kWh/m^2/day.
- The PV system cost is R30/W based on 2015 prices.
- The peak sun hours is 5 hours.

The electrical energy yield per module area is as follows:

$$Energy\ yield\ per\ module\ area = 5\ kWh\_solar/m^2/day \times 16\% \times 0.8$$

$$= 0.64\ kWh\_elec/m^2/day$$

The amount of power required from the PV array is as follows:

$$P_{PV\_AC} = \frac{Energy\ required\ from\ the\ PV\ system}{Peak\ sun\ hours}$$

$$= \frac{12\ 637\ kWh}{5\ h}$$

$$= 2\ 527\ kW$$

In order to ensure that the maximum power at the output of the inverter is 2 527 kW, a DC-to-AC ratio of 1.15 is assumed. Therefore, the PV array size required is as follows:

$$P_{PV\_DC} = 2\ 527 \times 1.15 = 2\ 906\ kWp$$

The specific space requirement is in the range of 8 m^2/kWp to 10 m^2/kWp. Assuming that the specific space requirement is 8 m^2/kWp, the amount of roof space required to accommodate this PV array is as follows:

$$Space\ required = 2\ 906\ kWp \times 8 \frac{m^2}{kWp} = 23\ 248\ m^2$$

The amount of space required is more than the roof space available at the Rietvlei main building.

The cost of a grid-tied PV system is R30/W; thus the PV system cost (excluding battery backup) is as follows:

$$PV_{system_{cost}} = 2\ 906\ kWp \times \frac{R30}{W} = R87.18\ mil$$

The O&M cost is estimated at 0.17% of the PV system cost, as shown below:

$$PV_{O\&M\_cost} = 0.17\%/year \times R87.18\ mil = R148\ 206/year$$

Assuming an inflation rate of 6% and a replacement cost of R0.00 the total lifecycle cost is as follows:

$$PV_{total_{cost}} = R87\ 180\ 000 + R\ 3\ 705\ 150 + R0 = R90\ 885\ 150.00$$

The energy that can be generated in 25 years is as follows:

$$E_{PV_n} = (397\ 127 * 10) + (0.9 * 397\ 127 * 15) = 111\ 989\ 814\ kWh$$

$$LCOE = \frac{R90\ 885\ 150.00}{111\ 989\ 814\ kWh} = R0.8115/kWh$$

The demand period for winter and summer is four and eight months, respectively. The annual electricity cost saving that can be achieved from this option is calculated using the winter and summer tariff rate as follows:

$$C_s = (397\ 127 \times 8 \times 0.9537) + (397\ 127 \times 4 \times 1.0924)$$

$$= R4\ 765\ 206/year$$

This is a conservative annual saving for the 25-year period because each year the tariff increases, there is an increase in the cost saving. The cost saving in year 11 is reduced as a result of the anticipated 10% reduction in the guaranteed energy production.

The anticipated cost saving in the 25-year period is as follows:

$$Total_{C_s} = R52\ 177\ 679.47 + R90\ 407\ 975.86 = R142\ 585\ 655.33$$

The simple payback period for the PV system is calculated as follows:

$$SPP = \frac{R90\ 885\ 150.00}{R4\ 765\ 206} = 19.07\ years$$

The results from this option indicate that:

1. The amount of space required to install the PV array is more than the roof space available at the Rietvlei building. In order to meet the solar electricity requirement, the most efficient and expensive PV module will have to be used in order to supply the daily electricity demand on a PV system.
2. Furthermore, this option requires battery storage to ensure that the surplus electrical energy generated is stored for future use or that the surplus electrical energy is fed into the grid. Battery storage and the infrastructure required to feed the electricity onto the grid will increase the system costs.
3. This PV system has the potential to reduce 12 637 kWh of energy consumed per day, which is equivalent to a reduction in carbon emissions of 4 504 tons/year.

