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# INVESTIGATING THE FEASIBILITY & IMPACT OF A SOLAR ARRAY FOR WITS WEST CAMPUS BY USING HISTORICAL SOLAR AND POWER DATA

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Master of Science in Engineering (Electrical)
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July, 2016

# Declaration

I declare that this dissertation is being submitted to fulfil the requirements for a Master's degree in Electrical Engineering for the University of the Witwatersrand, Johannesburg and is my own work, excepted where otherwise referenced. To my knowledge, it has not been submitted for any other degree in any other university.

_____

Ajeshni Singh
10-07-2016

# Abstract

This dissertation uses historical electrical consumption/load and actual solar radiation data to design a solar array for the University of the Witwatersrand's West Campus. The array must meet the campus's minimum demand as selling excess generated power back to the utility is not possible at this stage. The financial and spatial impact of adjusting the size of the array, design losses and cloud cover are also investigated. In addition to this, the influence on the payback period of financial variables such as taxes, electricity and start-up costs are also explored.

The solar array system design process starts by determining the amount of power that the array must produce or supplement. Thereafter, load estimates and electrical consumption figures that are provided by utility bills or measured with load monitoring equipment are analysed. Furthermore, system losses are factored in which ultimately increases the size of the array. Once all the input variables are analysed, the amount of available solar radiation in the area where the array will be installed is required to determine the amount of energy that the array can produce. Several free databases with this information are available but it is found that this data over predicts the availability of solar radiation.

The University has been monitoring the electrical consumption of West Campus since 2012 and solar radiation data is also available for this site. Comparing the satellite derived and measured datasets found that the ground monitored data is 25 % more accurate and therefore better suited for designing a solar array. Individually adjusting the design and financial variables changes the payback period between 3 – 17 %. Combining all the variables can reduce the payback of option 1 from 9.6 years to 6.1 years.

Clear legislation needs to be developed for the uptake of renewable energy resources and supported by better rebates for renewable users and harsher taxes for non-renewable users. Should legislation change and if additional capital is available, a larger array will benefit the University more and should be installed as the difference between payback periods is not significant. This is mainly due to decreased costs associated with a higher yield. The financial benefits of a larger array will also be more lucrative if better rebates are enforced.

# Acknowledgements

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## TABLE OF CONTENTS


| Chapter | Description | | Page |
|---|---|---|---|
| **ABBREVIATIONS AND ACRONYMS** | | | **IV** |
| **LIST OF FIGURES** | | | **V** |
| **LIST OF TABLES** | | | **VI** |
| **1** | **INTRODUCTION** | | **1** |
| | 1.1 | Research Objectives | 1 |
| | 1.2 | Motivation | 1 |
| | 1.3 | What is Solar Radiation? | 4 |
| | 1.3.1 | Measuring Solar Radiation | 5 |
| | | Ground Monitoring | 5 |
| | | Satellite Derived | 5 |
| | 1.4 | How is Electricity Generated from Solar Energy? | 5 |
| | 1.4.1 | Photovoltaics | 6 |
| | | Off-Grid | 7 |
| | | Grid connected | 7 |
| | 1.4.2 | Solar Array Design Considerations | 8 |
| | | (a) Location | 8 |
| | | (b) Orientation & Tilt | 8 |
| | | (c) Maintenance | 8 |
| | | (d) Losses | 9 |
| | 1.5 | Limitations of the use of Solar Energy in South Africa | 9 |
| | 1.5.1 | Taxes & Incentives | 10 |
| | 1.5.2 | Legislation | 10 |
| | 1.5.3 | Finance | 11 |
| | 1.6 | Accuracy & Availability of Solar Radiation Data | 12 |
| | 1.7 | Research Question | 13 |
| | 1.8 | Research Constraints, Assumptions and Limitations | 14 |
| | 1.9 | Research Significance | 14 |
| | 1.9.1 | Global Warming & Climate Change | 15 |
| | 1.9.2 | Electricity Security | 18 |
| | 1.9.3 | Consumer Education | 19 |
| | 1.10 | Review of Current Methods and Research | 19 |
| | 1.11 | Research Methodology | 20 |
| | 1.11.1 | Data Analysis | 20 |
| | 1.11.2 | Design Considerations | 21 |

| | | | |
|---|---|---|---|
| | 1.11.3 | Financial Considerations | 21 |
| | 1.12 | Conclusion | 21 |
| **2** | **DATA ANALYSIS** | | **23** |
| | 2.1 | Electricity Costs | 23 |
| | 2.2 | Consumption Patterns | 26 |
| | 2.3 | Available Solar Radiation Data | 33 |
| | 2.3.1 | SolarGIS | 33 |
| | 2.3.2 | PVGIS | 34 |
| | 2.3.3 | Wits Data | 34 |
| | 2.3.4 | Comparison of data sets | 35 |
| | 2.4 | Comparison of Load and Wits Radiation Data | 36 |
| | 2.5 | Determining the Required Yield | 37 |
| **3** | **DESIGN CONSIDERATIONS** | | **39** |
| | 3.1 | Losses | 39 |
| | 3.2 | Panels & Inverters | 39 |
| | 3.2.1 | Panel Efficiency | 41 |
| | 3.3 | Calculating the Array Output | 41 |
| **4** | **FINANCIAL CONSIDERATIONS** | | **43** |
| | 4.1 | Estimated Start-up Capital | 43 |
| | 4.2 | Estimated Savings | 43 |
| | 4.3 | Economic Viability | 45 |
| **5** | **RESULTS & ANALYSIS** | | **47** |
| | 5.1 | Final Array Size | 48 |
| | 5.2 | Solar Array Output | 49 |
| | 5.3 | System Design | 55 |
| | 5.4 | Estimated Cost and Savings | 55 |
| | 5.5 | Environmental Impact | 57 |
| | 5.6 | Comparing Solar Radiation Data | 58 |
| | 5.7 | Solar Array Size | 59 |
| | 5.8 | Cloud Cover | 62 |
| | 5.9 | Tax Incentives | 63 |

| | | | |
|---|---|---|---|
| | 5.10 | Carbon Taxes and Offsets | 64 |
| | 5.11 | Electricity and Start-up Costs | 65 |
| | 5.12 | Losses | 67 |
| | 5.13 | Feed-in Tariffs | 68 |
| | 5.14 | Combining Variables | 70 |
| **6** | **CONCLUSION & RECOMMENDATIONS** | | **71** |
| | **REFERENCES** | | **77** |
| **A** | **BILLING INFORMATION** | | **86** |
| **B** | **DATA ANALYSIS** | | **90** |
| | B.1 | COMPARING DATA SETS | 90 |
| | B.2 | NORMALISATION | 90 |
| **C** | **ECONOMICS** | | **93** |
| | C.1 | CAPITAL | 93 |
| | C.2 | INFLATION | 94 |
| | C.3 | SOLAR PANEL DEGRADATION AND MAINTENANCE | 94 |
| | C.4 | CARBON TAX AND OFFSETS | 94 |
| | C.5 | TAX INCENTIVES | 95 |
| | C.6 | ELECTRICITY PRICE INCREASES | 96 |
| | C.6 | FEED-IN TARIFFS | 97 |
| | C.7 | FINAL NPV EQUATION | 98 |
| **D** | **RESULTS** | | **99** |

## ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| AC | Alternating Current |
| BP | British Pertoleum |
| CSV | Comma Separated Values |
| DC | Direct Current |
| DNI | Direct Normal Radiation |
| DHI | Direct Horizontal Radiation |
| Eskom | Electricity supply commission of South Africa |
| GHI | Total Radiation |
| GW | Gigawatt |
| Ha | Hectare |
| kt | Kiloton (1000 tons) |
| kWh | Kilowatt hour (1000 Wh) |
| kVA | Kilovoltamps |
| kVArh | Kilovoltamps reactive hours |
| MW | Megawatt (1000 kW) |
| MVA | Megavoltamps |
| MWh | Megawatt hour (1000 kWh) |
| Mtoe | Million tonnes of oil equilvalent |
| NPV | Nett Present Value |
| NERSA | National Energy Regulator of South Africa |
| ppm | Parts per million |
| REIPPPP | Renewable Energy Independent Power Producer Procurement Programme |
| SANEDI | The South African National Development Institute |
| TWh | Terawatt hour |
| The University | The University of the Witwatersrand |
| $W_P$ | Watt peak |
| WACC | Weight Average Cost of Capital |
| West Campus | The west campus of the University of the Witwatersrand |
| ZAR | South African Rand |

## LIST OF FIGURES


Figure 1. 1: South Africa's energy consumption 2
Figure 1. 2: Global electricity generation per resource 3
Figure 1. 3: Basic system configuration 7
Figure 1. 4: Carbon emissions per fuel 15
Figure 1. 5: South Africa's non-renewable consumption 16
Figure 1. 6: South Africa's electricity consumption by sector for 2006 18
Figure 2. 1: Power triangle 24
Figure 2. 2: Percentage difference in the cost of electricity for 2013/2014 and 2011/2012 25
Figure 2. 3: Percentage share of total electricity costs 26
Figure 2. 4: Wits activities and accompanying electricity demand 27
Figure 2. 5: West Campus's load profile for 11/02/2014 28
Figure 2. 6: West Campus's load profile for 03/03/2014 28
Figure 2. 7: West Campus's load profile for 16/07/2013 29
Figure 2. 8: West Campus's load profile for 30/12/2013 30
Figure 2. 9: West Campus's load profile for December 2013 30
Figure 2. 10: West Campus's load profile for 2013/2014 32
Figure 2. 11: South Africa's global horizontal radiation [58] [1] 33
Figure 2. 12: Wits Solar Radiation for 2013/2014 34
Figure 2. 13: Solar radiation for data sets 36
Figure 2. 14: Normalised Data 37
Figure 2. 15: Maximum, minimum and average load for the selected period 38
Figure 3. 1: Power triangle for the system 42
Figure 5. 1: Total available solar radiation per activity 48
Figure 5. 2: Total available solar radiation per month 49
Figure 5. 3: Solar Array Output Methodology 50
Figure 5. 4: Solar Yield for three Options 51
Figure 5. 5: Load and Solar output for Option 1 52
Figure 5. 6: Load and Solar output for Option 2 53
Figure 5. 7: Load and Solar output for Option 3 54
Figure 5. 8: Peak Demand Savings per Option 55
Figure 5. 9: Total $CO2$ emission savings for each array 57
Figure 5. 10: Solar radiation for data sets 58
Figure 5. 11: Load and solar output for Option 1 (week 23 – 39) 60
Figure 5. 12: Maximum recorded solar radiation 60
Figure 5. 13: Load and solar output for 3931 kW array (week 23 – 39) 61
Figure 5. 14: Load and solar output for 4310 kW array (week 23 – 39) 61
Figure 5. 15: Amount of days with rain 62
Figure 5. 16: Average Electricity Price Increase/Decrease Since 2000 65
Figure 5. 17: Comparison of cost per kW and payback 66
Figure 5. 18: Consumption, solar yield and nett energy for Option 1 68
Figure 5. 19: Consumption, solar yield and nett energy for Option 2 69
Figure 5. 20: Consumption, solar yield and nett energy for Option 3 69
Figure B. 1: Load profile and available radiation 91
Figure B. 2: Normalised data 92
Figure D. 1: Cumulative NPV for Option 1 99
Figure D. 2: Cumulative NPV for Option 2 99
Figure D. 3: Cumulative NPV for Option 3 100

## LIST OF TABLES


Table 1. 1: Costs associated with solar and coal electricity generation 11
Table 1. 2: 75th percentile of carbon dioxide emissions per fuel 17
Table 2. 1: Average tariffs for 2013/2014 and 2011/2012 periods 25
Table 2. 2: Term Schedule for the selected period 27
Table 2. 3: Term Schedule for the selected period 36
Table 3. 1: Summary of losses 39
Table 3. 2: Summary of 310 W panel area 40
Table 4. 1: Electricity tariff costs 44
Table 4. 2: Economic variables 45
Table 5. 1: Final array size 49
Table 5. 2: Summary of each options system design 55
Table 5. 3: Capital costs, savings and payback 56
Table 5. 4: Percentage penetration for each option 56
Table 5. 5: Percentage differences for each option 57
Table 5. 6: Mean Bias Error 58
Table 5. 7: System Design and Payback 59
Table 5. 8: Summary of selected options 59
Table 5. 9: Highest Radiation's load and occurrence 61
Table 5. 10: Effect of changing the number of rain days for year 1 63
Table 5. 11: Effect of Changing the Tax Incentive Rate 64
Table 5. 12: Effect of Changing the Carbon Tax Rate 64
Table 5. 13: Effect of Changing the Carbon Offset Rate 64
Table 5. 14: Effect of Changing the Electricity Tariff Increases 65
Table 5. 15: Effect of Changing the Cost per kW 66
Table 5. 16: Effect of adjusting contributing inefficiencies 67
Table 5. 17: Effect of Feed-in Tariffs 70
Table 5. 18: Effect of changing several variables 70
Table 6. 1: Summary of space and equipment required for solar arrays 73
Table 6. 2: Summary of costs and savings, (year 1), for three options 73
Table 6. 3: Impact of changing variables 75
Table A. 1: Total Electricity Costs for June 2013 – May 2014 86
Table A. 2: Total Real Energy Costs for June 2013 – May 2014 86
Table A. 3: Total Peak Demand Costs for June 2013 – May 2014 86
Table A. 4: Total Reactive Energy Costs for June 2013 – May 2014 87
Table A. 5: Total other costs for June 2013 – May 2014 87
Table A. 6: kWh cost per month 87
Table A. 7: kVA cost per month 88
Table A. 8: kVArh cost per month 88
Table A. 9: Other costs per month 88
Table A. 10: Total costs per month 89
Table B. 1: Various data sets for the campus 90
Table B. 2: Significant periods and accompanying data 90
Table B. 3: Normalised data 91
Table C. 1: Vendor prices 93
Table C. 2: Indicative year on year electricity tariff increases 96
Table C. 3: Actual electricity tariff increases 97

# 1 INTRODUCTION

This dissertation determines the feasibility and impact of a solar array on electricity costs using historical solar radiation data as well as accurate load measurements instead of freely available estimated data. This could improve the overall efficiency when designing a solar array.

## 1.1 Research Objectives

The main objective of this research is to use actual data to investigate if a suitably sized solar array can reduce the costs of electricity for the University of the Witwatersrand without generating excess electricity. In addition to this, the following objectives are identified:

- Economic feasibility of the solar array.
- Establish what the effect of changing the size of the array would be and corresponding financial impact.
- Identify the most feasible array size to optimise the use of the solar generated electricity.
- Compare solar radiation data sets and their impact on the design.
- Quantify the effects of the following design and financial variables:
    - Cloud cover
    - Tax incentives
    - Carbon tax
    - Carbon offsets
    - Electricity costs
    - Capital investment
    - Losses
    - Feed-in tariffs

## 1.2 Motivation

Energy availability, affordability and sustainability is a problem for all countries of the world. The amount of natural resources to produce energy are decreasing and its continuous usage has resulted in global warming and will affect everyone on the planet if nothing is done to mitigate and curb carbon emissions. Some solutions to reduce the effects of global warming are [1]:

- Increasing energy efficiency – in all sectors, ranging from electricity production, fuel production and use and appliance efficiency

- Reducing deforestation
- Switching from non-renewable energy sources to renewable sources

South Africa's energy needs are mostly serviced by oil and coal resources, the sum of which is almost 95 % of the country's entire energy consumption. A pie graph illustrating this and other sources of consumed energy is shown in Figure 1.1, and is adapted from BP's 2013 Statistical review of World Energy [2].

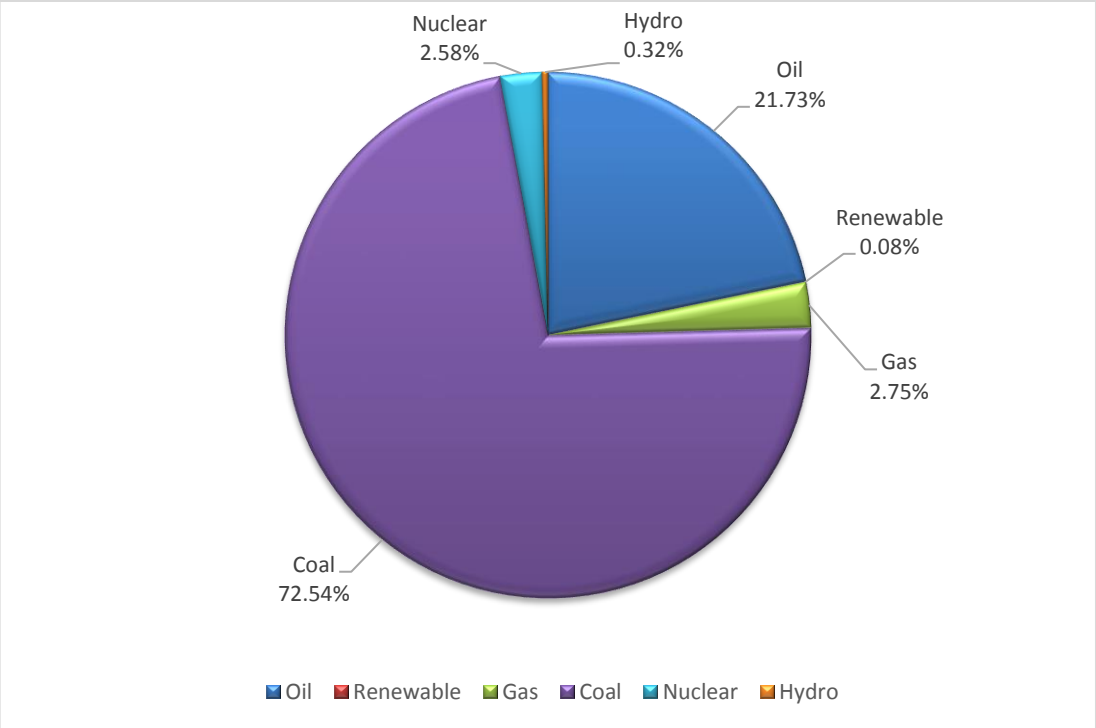



Figure 1. 1: South Africa's energy consumption

The International Energy Agency's Key World statistics in 2013 stated that almost 80 % of non-renewable energy sources were used for Electricity generation, [3]. A breakdown of the resources used to generate electricity in 2011 is shown in Figure 1.2, where *"Other"* includes geothermal, solar, wind, biofuel, waste & heat.