Option 2: A PV system installed on the available roof space, 6 225 m^2

The amount of roof space available for the PV system is 6 225 m^2. For the specific space area requirement of 8 m^2/kWp, the size of the PV array that can be installed on the available roof space is as follows:

$$P_{PV\_DC} = \frac{6\ 225m^2}{8\ {m^2}/{kWp}} = 778\ kWp$$

In order to ensure that the maximum power at the input of the inverter is 778 kW, a DC-to-AC ratio of 1.15 is assumed. Therefore, the AC power output is as follows:

$$P_{PV\_AC} = \frac{778\ kW}{1.15} = 676\ kW$$

The amount of energy required from this PV array for five hours of peak sun, with the assumption that there is no energy loss is as follows:

$$E_{PV_{ac}} = 676 \times 5 = 3\ 380\ kWh/day$$

This is equivalent to $\frac{3\ 380}{12\ 637} \times 100\% = 27\%$ of the daily electricity requirement of the building. The cost of a grid-tied PV system is R30/W; thus the cost of the PV system, excluding battery backup, is as follows:

$$PV_{system_{cost}} = 778\ kWp \times \frac{R30}{W} = R23.34\ mil$$

The O&M cost is estimated at 0.17% of the PV system cost, as shown below:

$$PV_{O\&M\_cost} = 0.17\%/year \times R23.34\ mil = R39\ 678/year$$

Assuming an inflation rate of 6% and a replacement cost of R0.00 the total lifecycle cost is as follows:

$$PV_{total_{cost}} = R23\ 340\ 000 + R\ 991\ 950 + R0 = R24\ 331\ 950.00$$

The energy that can be generated in 25 years is as follows:

$$E_{PV_n} = (3\ 380 * 30 * 12 * 10) + (0.9 * 3\ 380 * 30 * 12 * 15) = 28\ 594\ 800\ kWh$$

$$LCOE = \frac{R\ 24\ 331\ 950.00}{28\ 594\ 800\ kWh} = R0.8509/kWh$$

The demand period for winter and summer is four and eight months, respectively. The annual electricity cost saving that can be achieved from this option is calculated using the winter and summer tariff rate as follows:

$$C_s = (3\ 380 \times 30 \times 8 \times 0.9537) + (3\ 380 \times 30 \times 4 \times 1.0924)$$

$$= R1\ 216\ 718.88/year$$

The anticipated cost saving in the 25-year period is as follows:

$$Total_{C_s} = R13\ 322\ 732.27 + R23\ 084\ 224.32 = R36\ 406\ 956.59$$

The simple payback period for the PV system is calculated as follows:

$$SPP = \frac{R24\ 331\ 950.00}{R1\ 216\ 718.88} = 20\ years$$

The baseload at Rietvlei is 450 kW; thus the amount of energy required to supply the baseload during peak sun hours is as follows:

$$Energy_{BASELOAD} = 450\ kW \times 5\ hours = 2\ 250\ kWh/day$$

This is equivalent to $\frac{2\ 250}{12\ 637} \times 100 = 18\%$ of the daily electricity requirements of the building.

The results from this option indicate that:

1. The amount of energy that can be generated from installing a PV system on the available roof space will result in a 30% reduction in the average daily electricity consumption of the building.
2. If the entire roof space is used, the PV system will generate an excess energy of 12%. The excess energy is the remaining energy after the baseload energy requirements are fulfilled. This energy can either be stored for later use or it can be fed back into the grid. This will require battery storage and infrastructure to feed electricity onto the grid, which will increase the system costs and complexity. The PV system peak electricity generation occurs for five hours and the amount of energy generated will be used to supply the average load. The system can afford to curtail some energy generated within those five hours and this is done using a monitoring system that monitors and controls the output from the inverter.
3. The LCOE is lower than the current cost of each unit of electricity on the low-voltage demand tariff for both the summer and winter period.
4. The simple payback period for this system, without battery storage, is 20 years.
5. This PV system has the potential to reduce 3 380 kWh of energy consumed per day, which is equivalent to a reduction in carbon emissions of 1 204 tons/year.