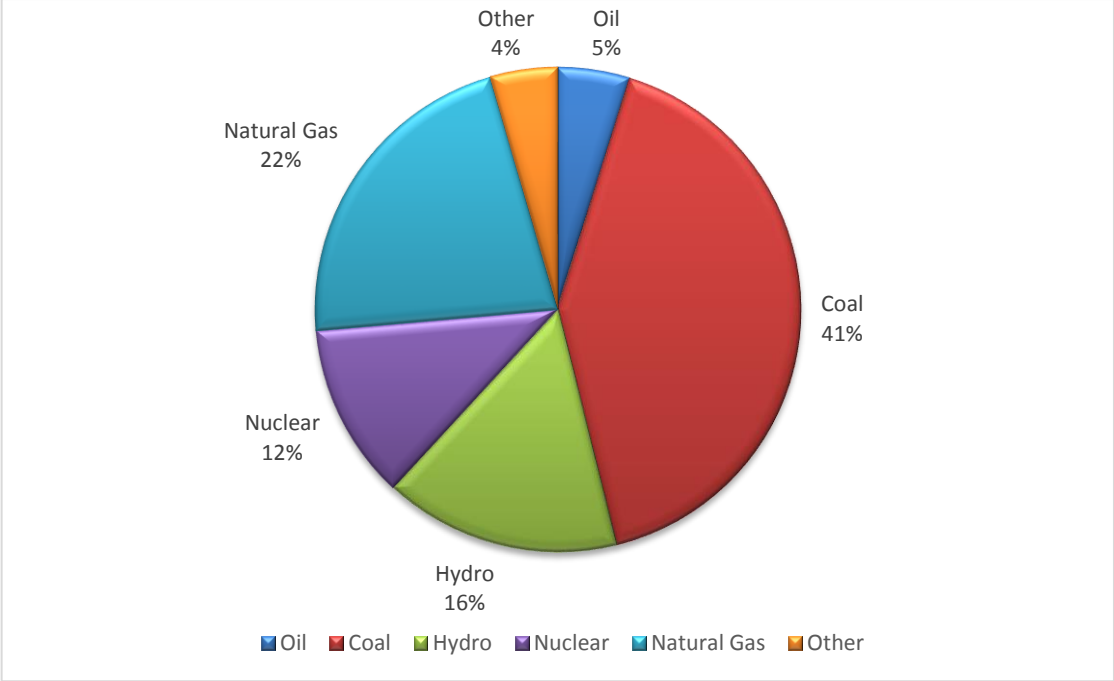


Figure 1. 2: Global electricity generation per resource

The World's electricity demand per annum for 2013 was just over 22 000 TWh [3] and is expected to double by 2050 [4]. Should coal continue to be the dominant resource used in electricity generation, carbon emissions will continue to increase and the possibility of the Earth's temperature rising is likely. Renewable energy resources fluctuate, however experts believe that the sum of the global renewable energy supplies is sufficient to supply the World's current electricity demands six times over [5].

With decreasing supply of non-renewable sources for electricity generation, climate change and increasing costs, countries are realising that they need to look for alternative, more environment friendly options for their electricity needs. Some examples are Germany and Sweden whose success is accredited mainly to tax incentives and the offer of feed-in tariffs [6]. America has also recently had a large uptake of solar installations and offered most customers a rebate of $ 3.7 per $W_p$. This rebate has since decreased to $ 1.1 per $W_p$ in 2010 [7].

South Africa uses the bulk of its coal for electricity generation [8], and has recently commissioned two large coal fired power stations – Medupi (4764 MW) and Kusile (4800 MW). South Africa has committed to a staggering 42 % carbon emission reduction by 2025 and developed the "*The White Paper on Renewable Energy*" [9] but more money has been invested in coal than in renewable energy. The Renewable Energy Independent Power Producer Procurement Programme, (REIPPPP), sets out the plan to only have 9 % renewable energy

penetration by 2030 [10], in spite of the fact that some areas of South Africa are fortunate to have an average solar radiation of 5.5 kWh/m² per day [11].

The likes of the rebates experienced in America are not on offer in South Africa as yet. Eskom started the "*Solar Water Heating Rebate Programme*" in 2008, which offered consumers rebates for installing solar water heaters instead of conventional geysers [12]. NERSA also developed feed-in tariffs from 2009-2011 and the South African government is in the process of implementing a tax on carbon emissions and has implemented tax incentives for the use of renewable resources. These items are discussed in Section 1.3 along with the cost of solar projects and South Africa's ranking in the World's Energy trilemma index.

## 1.3 What is Solar Radiation?

Solar radiation is electromagnetic energy emitted from the Sun. Approximately 30 % of the energy emitted by the Sun is lost to space and a further 20 % is reflected by particles and gases in the atmosphere [13]. The maximum amount of energy available on 1 m² of the Earth's surface in direct sunlight is approximately 1.37 kW and is known as the solar constant [14 & 15]. Some of the factors that affect the amount of available energy for harnessing are:

- Cloud cover
- The consistency of the atmosphere
- Seasons

The Sun's energy may be divided into direct normal and diffuse horizontal radiation [16] and expressed as instantaneous power density in units of $kW/m^2$. The direct component, (DNI), is the portion of radiation that the Earth receives directly from the Sun and the diffused component, (DHI), is the radiation that is reflected from the atmosphere and clouds [16]. The ratio of both forms of radiation varies depending on the weather and location and is governed by Equation 1.1 [14] where GHI is the total radiation received from the sun on the Earth's surface

$$GHI = DNI \cos \emptyset + DHI \quad \text{.....[1.1]}$$

Where,

- $\emptyset$ is the angle between the location and the sun
- $DNI$ is direct normal radiation
- $DHI$ is direct horizontal radiation

### 1.3.1 Measuring Solar Radiation

Numerous methods exist for measuring solar radiation, two of the main methods are:

- Ground monitoring
- Satellite derived

**Ground Monitoring**

The ground monitoring method utilises three different instruments to measure the three above mentioned components of solar radiation [14]:

- Pyranometer – measures total GHI
- Pyranometer and shading ball – measures DHI
- Pyrheliometer – measures DNI

By using all three instruments, the measured values of each component of solar radiation can be validated with Equation 1.1.

**Satellite Derived**

In this method, the amount of available solar radiation for a particular site is determined by comparing each pixel in a satellite image to a reference image with no clouds [14]. Each pixel is then allocated a cloud index number based on the amount of cloud cover in the pixel and inserted into a mathematical model. The model applies other atmospheric parameters such as ozone and water content to calculate the final available solar radiation [14].

## 1.4 How is Electricity Generated from Solar Energy?

Converting the Sun's energy into a usable form can be achieved with several technologies such as photovoltaics, solar ponds and concentrated solar power [17]. Producing electricity from solar energy is currently much more expensive when compared to traditional methods [18] but as demand for cleaner energy increases and availability of non-renewable sources decline this cost should decrease. Since these technologies require the Sun, electricity generation is maximum during the day and depends on the average number of sunshine hours available in the installation area [18]. Electricity generation at night is zero and batteries may be used to store excess electricity generated during the day for night time requirements [19].

Photovoltaics are one of the most popular technologies because they do not require as much space as the other two technologies mentioned above [17]. Despite the high capital costs, the demand for photovoltaic panels are increasing at an annual rate of 45 % [20] which means that the total installed capacity in the World almost doubles every 2 years. Photovoltaics are briefly discussed in the Section 1.4.1.

### 1.4.1 Photovoltaics

The first solar panel that converted solar radiation to electricity as it is known today was only in production by 1954 [21]. A photovoltaic panel utilizes sunlight to excite electrons on its surface and is usually made out of silicon and chemicals like cadmium sulphide or gallium arsenide. Once the electrons are excited an electric field is created and DC electricity is generated. These chemicals may also contaminate the environment if the panels are not properly disposed of when their lifespan has been exceeded. Depending on the required power output, panels can be strung together in series or parallel to provide the necessary voltage and required current. If a higher operating current is required, the panels are connected in parallel and in series if a higher voltage is required [22].

Besides photovoltaic panels, the following equipment is required to complete the installation:

- Charge controllers
- Batteries
- Inverters
- Sundry equipment, (brackets and cabling etc.)

A very simplified illustration of a complete solar generating plant is shown in Figure 1.3 and adapted from Sen et al. [23].

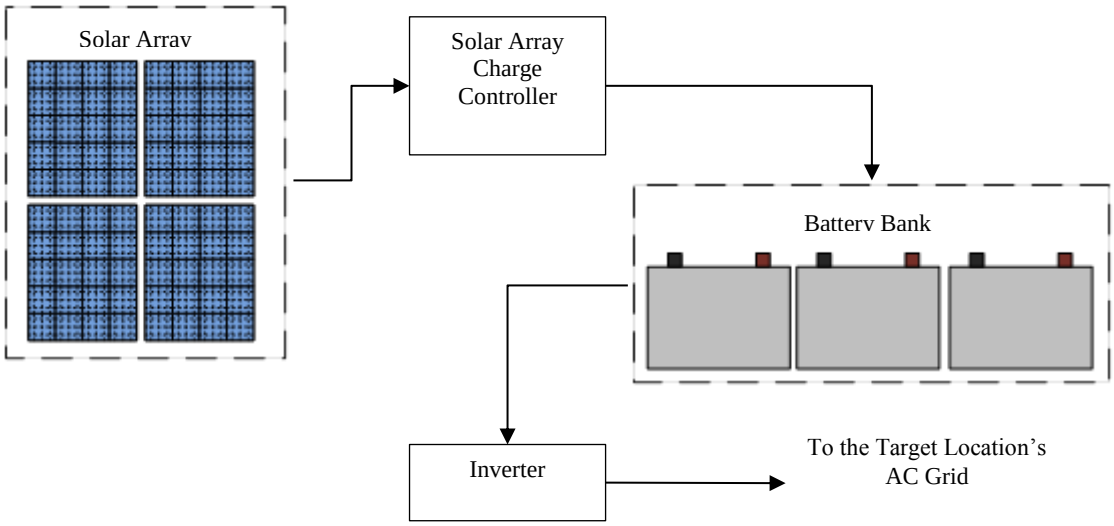



Figure 1. 3: Basic system configuration

A charge controller ensures that the bank of batteries is correctly charged and an inverter converts DC power from the array or batteries into usable AC power. The inverter must be appropriately sized to meet the load's peak requirements [19]. Depending on the system configuration and size, several small inverters can be added to handle the output from the solar array. In larger projects, central inverters need to be added to the system to decrease efficiency losses and costs [23]. Subject to the operating parameters of the grid and the output voltage of the solar array, a transformer may be needed to increase the solar output to match the grid's voltage [23]. Finally, appropriate wiring and other equipment such as brackets, a combiner box for the panels that ensures proper connection of the panels in series or parallel is required. Proper wiring reduces power losses.