Option 3: A PV system that will feed the baseload during peak sun hours, 450 kW

The baseload at Rietvlei is 450 kW and the amount of energy required to supply the baseload during peak sun hours is as follows:

$$Energy_{BASELOAD} = 450\ kW \times 5\ hours = 2\ 250\ kWh/day$$

In order to ensure that the maximum power at the output of the inverter is 450 kW, a DC-to-AC ratio of 1.15 is assumed. Therefore, the PV array size required is as follows:

$$P_{PV\_DC} = 450\ kW \times 1.15 = 518\ kWp$$

$$Area\ (m^2) = 518\ kWp \times 8\ {m^2}/{kWp} = 4\ 144\ m^2$$

The cost of a PV system is R30/W; thus the PV system cost, excluding battery backup, is as follows:

$$PV_{system_{cost}} = 518\ kWp \times \frac{R30}{W} = R15.54\ mil$$

The O&M cost is as follows:

$$PV_{O\&M\_cost} = 0.17\%/year \times R15.54\ mil = R26\ 418/year$$

Assuming an inflation rate of 6% and a replacement cost of R0.00 the total lifecycle cost is as follows:

$$PV_{total_{cost}} = R15\ 540\ 000 + R\ 660\ 450 + R0 = R16\ 200\ 450.00$$

The energy that can be generated in 25 years is as follows:

$$E_{PV_n} = (2\ 250 * 30 * 12 * 10) + (0.9 * 2\ 250 * 30 * 12 * 15) = 19\ 035\ 000\ kWh$$

$$LCOE = \frac{R16\ 200\ 450.00}{19\ 035\ 000\ kWh} = R0.8511/kWh$$

The annual electricity cost saving that can be achieved from this option is as follows:

$$C_s = (2\ 250 \times 30 \times 8 \times 0.9537) + (2\ 250 \times 30 \times 4 \times 1.0924) = R809\ 946/year$$

The anticipated cost saving in the 25-year period is as follows:

$$Total_{C_s} = R8\ 868\ 682.72 + R15\ 366\ 717.37 = R24\ 235\ 400.10$$

The simple payback period for the PV system is calculated as follows:

$$SPP = \frac{R16\ 200\ 450.00}{R809\ 946} = 20\ years$$

The results from this option indicate that:

1. The amount of energy that can be generated from installing a PV system on the available roof space will result in an 18% reduction in the average daily electricity consumption of the building.
2. The amount of space required (4 144 m^2) to install the PV system is less than the available roof space (6 225 m^2).
3. The amount of energy generated will be used to supply the baseload, therefore the system does not require additional battery storage.
4. The LCOE is lower than the current cost of each unit of electricity on the low-voltage demand tariff for both the summer and winter period.
5. The simple payback period for this investment is 20 years.
6. This PV system has the potential to reduce 2 250 kWh of energy consumed per day, which is equivalent to a reduction in carbon emissions of 802 tons/year.

Option 4: A PV system that will feed the average daily load that occurs at 12:00, 700 kW

The average load that occurs at 12:00 for Rietvlei is 700 kW and solar energy production is at its peak at midday, as shown in Figure 4. The amount of energy required to supply the average load at midday is as follows:

$$Energy_{LOAD@12:00} = 700\ kW \times 5\ hours = 3\ 500\ kWh/day$$

In order to ensure that the maximum power at the output of the inverter is 700 kW, a DC-to-AC ratio of 1.15 is assumed. Therefore, the PV array size required is as follows:

$$P_{PV\_DC} = 700\ kW \times 1.15 = 805\ kWp$$

$$Area\ (m^2) = 805\ kWp \times 8\ {}^{m^2}/_{kWp} = 6\ 440\ m^2$$

The cost of the PV system is R30/W; thus the PV system cost, excluding battery backup, is as follows:

$$PV_{system_{cost}} = 805\ kWp \times \frac{R30}{W} = R24.15\ mil$$

The O&M cost is as follows:

$$PV_{O\&M\_cost} = 0.17\%/year \times R24.15\ mil = R41\ 055/year$$

Assuming an inflation rate of 6% and a replacement cost of R0.00 the total lifecycle cost is as follows:

$$PV_{total_{cost}} = R24\ 150\ 000 + R\ 1\ 026\ 375 + R0 = R\ 25\ 176\ 375.00$$

The energy that can be generated in 25 years is as follows:

$$E_{PV_n} = (3\ 500 * 30 * 12 * 10) + (0.9 * 3\ 500 * 30 * 12 * 15) = 29\ 610\ 000\ kWh$$

$$LCOE = \frac{R25\ 176\ 375.00}{29\ 610\ 000\ kWh} = R0.8503/kWh$$

The annual electricity cost saving that can be achieved from this option is as follows:

$$C_s = (3\ 500 \times 30 \times 8 \times 0.9537) + (3\ 500 \times 30 \times 4 \times 1.0924) = R1\ 259\ 916/year$$

The anticipated cost saving in the 25-year period is as follows:

$$Total_{C_s} = R13\ 795\ 728.68 + R23\ 903\ 782.58 = R37\ 699\ 511.26$$

The simple payback period for the PV system is calculated as follows:

$$SPP = \frac{R25\ 176\ 375.00}{R1\ 259\ 916} = 19.98\ years$$

The results from this option indicate that:

1. The amount of energy that can be generated from installing a PV system on the available roof space will result in a 27% reduction in the average daily electricity consumption of the building.
2. The amount of space required (6 440 m^2) to install the PV system is more than the available roof space (6 225 m^2). The system can be optimised by making use of PV modules with higher efficiency to ensure that the amount of electrical energy required is produced.
3. The PV system will generate an excess of 9% of baseload energy. The system can curtail excess energy generated within the five hours; this is done with the use of a monitoring system that monitors and controls the output from the inverter.
4. The LCOE is lower than the current cost of each unit of electricity on the low-voltage demand tariff for both the summer and winter period.
5. The simple payback period for this investment is 19.98 years.
6. This PV system has the potential to reduce 3 500 kWh of energy consumed per day, which is equivalent to a reduction in carbon emissions of 1 248 tons/year.