A photovoltaic solar system as described above can be configured in two different ways which are briefly discussed below [24 & 26]:

**Off-Grid**

Off-grid systems are not connected to a local electricity grid and require batteries to store solar energy for use when the sun is not available

**Grid connected**

A grid connected system is connected to a local electricity grid and could possibly supply excess electricity back into the grid depending on local legislation. These systems can be backed up with batteries and electricity from the local utility will only be used when the batteries are depleted. The system can also be stand-alone with no battery backup so the local utility's

electricity will be utilised when the sun is not available. One disadvantage of grid connected systems is that it will shut down if the local electricity grid cannot supply electricity during a power outage.

### 1.4.2 Solar Array Design Considerations

To begin designing a solar array, the size of the output power required is first calculated by investigating the end user's load. The above mentioned system components and their unique characteristics are needed to continue with the design [22]. Other design considerations of a solar are location, orientation, tilt, maintenance and losses. These are discussed in the subsequent sections.

(a) Location

The location of a solar array is critical to its output as photovoltaic panels perform optimally under full sun conditions but inverters require shade. If an array is mounted on an existing roof, the chances of theft is decreased as the panels are not easily accessible. But the condition and type of roof needs to be considered along with fixing details for array structure [7]. Theft and vandalism become a deciding factor for a ground mounted array. Existing vegetation, drainage and the type of soil need to be taken into account as well [7]. The location of the array also determines the amount of shading that the array will be exposed to. Shading lowers the output of a panel and thus the output of a string or panels in an array [22].

(b) Orientation & Tilt

Orientation and the tilt of the array are other variables to consider when determining a suitable location. In the Southern Hemisphere, this means that for optimal output – installed solar arrays need to face North [7]. Upon installation, common practice suggests that the array be tilted to match the location's latitude.

(c) Maintenance

Regular maintenance and cleaning of the panels is required to ensure that they operate at the highest efficiency [8]. The frequency of cleaning depends on the climate conditions in the area. Dirt, leaves, bird droppings and frost are examples of natural occurrences that can impact a panel's efficiency and output [7].

(d) Losses

All panels are tested under standard test conditions which according to the IEC 60904-3 are under an irradiance of 1 $kWm^{-2}$, temperature of 25°C and an atmospheric thickness of 1.5 times the earth's atmosphere [25]. In practice these standard test conditions are not always met, several inefficiencies are therefore introduced in a solar array system design that need to be considered and result in a reduction of panel output:

- Production tolerance. As mentioned, panels do not operate under standard test conditions and most manufacturers offer a tolerance of 5% on the stated output. For example a 200 W panel can produce anything from 190 W – 210 W. it is assumed that a panel will produce less than the stated output, this results in a panel efficiency of 95 % [26].
- Temperature. Depending on the location of the installation, the temperature of the installed panels can rise up to 50°C - 70°C. A good approximation to take this inefficiency into account is 89% [26].
- Dirt. As with everything, dirt and other particles can accumulate on the panels. Wind and rain can usually wash most of the dirt away, but assuming an efficiency of 93 % [26] is a good approximation that will take this inefficiency into account.
- Component mismatch. A mismatch between panels in the array or cable can result in 5 % losses [26] which equates to 95% efficiency. These mismatches are difficult to predict as they can be attributed to performance, installation or location.
- Conversion losses. An inverter is required to convert DC generated solar power to AC usable power. This conversion process also creates losses in the system. 10 % [26] losses are assumed in this analysis.

## 1.5 Limitations of the use of Solar Energy in South Africa

A solar array harnesses solar energy to produce electricity. Solar energy is a natural renewable resource that South Africa has an abundance of, although it does fluctuate and is not as consistent as its non-renewable counterparts. In spite of this, this resource remains largely untapped [11]. Several challenges prevent solar energy's exploitation in the market [10] some of which are:

- High capital costs. Solar array installations are expensive and consumers are not familiar with the concept of "paying off" or "paying back" electrical equipment as they would a building, a piece of land or an investment.

- Irregular resource. Since solar is a natural resource, constant electricity generation is not guaranteed and dependent on fluctuating weather patterns.
- Selling back to the grid. At this juncture, all consumers cannot sell excess power back to the grid. This makes the feasibility of solar arrays weak and difficult to design because consumer usage needs to be accurate and adhered to.
- Lack of political backing. Government has recently approved the building of two huge coal-driven power stations amounting to almost 10 000 MW. Investment grants are also difficult to attain.
- Cheap non-renewable generated electricity.

### 1.5.1 Taxes & Incentives

A new tax on carbon emissions in South Africa is also in its final stages of approval, once implemented users will be taxed on the usage of non-renewable resources to the value of R 120 per ton of emitted carbon dioxide with a 10 % annual increase [27]. Once implemented, users can be exempted by up to 60 % of carbon dioxide emissions. Various other relief methods including buying carbon offsets and immitigable circumstances can reduce the tax payable to a minimum of 10 % [28]. Since South Africa is heavily dependent on non-renewable resources for energy needs, these tax reliefs will ensure that the economy is not severely affected but the carbon tax legislation will not promote the usage of renewable resources such as solar. The South African government decided that the carbon content of the non-renewable resource will be used as a basis to quantify the amount of carbon emissions [29].

South Africa has also recently adopted a tax incentive for proven energy efficiency savings. The incentive will pay R 0.45 per approved kWh [30].

### 1.5.2 Legislation

Currently, there is no legislation that specifically covers the integration of solar arrays into the current electricity network [31] but they are being developed.

According to the *Electricity Regulation Second Amendment Bill*, no person is allowed to construct or operate a generating facility without being approved as an independent power producer [32]. If there are plans on generating electricity for private use then no licence is required. NERSA has also recently reviewed and published *Renewable Energy Feed-In Tariffs – REFIT* – in March 2011. The REFIT for solar photovoltaic installations larger than 1 MW is R 3.94 but this only applies to a ground mounted installation with single axis tracking [33]. To qualify for the REFIT, the owner of the installation will have to apply to NERSA for a licence

to generate electricity and sell it back to the grid. Following this, the owner will enter into a 20 year agreement with NERSA [33].

Smaller installations are covered by NERSA's *Standard Conditions for Embedded Generation within Municipal Boundaries*. In this document, generators of electricity are allowed to sell excess electricity to the grid by paying a monthly service fee to use the grid provided that they have a licence to do so from the governing municipality [34]. Bi-directional or smart meters will also need to be installed so that all electricity exports from generators can reverse the meter readings – a concept known as net metering. The entire installation will also need to be tested before final approval is given by the relevant municipality. Each municipality will also need to monitor and record the amount of electricity sold back to the gird and report back to NERSA on a regular basis [35]. NERSA will need to monitor the capacity of the grid to ensure that it is not overloaded.

The only two municipalities who have embraced small scale generation are the Nelson Mandela Bay and City of Cape Town municipalities, with the latter wanting to contribute to the Western Cape being the country's lowest carbon emitting province. Both these municipalities have also driven NERSA to develop the standard conditions document [34].

### 1.5.3 Finance

Renewable energy technologies – such as solar – are generally seen as more expensive when compared to other non-renewable technologies and are also deemed to be unreliable due to their unpredictable behaviour. de Groot et al. compared the costs of solar and coal generated electricity – the price associated with each technology but also the accompanying water usage and environmental costs. The authors completed this exercise for a large solar farm, (81 MW), a private installation, (131 kW), and a coal fired power plant, (3600 MW). Some major findings from this paper are listed in Table 1.1 and adapted from [8]. In each column, the associated costs are compared to the corresponding costs in the coal fired power plant and are represented as a percentage.

Table 1. 1: Costs associated with solar and coal electricity generation

| | **Private solar Installation** | **Solar Farm** |
|---|---|---|
| Water use | -100% | -93% |
| Carbon emissions | -100% | -100% |
| Price of electricity | 34% | 159% |

- Water usage for a private installation is very low when compared to coal generated electricity due to the size of the array. More water is needed for a solar farm installation because a larger amount of panels are installed and not cleaning them regularly has a significant impact on the amount of electricity generated.
- Carbon emissions are calculated based on the amount of greenhouse gases generated during electricity generation – not during the manufacturing of each technology's capital equipment. As expected, coal generated electricity emits more carbon than its solar counterpart.
- The price of electricity when generated onsite for private use is 34 % higher than electricity generated from coal. The main reason for this is the high capital costs required for a solar installation. de Groot et al also did not take into account the cost to build a new coal plant since the plant used in the study has all its assets already paid off [8]. The price of electricity for a solar farm are also found to be higher due to high capital costs, transmission costs and maintenance.

From this paper it is evident that if the capital costs for a private solar installation continues to decrease as the trend is showing then this type of installation will become more and more feasible.

The National Energy Regulator of South Africa, (NERSA), first released feed-in tariffs for various renewable energy generators in 2009 [8]; but local municipalities have a difficult time accepting and approving feed-in tariffs. According to Greenpeace, most municipalities view the sale of electricity as the backbone to their business plan [10] so they view selling coal generated electricity as a low risk with guaranteed income. During optimal conditions, Germany generates approximately 38 % of its electricity from renewable resources, a study conducted in 2006 on electricity demand and pricing showed that these two parameters followed each other closely [10]. The same study conducted in 2012 showed that the prices have been driven down significantly. South Africa may have a reason to be concerned about the loss in revenue from coal provided electricity but when all the factors are weighed, continuous investment in non-renewable resources should be reduced.

## 1.6 Accuracy & Availability of Solar Radiation Data

According to Dekker et al. "*studies have shown that the accuracy of certain ground monitored data could deviate up to 2 % to 10 %*", so continuous calibration and verifying of measured data becomes critical [14]. To improve accuracy – multiple instruments are required to cover a

larger area. It has also been found that when satellite data is compared to ground measured data, solar radiation can be overestimated by up to 10 % [36].

For large scale projects, designers do not necessarily have the funding or time for ground monitoring instruments. Several free satellite solar radiation databases are available, some of which are:

- PVGIS
- NASA SSE
- HelioClim-1
- World Radiation Data Centre

The period that data is available for free data is not current, resolution and accuracy also differs across providers [14].

## 1.7 Research Question

The main research question is:

- To theoretically design a suitably sized solar array based on real historical data and to determine the impact on electricity costs for the University of the Witwatersrand's West Campus without over generation.

The School of Electrical and Information Engineering at the University of the Witwatersrand began monitoring electricity usage on its West Campus in 2012. The University of the Witwatersrand covers 400 Ha, 34 of these hectares make up West Campus so there is adequate space to install a solar array. The campus is home to various faculties, laboratories, part time lecture venues and various residences. This makes West Campus a prime example of a mixed use faculty as power is required during the day and at night.

Energy meters have been installed at the main electrical incomer and have been recording consumption data, (kWh, kVA and kVArh), every half hour of every day since inception. However, not all data sets are complete due to human and/or equipment error. The School also has access to accurate solar radiation data that the School of Education has provided [37] and the cost of electricity for the campus is also available.

The size of the array will be limited by the current legislation which prohibits consumers to feed excess generated electricity back into the grid. In addition to the research question above, the following questions will also be explored:

- What is the required capital for the solar array?
- When will the installation be paid off?
- How does this design compare to one that utilises average solar radiation?
- What will happen to the payback period if selling back to the grid was not an issue and the size of the array could be increased?
- Does the economic feasibility change if the percentage increase in electricity is not conservative?
- Would the implementation of rebates and tax incentives increase the economic feasibility?

## 1.8 Research Constraints, Assumptions and Limitations

When designing a solar array, various inefficiencies have to be taken into account, some of these include cable losses, inverter losses and panel inefficiencies. As this research is centred on a theoretical installation with historical data, these inefficiencies are estimated. The costs associated with installing the solar array are also estimated and based on costs associated with previous installations.

It is assumed that the received consumption, radiation and billing information is true and correct. The demand side management, sundries and connection charges are not considered of the savings calculations as they are insignificant in comparison to the consumption charges and the manner in which they are calculated are not clear. The costs associated with reactive energy are also excluded from calculations as it is also small in comparison to the cost of peak demand and real energy as determined when analysing the utility supplied electricity bills.

## 1.9 Research Significance

With the demand for photovoltaics increasing at a rate of almost 50 % per annum, accurate solar radiation data is required to determine whether a solar array's output will be substantial and whether it will be financially feasible [38]. The significance of this investigation is discussed in the subsequent sections.

### 1.9.1 Global Warming & Climate Change

The Sun warms the Earth by emitting radiant energy. The Earth is covered by a protective atmosphere that is made up of various gases; such as Nitrogen, Oxygen and Carbon Dioxide. Some of these gases, along with water vapour create a greenhouse effect that warms the Earth – making all life on earth possible. The Earth cannot be too hot or too cold and therefore emits radiant energy back into space. If the concentration of gases in the atmosphere are unbalanced, the Earth's temperature will have to rise/fall to restore balance once again. This is detrimental because a rise in the Earth's temperature will change the climate that has been stable for almost 11 000 years [20].

Global warming is largely attributed to mankind's activities – such as utilising non-renewable energy sources and deforestation. These activities release excess carbon dioxide into the atmosphere, carbon dioxide that the Earth cannot absorb or use [15]. Scientists believe that the sudden rise in temperature is due to the increase in excess carbon dioxide emissions since these levels have increased faster since 1900 than in the last 22 000 years [39]. The percentage share of carbon emissions by popular energy sources is illustrated in Figure 1.4 and adapted from the International Energy Agency's 2013 Key World Energy Statistics [3].

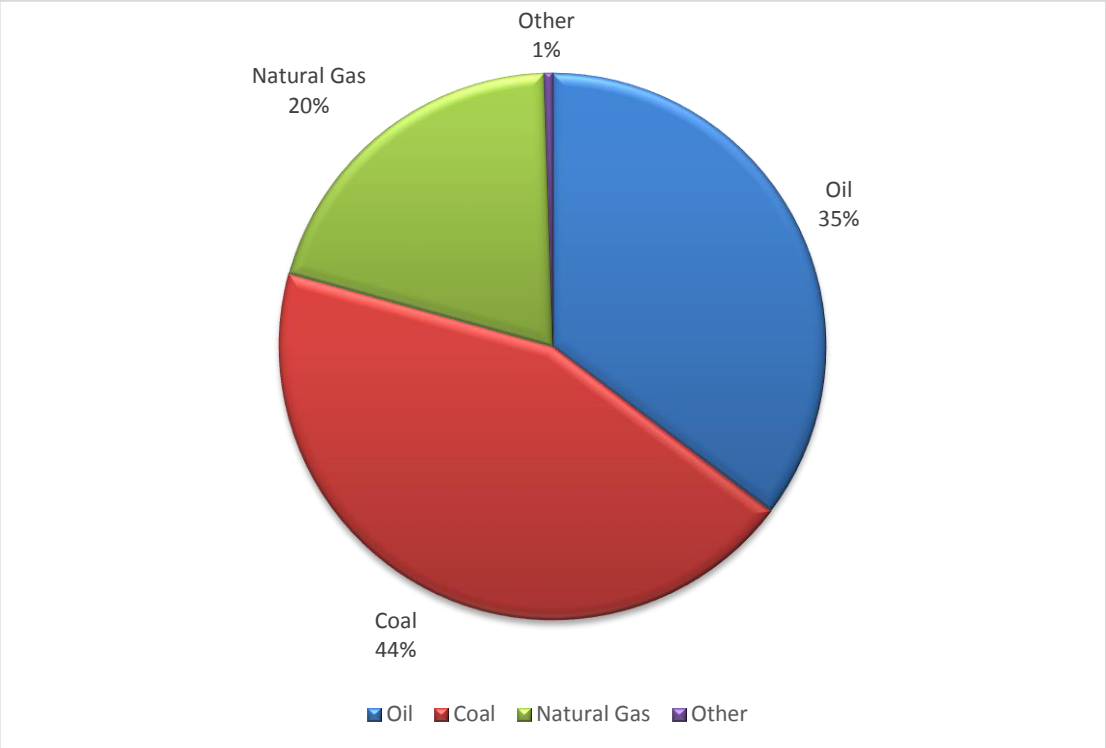



Figure 1. 4: Carbon emissions per fuel

If the current Carbon Dioxide concentration of approximately 400 ppm [40], were to double the Earth's temperature would rise from anywhere between 1°C and 3°C [15], depending on other

contributing factors. A rise of 3℃ may also end up killing off particular species of plants and animals and almost 2000 km² of land may also be lost to rising sea levels [41]. To prevent runaway climate change, carbon emissions need to be greatly reduced. Brown in his book "Plan B 4.0" states that carbon emissions need to be cut by 80 % by the year 2020 [20]. The world currently emits 34.5 billion tonnes of Carbon dioxide [42]. Brown's statement means that global carbon emissions need to be stabilised at 6.9 billion tonnes and cut by 27.6 billion tonnes. This may seem like an unreachable goal but Brown also lays out plans to get the world through the goal posts. The Netherlands Environmental Assessment Agency has also noted that global carbon emissions from fossil fuel combustion has slowed down in 2012 [42]. So the world is – slowly – changing consumption habits and is thinking about climate change and mitigation.

South Africa's non-renewable energy consumption displayed in Figure 1.5 [2] accounts for 95 % of the country's energy usage and makes them 12th largest carbon emitter in the World [43].

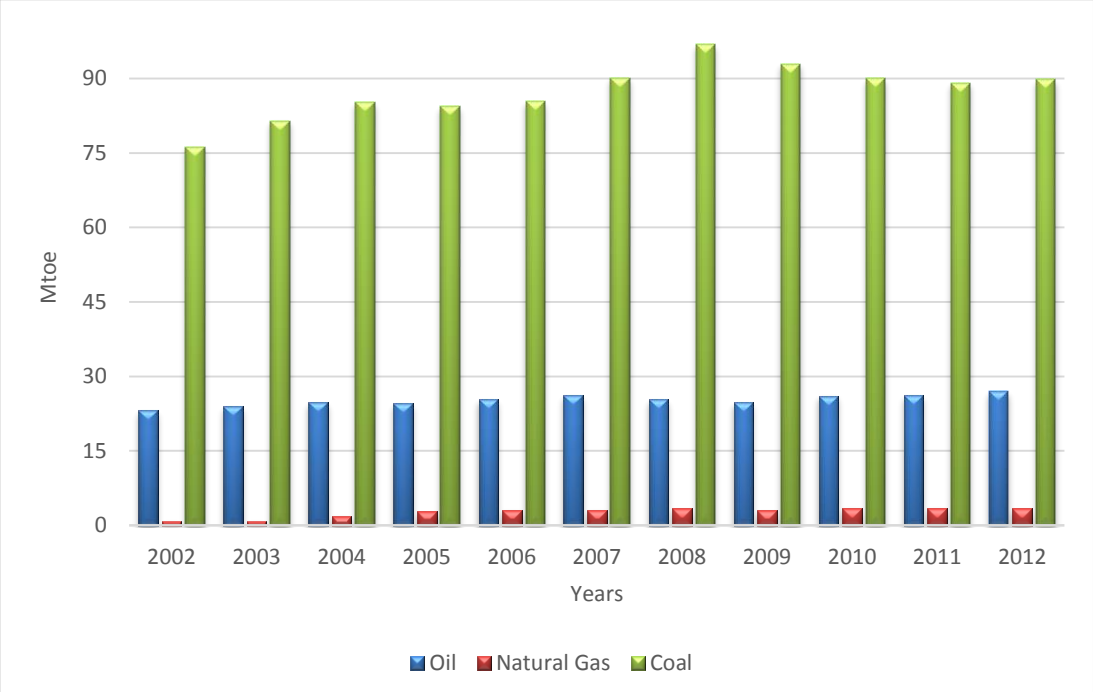



Figure 1. 5: South Africa's non-renewable consumption

Coal is South Africa's largest contributor to carbon emissions from all the available non-renewable resources and as can be seen in Figure 1.5. It is also known as one of the "dirtiest" fuels since burning it emits particles into the atmosphere as well as greenhouse gases [20] and [44]. The carbon dioxide emissions per fuel was studied by the Intergovernmental Panel on Climate Change in 2011 [45] the 75th percentile of total life cycle emissions of the major fuels are displayed in Table 1.2 and it can be seen that coal releases the most amount of carbon emissions.