APPENDIX II

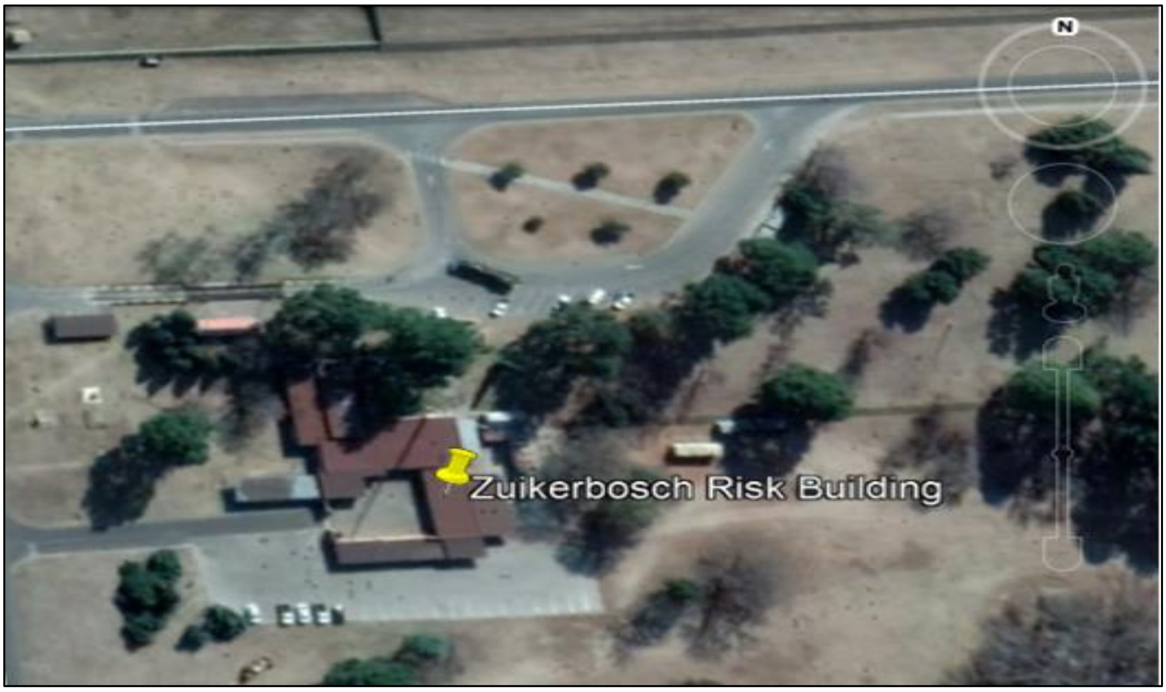
Identified Rand Water buildings

Zuikerbosch

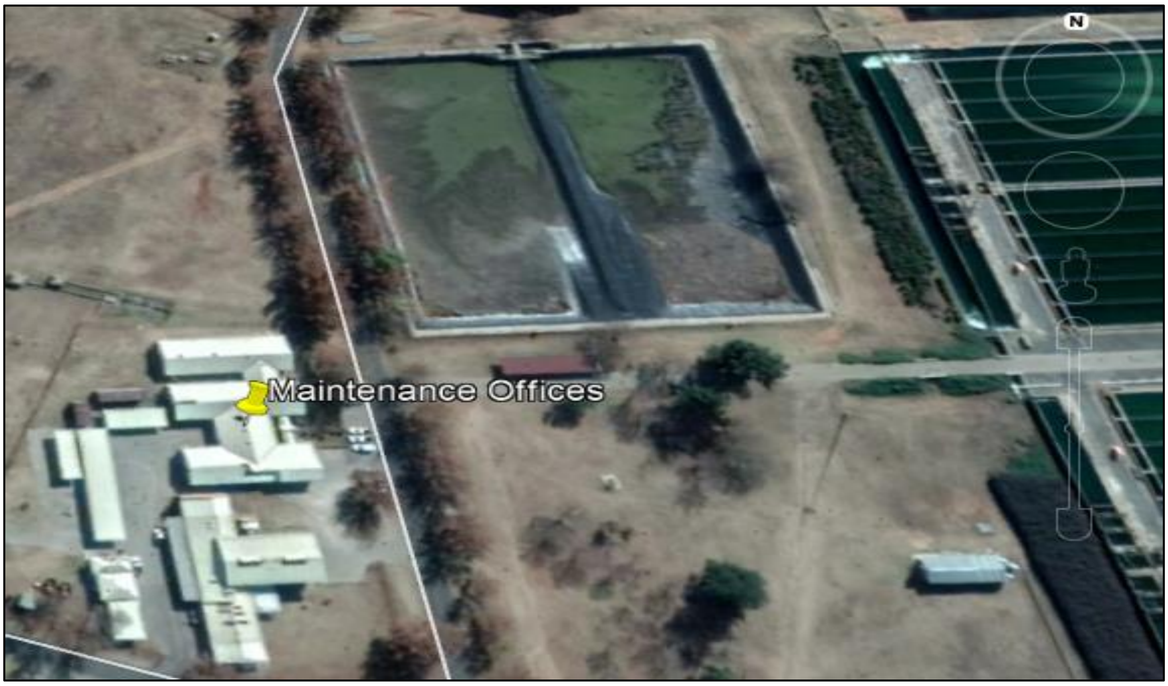
The Zuikerbosch Administration Building is located at the Zuikerbosch water treatment plant; GPS coordinates 26°41’36.76”S 28°00’25.57”E, in Vereeniging. The roof comprises of hipped and flat corrugated-steel sections.

The hipped roof has two sections which combine to form a T-shape; one section is orientated to the south-north and the other section to the east-west. The roof sections face east, south, west or north and the flat section is orientated towards the south-north.

The Zuikerbosch Risk Building is located at the Zuikerbosch water treatment plant; GPS coordinates 26°41’14.35”S 28°00’29.11”E, in Vereeniging. The building has a hipped corrugated-steel roof. It has three sections; one section is orientated to the south-north and the other two sections are orientated towards the east-west. The roof sections face slightly towards the northeast, southeast, northwest or southwest.



The Zuikerbosch Maintenance Offices are located at the Zuikerbosch water treatment plant; GPS coordinates 26°40’52.22”S 28°00’21.86”E, in Vereeniging. The building has a gabled corrugated-steel roof. The building has three sections which combine to form an I-shape; the middle section is orientated towards the northwest–southeast and the other two sections are orientated towards the northeast–southwest.



The roof sections face either slightly towards the northeast, southeast, northwest or southwest. There is an extension to the building leading to a workshop; the roof sections of the extension are orientated northwest–southeast and northeast–southwest.

Vereeniging

The Vereeniging Administration Building is located at the Vereeniging water treatment plant; GPS coordinates 26°41’26.85”S 27°55’08.06”E, in Vereeniging. The building has a flat, concrete roof, with services on the roof. The advantage of a flat roof is that the PV modules can either be mounted flat or at a tilt angle for maximum solar energy production.

The building is orientated towards the northeast–southwest.

The Vereeniging Process Technology building is located at the Vereeniging water treatment plant, GPS coordinates 26°20’50.26”S 28°03’51.99”E, in Vereeniging. The building has a gabled corrugated-steel roof.

The building has about seven sections; three sections have one side of the roof orientated towards the northeast and the rest of the sections are orientated towards the northwest. About three sections of the roof, including the two carports, face northeast. The rest of the roof sections face either southeast, northwest or southwest.

Zwartkopjes

The Zwartkopjes administration block comprises of maintenance offices, an HR administration building and the main administration building. It is located in the south of Johannesburg; GPS coordinates 26°20’48.96”S 28°03’35.73”E.

The maintenance offices have a gabled corrugated-steel roof, while the HR administration building has a hipped corrugated steel-roof. The orientation of the maintenance offices is northwest–southeast, while the HR administration building has a slight northeast–southwest orientation.

The main administration building has a flat concrete roof, and the PV modules can be mounted flat or tilted to a desired angle for maximum solar energy production. The roof sections of the maintenance offices face either northeast or southwest, while the sections of the HR administration building face either northwest, southeast, northeast or southwest.

The Zwartkopjes Conference Centre is located at the Zwartkopjes booster station in the south of Johannesburg; GPS coordinates 26°20’48.96”S 28°03’35.73”E. The building has a gabled corrugated-steel roof.

There are two sections which form a T-shape; one section is orientated towards the northeast–southwest, while the other section is orientated towards the northwest–southeast. The roof sections face either northeast, southeast, northwest or southwest.

The Emhlangeni Workshop is located south of the Zwartkopjes booster station, in the south of Johannesburg, GPS coordinates 26°21’16.05”S 28°03’39.10”E. The building has a gabled steel roof. Its orientation is towards the northeast–southwest and the two sections of the roof face either northwest or southeast.

The Emhlangeni Administration Building is located south of the Zwartkopjes booster station, in the south of Johannesburg, GPS coordinates 26°21’16.05”S 28°03’39.10”E. The building has a gabled steel roof.

Emhlangeni Administration Building has three sections which form a U-shape; the sections are orientated towards the northeast, southwest and northwest.

The EMS block is located south of the Zwartkopjes booster station, in the south of Johannesburg, GPS coordinates 26°21’09.39”S 28°03’39.10”E. The EMS block comprises buildings with both flat and gabled steel roofs. The EMS block is orientated towards the northeast.

Libanon

The Libanon Administration Building is located in the west rand of Johannesburg, GPS coordinates 26°21’35.44”S 27°37’33.41”E. The building has a gabled steel roof and it is orientated towards the northeast–southwest. The roof sections face either southeast or northwest.

Zuurbekom

The Zuurbekom Administration Building is located in the west rand of Johannesburg, GPS coordinates 26°21’35.44”S 27°37’33.41”E. It has a pyramid-hip steel roof, with each part of the pyramid facing either northeast, southeast, northwest or southwest.