Table 1. 2: 75th percentile of carbon dioxide emissions per fuel

| **Fuel** | **Carbon Emissions (g/kWh)** |
|---|---|
| Coal | 1130 |
| Oil | 907 |
| Natural Gas | 548 |
| Solar PV | 80 |
| Geothermal | 57 |
| Nuclear | 45 |
| Biofuels | 37 |
| Solar CSP | 32 |
| Wind Energy | 20 |
| Ocean Energy | 9 |
| Hydropower | 7 |

In 2014, South Africa dropped four places in the World Energy Council's Trilemma Index [35] and now stands at position 83 out of 129 countries. The trilemma ranking is made up of three components [35]:

- Security of energy supply: from international and domestic supplies – to meet current and future demand.
- Equity of energy: the penetration of energy across a country for all its people at an affordable price.
- Environment considerations: to ensure the above two items are met while taking the environment into consideration. This includes energy efficiency, the incorporation of renewable energy resources and the decrease of non-renewable dependence.

South Africa's ranking for energy security has increased – mainly due to the commissioning of two new coal fired power plants – but the ranking for equity and environment remain stagnant. The 2014 Index was released early in November 2014 – just before Eskom had severe supply issues, from a collapsed silo to a lack of diesel. In their scramble to keep the lights on, South Africa experienced load shedding schedules that surpassed anything experienced since 2008. It is unknown how long the load shedding will carry on for but the costs associated with the loss of supply are exorbitant and unrecoverable. Taking this into account, South Africa's trilemma ranking will surely slip again in the years to come. Without security of supply, investing in South Africa will also become stifled.

### 1.9.2 Electricity Security

The bulk of South Africa's coal is used for electricity generation [46]. The largest consumer of electricity is the industrial sector as illustrated in Figure 1.6 [47].

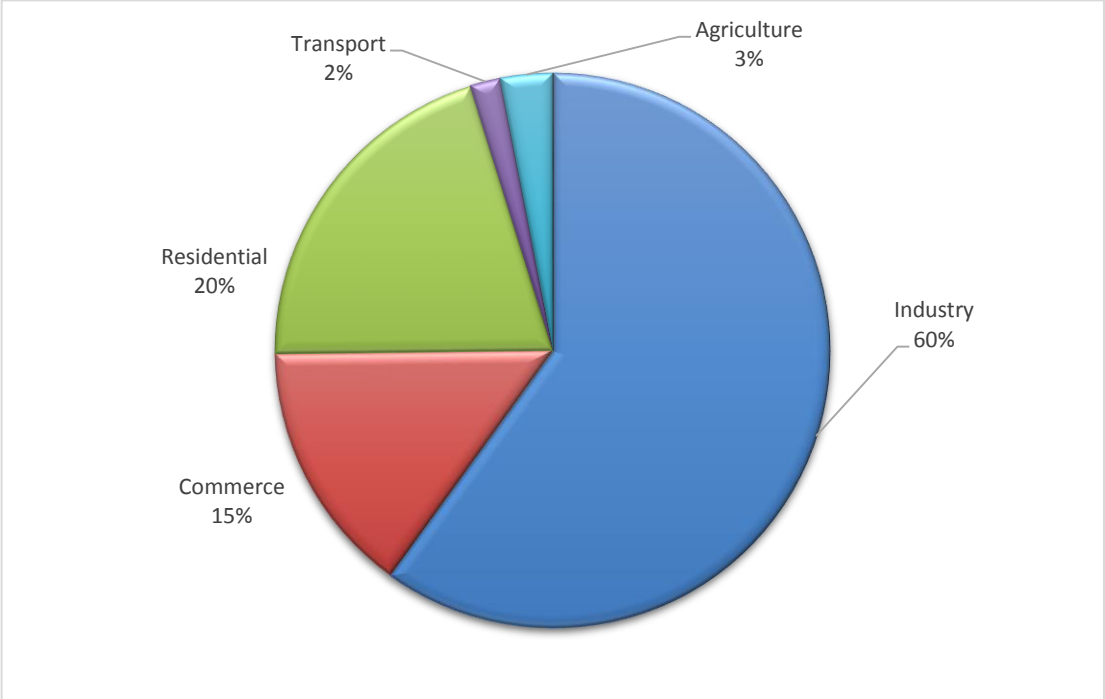



Figure 1. 6: South Africa's electricity consumption by sector for 2006

Electricity prices in South Africa have been fairly low with an average increase of 5.3 % between 2002 and 2007 [48]. In 2008, the price of electricity increased by a staggering 27.5 % [48]. In 2008 South Africa experienced days of blackouts and Eskom has since then embarked on a plan to increase its electricity generation capacity to meet the rising demand for electricity [5]. Since this incident, electricity price increases have remained well over 20 % per annum and this trend seems likely to continue [48].

The South African government has however taken steps in the right direction by developing the "The White Paper on Renewable Energy", which maps out a plan to ensure energy security in light of climate change issues by using more renewable resources [11]. South Africa has also committed itself to reduce carbon emissions by a staggering 42% by 2025 at the 15th meeting of the United Nations Framework Convention on Climate Change in 2009 [9]. Whether this goal will be achieved remains to be seen as only 9% renewable energy penetration has been targeted in the Renewable Energy Independent Power Producer Procurement Programme, (REIPPPP) [10].

Alternative options need to be considered because the cost of non-renewable resources and electricity will continue to rise as these resources are being depleted. South Africa is fortunate to have an average solar radiation of 5.5 kWh/m² per day [11], so harvesting solar energy for electricity generation is a viable option.

The average cost of coal generated electricity has risen by over 100 % from 2001, (20.82 c/kWh), to 2011, (44.80 c/kWh) – as extracted from the Department of Energy's 2012 price report. The cost presented is the average cost of electricity for all types of customers – domestic, industrial, international etc, [48]. The cost of solar photovoltaic generated electricity on the other hand is set to become the cheapest generating resource by as early as 2020 and will possible reach grid parity by 2018 [49], thus making it a viable alternative to non-renewable generated electricity and therefore contributing to electricity security.

### 1.9.3 Consumer Education

According to the Department of Minerals and Energy's white paper on renewable energy [11]:

*"At present public awareness of the existence of renewable energy or its economic, environmental and social benefits, is limited"*

Consumer education is vital to the successful uptake of photovoltaics. Many consumers believe that installing a solar array is expensive. This is true but there could possibly be long term benefits in light of the current drive for global climate change and the increasing costs of electricity in South Africa. These benefits as well as the above mentioned benefits need to be scientifically proven to ensure proper consumer education.

## 1.10 Review of Current Methods and Research

The design of photovoltaic systems is based on trial and error according to Keyhani [22]. In normal practice the design of the array begins with defining the power required from the array, which is governed by the load that it will be supplying. Load estimates are either provided by utility bills if available or accurate load measurements can be taken if the equipment and funding is available. Walker suggests the use of the "Simple Heuristic Load Estimate" of 50 $W/m^2$ for buildings during the day and 5 $W/m^2$ at night [50]. System losses are then added and multiplied by the amount of sun hours at the point of installation to estimate the expected kWh [19]. The amount of available sun hours or solar radiation is estimated or measured as discussed in Section 1.3.1.

Research into the effect of averaged satellite derived data and accurate ground monitored data has been conducted for a residential load of 5.6 kW using simulation software by Chowdhury et al. [14] and it was found that satellite data had over predicted the actual availability of solar radiation. The authors suggested that if satellite data is used, the final amount of panels in the photovoltaic array needs to be increased by 8 % [14].
Kumi et al. conducted research into the impacts of a large scale grid connected 1 MW on a university campus in Ghana and found that it was not feasible to install due to Ghana's current tariff structure [51]. For this research, an average load for the campus was used in the simulation software.

Depending on the available funding, most solar arrays are designed using satellite derived data or average insolation maps and tables [14, 19 & 52].

In these studies, average radiation and load data was utilised. Also, the implications of increasing the size of the solar array were not explored. No studies based on actual radiation and load data could be found.

## 1.11 Research Methodology

The research methodology is made up of the following components:

- Data Analysis
- Design Considerations
- Financial Considerations

### 1.11.1 Data Analysis

Analysis of West Campus's electricity costs, consumption and solar radiation data is necessary to understand the following:

- Identify the current costs of electricity
- The load profile of the campus for a significant period.
- Identify periods of low and high demand.
- The amount of radiation available and how this fluctuates for a significant period.
- Identify critical junctions, interceptions and peaks
- Identify points of coincident with the periods of high/low demand that the campus experiences.

### 1.11.2 Design Considerations

The size of the solar array is based on the analysis of the data and aims to answer the questions set out in Section 1.5. As this dissertation deals with the theoretical design of a solar array, the design is briefly explained along with various associated losses. Potential losses for the installation are also discussed as this impacts the size of the array and the required start-up capital. Three options form the basis for the size of the array:

- Lowest load in the selected period. This option will ensure that no excess electricity is generated and will therefore meet the minimum objective.
- Average consumption when campus is in session. This option is investigated because electricity demands on the campus are high when campus is in session. Therefore more of the campus's electrical load will be provided by solar generated electricity and this may or may not be more financially viable as more or less utility provided electricity would be used.
- Highest load in the selected period. This option is explored as it is the worst case scenario for the selected period and may be a financially feasibly option for the university if selling electricity back to the local utility becomes an option

### 1.11.3 Financial Considerations

The economics surrounding the theoretical installation is examined and includes the following:

- The start-up capital required for the various installations.
- The savings generated from the kWh produced by the arrays.
- The nett present value and estimated payback period of the options.