Krugersdorp

The Krugersdorp Administration Building is located in the west rand of Johannesburg, GPS coordinates 26°06’47.63”S 27°48’35.87”E. The building has a pyramid-hip steel roof. Each part of the pyramid is orientated either south-north or east-west, and faces either east-west, south or north.

Germiston

The Germiston Administration Building is located at the Germiston reservoir site in the east of Johannesburg; GPS coordinates 26°11’23.16”S 28°08’40.04”E. The building has a gabled steel roof that is orientated northeast–northwest. One half of the roof faces northeast while the other half faces southwest.

Brakpan

The Brakpan Administration Building is located at the Brakpan reservoir site in the east of Johannesburg; GPS coordinates 26°16’02.26”S 28°22’27.30”E. The building has a pyramid-hip steel roof. Each part of the pyramid is orientated and faces the northwest, southwest, northeast or southeast.

Esselen Park

The Esselen Park Administration Building is located at the Esselen Park reservoir site in the east of Johannesburg, GPS coordinates 26°01’10.48”S 28°15’17.56”E. The building has a gabled steel roof that is orientated towards the northwest–southeast. One half of the roof faces northeast while the other half faces southwest.

APPENDIX III

PV system simulations

These simulations were done on Helioscope: Advanced Solar Design Software with the following inputs:

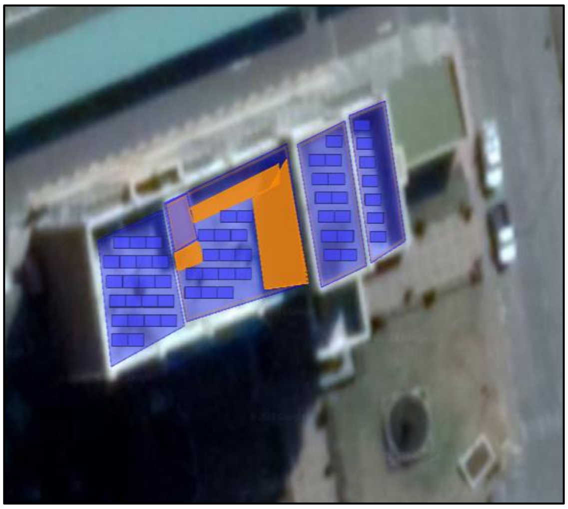
- Location in terms of GPS coordinates;
- Type of PV system (ground-mounted, commercial or residential); and
- Field segment variables such as tilt angle, azimuth angle, module spacing and maximum kWp.

Zuikerbosch Administration 157.4 kWp

Zuikerbosch Risk 36.5 kWp

Zuikerbosch Maintenance 35.2 kWp

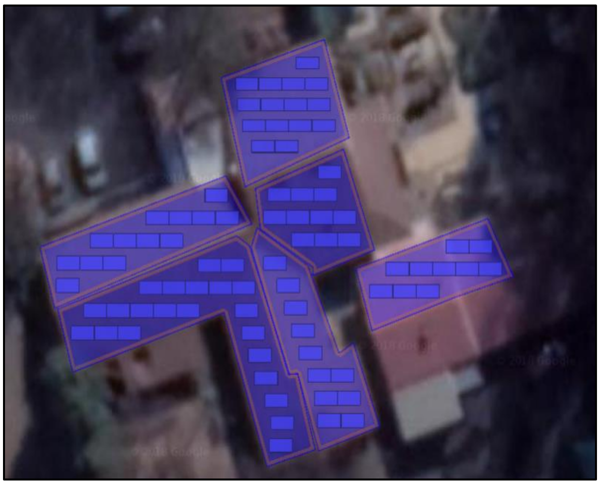
Vereeniging Administration 17.6 kWp



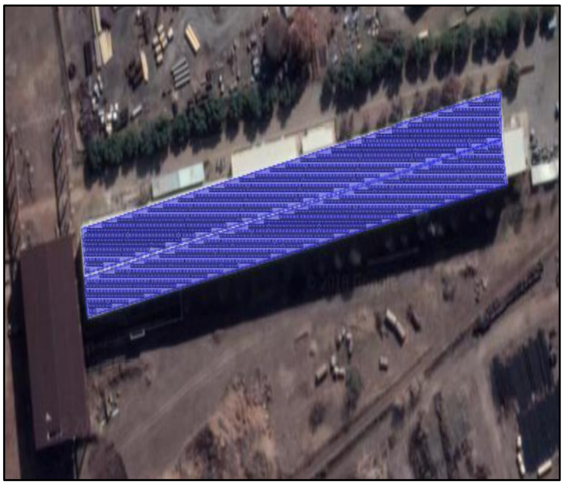
Vereeniging Process Technology 81.6 kWp

Zwartkopjes Administration 188.5 kWp

Zwartkopjes Conference Centre 26.2 kWp



Emhlangeni Workshop 618.6 kWp



Libanon 2.56 kWp

Germiston 4.48 kWp

Brakpan 3.52 kWp

Esselen Park 15.4 kWp

APPENDIX IV

Summary of calculations

Useful peak sun hours	5		**Cost (R/W)**	R12/W	R15/W		**O&M (%/year)**	0.17		
	System size (kW)	**PV system cost (R)**	**O&M (R/year)**	**Replacement cost (R)**	**Total lifecycle cost (R)**	**kWh/day**	**kWh/25 years**	**Cost saving (R/year)**	**Simple payback period (years)**	**LCOE (R/kWh)**
ZB Administration	157.4	1 888 800	3 210.96	2 270 214.41	4 239 288.41	787	6 658 020	204 745.92	20.71	0.6367
ZB Risk	36.5	438 000	744.60	526 447.43	983 062.43	182.5	1 543 950	46 241.3	20.71	0.6367
ZB Maintenance	35.2	422 400	718.08	507 697.25	948 049.25	176	1 488 960	44 594.35	20.71	0.6367
VG Administration	17.6	211 200	359.04	253 848.62	474 024.62	88	744 480	27 164.81	16.95	0.6367
VG Process Technology	81.6	979 200	1 664.64	1 176 934.53	2 197 750.53	408	3 451 680	125 945.93	16.95	0.6367
Libanon	2.56	38 400	65.28	36 923.44	76 955.44	12.8*	108 288	3 243.23	23.11	0.7107
Germiston	4.48	67 200	114.25	64 616.01	134 672.01	22.4*	189 504	12 561.70	10.51	0.7107
Zuurbekom	0.96	14 400	24.48	13 846.29	28 858.29	4.8*	40 608	1 177.5	18.92	0.7107
Brakpan	3.52	42 240	71.81	50 769.72	94 804.92	17.6*	148 896	9 869.9	9.41	0.6367
Esselen Park	15.4	184 800	314.16	222 117.55	414 771.55	77	651 420	43 180.83	9.41	0.6367
ZK Administration	67.8	813 600	1 383.12	977 894.13	1 826 072.13	339	2 867 940	88 194.24	20.71	0.6367
ZK Maintenance	87	1 044 000	1 774.8	1 254 819.91	2 343 189.91	435	3 680 100	113 169.60	20.71	0.6367
ZK HR Administration	34	408 000	693.6	490 389.39	915 729.39	170	1 438 200	44 227.2	20.71	0.6367
ZK Conference Centre	26.2	314 400	534.48	377 888.29	705 650.29	131	1 108 260	34 080.96	20.71	0.6367
EMS	24.6	295 200	501.84	354 811.15	662 557.15	123	1 040 580	31 999.68	20.71	0.6367
Emhlangeni Workshop	618.6	7 423 200	12 619.44	8 922 202.23	16 660 888.23	3093	26 166 780	804 674.88	16.95	0.6367
Emhlangeni Administration	11.8	141 600	240.72	170 193.96	317 811.96	59*	499 140	15 349.44	16.95	0.6367

* *The cost of R15/W was used for smaller PV systems.*