## 1.12 Conclusion

No studies based on actual radiation and load data could be found. Research has been conducted with actual solar radiation data and small scale solar arrays, the impacts of large scale solar arrays have also been explored but the radiation data used here was provided from simulation software. Depending on the available funding, the radiation data used in research and designs are approximated or provided by free simulation software. The global demand for photovoltaics is increasing and therefore studies into this technology's financial feasibility and the impacts of the radiation data used are driven by the following factors:

- Finding solutions to global warming and climate change

- Improving electricity security in South Africa
- Educating consumers so that awareness is created

The balance of this thesis is structured as follows:

- Section 2 outlines the process followed in analysing the available data. This analysis is significant to determine the solar array yield required for the campus.
- Section 3 covers the variables that contribute to the designing of the solar array and calculating the final array output
- Section 4 investigates the factors contributing to the financial viability of the solar array
- The results and analysis of the research are presented in Section 5
- Section 6 concludes the dissertation and presents recommendations

# 2 DATA ANALYSIS

Data analysis is the first component of this research and is necessary to determine whether a suitably sized solar array can reduce the costs of electricity for west campus as discussed in Section 1. Electricity costs are analysed to determine a baseline to use when comparing the savings from solar energy. In addition to this, each component that makes up the electricity costs are also analysed to ascertain their individual monetarily contribution to the campus's electricity costs.

The campus's consumption patterns for the selected period are analysed to determine the general load profile of the campus as well as periods of high and low demand. This analysis also aids in determining what the required yield of the selected solar array needs to be.

The University's solar radiation data is analysed to determine how much radiation is available and how the availability fluctuates for the selected period. SolarGIS and PVGIS data are the two selected data sets that are freely available. Both data sets are analysed and compared to the Wits data. This comparison aids in determining the accuracy between all the data sets.

Normalisation is used to compare the Wits radiation data to West Campus's electricity load and identify any periods of correlation. To ensure that no excess power is generated from the array, the maximum yield is based on the minimum load on the campus in the selected period.

## 2.1 Electricity Costs

The cost of electricity for June 2011 - May 2012 and the June 2013 – May 2014 periods are available for analysis [53]. The information for the June 2012 – May 2013 is not complete and therefore not used in this analysis.

Electricity for West Campus has cost the University almost R 20 million from June 2013 to May 2014. The cost for the previous 2011/2012 period was 31 % lower. From this simple analysis of billing information, it is evident that the cost of electricity is increasing quite substantially with each passing year. Since West Campus is considered a large consumer, their bills are made up of three components of energy:

- Real energy in kWh
- Peak Demand in kVA
- Reactive energy in kVArh

Where

- Peak demand is the highest recorded amount of average half-hourly apparent power (kVA) measured in a month.
- Real energy is the actual energy used to power equipment
- Reactive energy is the component of power that cannot be physically used and is generated from magnetic fields

The three components of power are related to each other by the power triangle shown in Figure 2.1 [54].

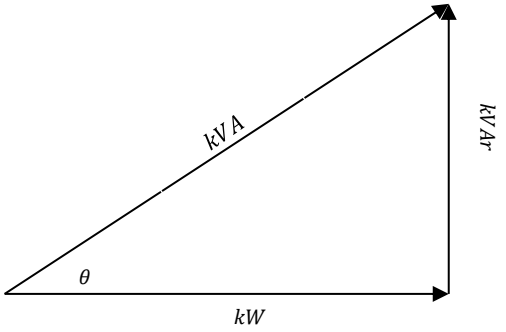



Figure 2. 1: Power triangle

The utility measures electricity consumption every half hour at the main incoming electrical supply on West Campus. The real and reactive energy components are separately measured and summed for the month, then multiplied by the appropriate tariff and added to the bill. The apparent power is also measured every half hour, but only the highest recorded amount per month is multiplied by the peak demand tariff and added to the bill. In addition to this, the University also pays a fixed service charge for the connection to West Campus, a sundry amount that varies every month and a demand side management levy that is based on value of peak demand.

Due to the confidential nature of this information, the 2013/2014 period's cost are presented as a multiple of the 2011/2012 period, which forms a base for analysis. Figure 2.2 shows this difference as a percentage of the 2011/2012 period. The billing information is summarised and attached in Appendix A.

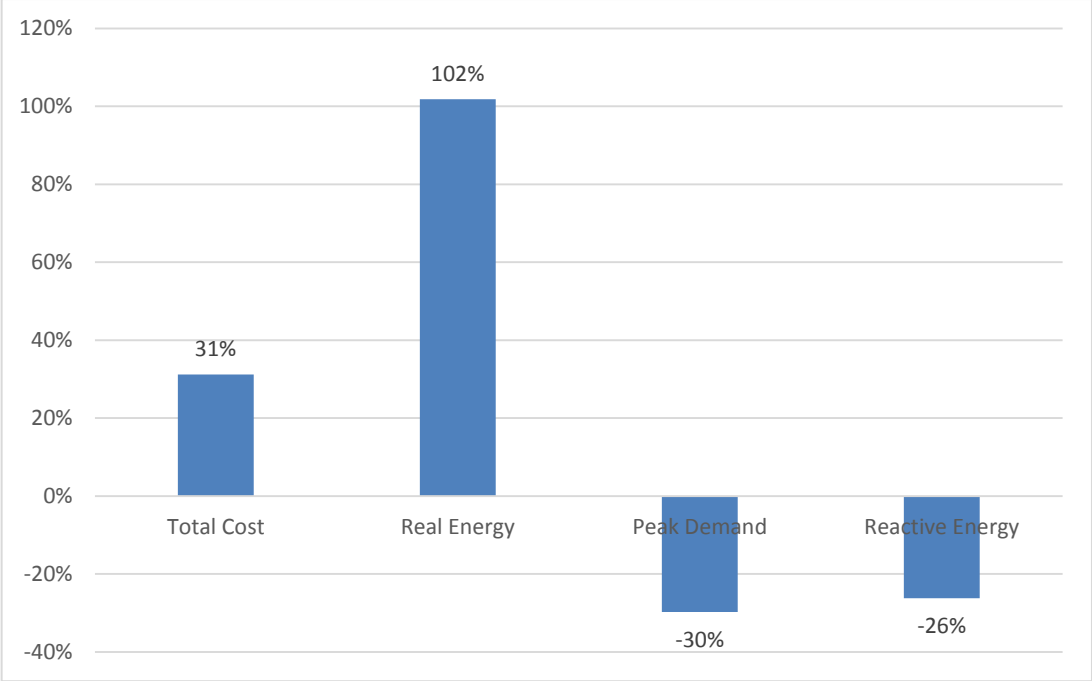



Figure 2. 2: Percentage difference in the cost of electricity for 2013/2014 and 2011/2012

As can be seen from Figure 2.2, the total cost of electricity in 2013/2014 increased by 31 % when compared to the 2011/2012 period. This is mainly due to the increase in cost of real energy. The average tariff for each of the above components for the 2013/2014 and 2011/2012 period are tabulated in Table 2.1

Table 2. 1: Average tariffs for 2013/2014 and 2011/2012 periods

| | **2011/2012** | **2013/2014** | **% Increase/Decrease** |
|---|---|---|---|
| **kWh** | R 0.60 | R 0.83 | 38 % |
| **kVA** | R 167.87 | R 159.72 | -5 % |
| **kVArh** | R 0.07 | R 0.14 | 100 % |

From Table 2.1, it is evident that the largest contributor to costs in the 2013/2014 period is real energy, whereas the largest contributor in the 2011/2012 period was peak demand. Figure 2.3 displays the three components of energy and their total share in the electricity costs for the respective periods.

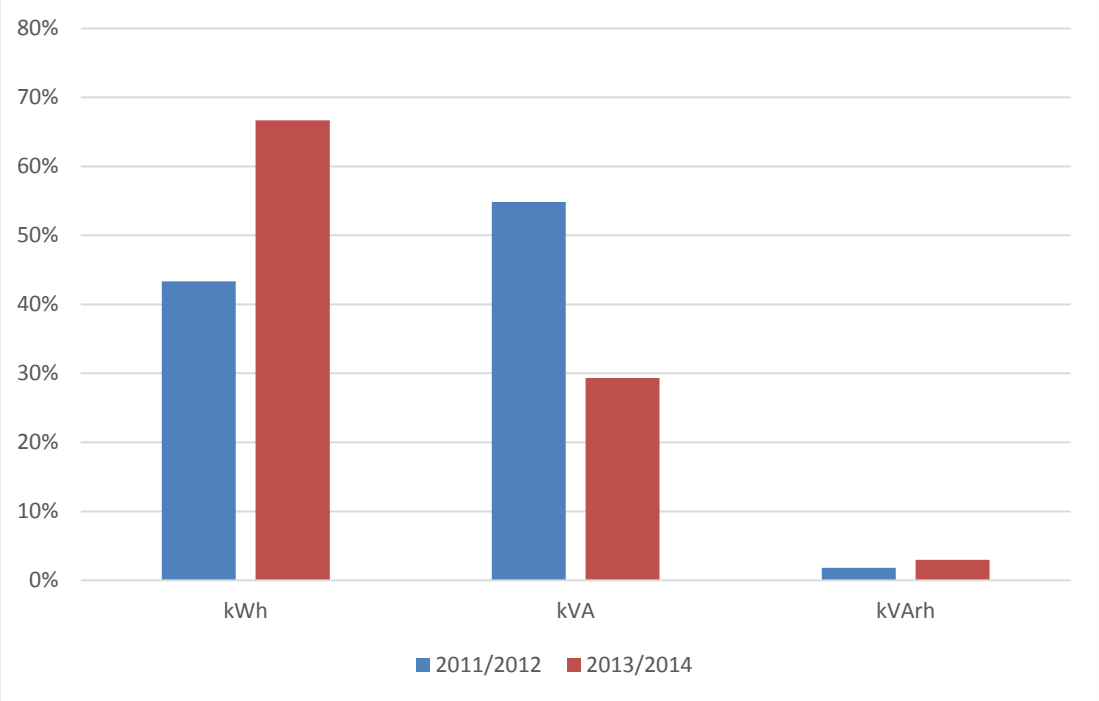


Figure 2. 3: Percentage share of total electricity costs

Although the total peak demand percentage increased, the associated cost decreased – due to the decrease in peak demand tariff costs. The percentage of real energy also increased and so did the associated tariff.

The impact of the solar array can be influenced by the amount of cloud cover. If the peak demand for a month is recorded on a cloudy day when the solar array is not functioning optimally, the associated electricity costs would not be reduced.

To begin determining the size of the solar array, the consumption patterns for various days in the 2013/2014 period are studied. The findings from this investigation are presented in the next section.

## 2.2 Consumption Patterns

The University of the Witwatersrand's Term Schedule for the June 2013/ May 2014 period is copied in Table 2.2 [55 & 56]. The maximum load measured during these milestones is presented in Figure 2.4.

Table 2. 2: Term Schedule for the selected period

| **Activity** | **Date** |
|---|---|
| Mid-year Exams | 27 May 2013 – 24 June 2013 |
| Study/Research Break/Winter Holidays | 25 June 2013 – 14 July 2013 |
| 3rd Term | 15 July 2013 – 30 August 2013 |
| Study/Research Break/Spring Holidays | 31 August 2013 – 8 September 2013 |
| 4th Term | 9 September 2013 – 21 October 2013 |
| End-year Exams | 22 October 2013 – 18 November 2013 |
| Study/Research Break/Summer Holidays | 19 November – 5 January 2014 |
| Registration & Orientation | 6 January 2014 – 6 February 2014 |
| 1st Term | 10 February 2014 – 28 March 2014 |
| Study/Research Break/Autumn Holidays | 29 March 2014 – 6 April 2014 |
| 2nd Term | 7 April 2014 – 23 May 2014 |
| Examination Block | 28 May 2014 – 25 June 2014 |

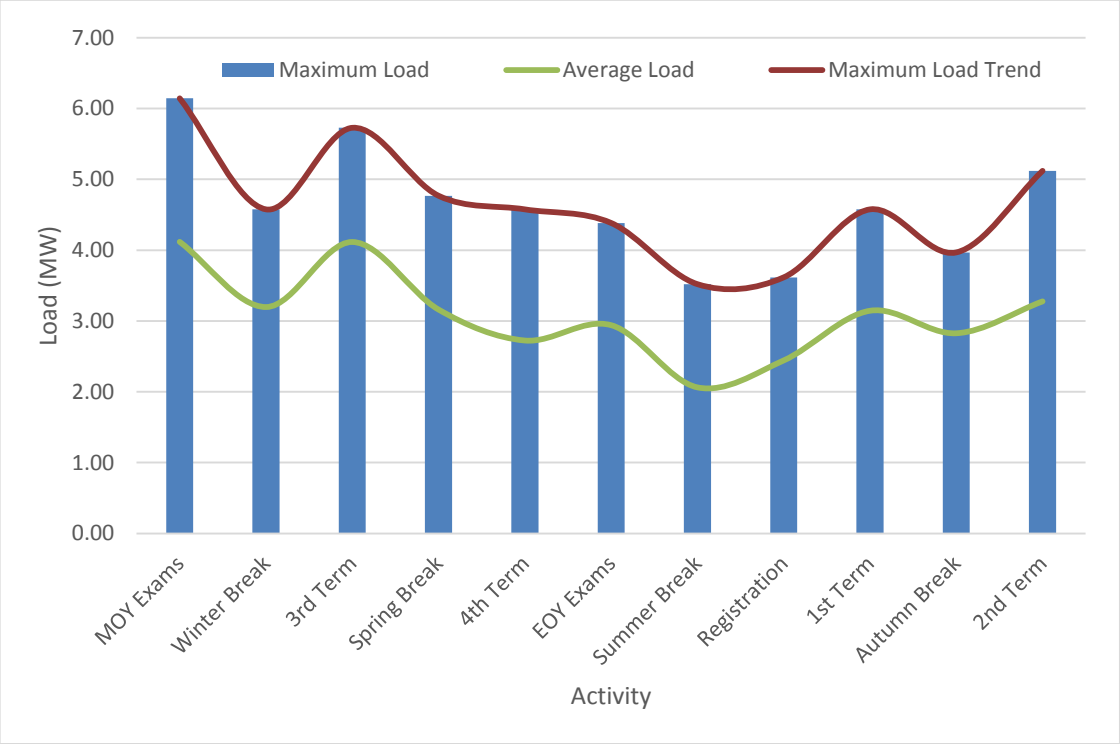



Figure 2. 4: Wits activities and accompanying electricity demand

The University of the Witwatersrand officially opened and the first teaching block began on the 10 February in 2014, the varying load for the 11th is shown in Figure 2.5 and compared to the 3rd of March 2014 when campus was in full operation – shown in Figure 2.6.

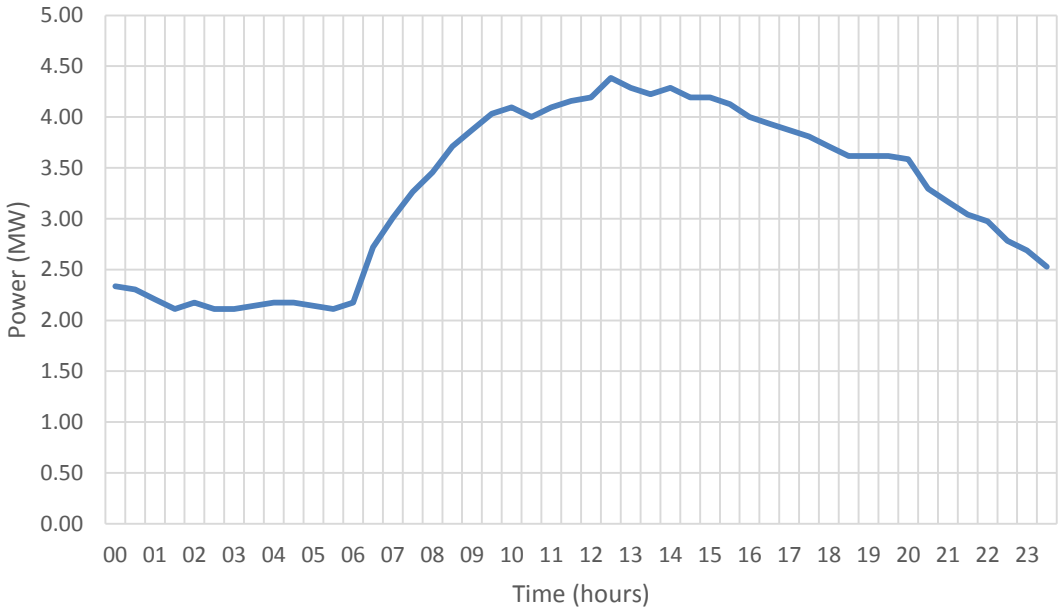



Figure 2. 5: West Campus's load profile for 11/02/2014

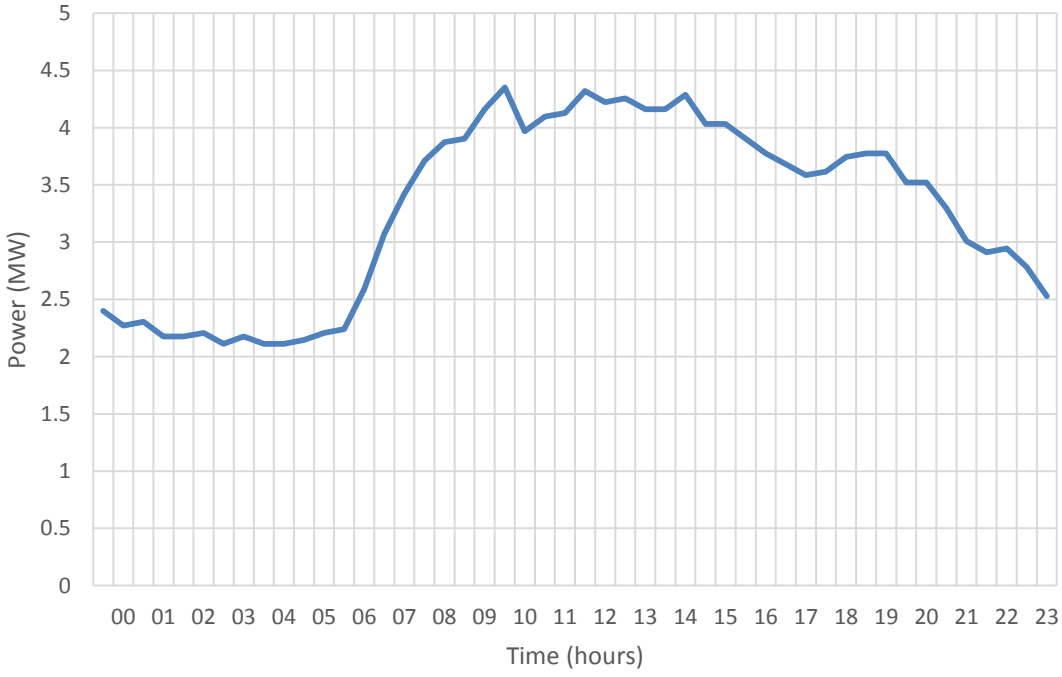



Figure 2. 6: West Campus's load profile for 03/03/2014

Figures 2.5 and 2.6 show a distinct pattern in how electricity is consumed on the campus, the base load remains relatively the same in both figures with a sharp rise from 06:30 on both mornings. The consumption stays high and starts to decrease from 16:30. A slight increase can be seen at approximately 19:30 – this is more distinct in Figure 2.6 – and is attributed to the consumption by the residences on West Campus as well as other night time activities.

Figure 2.7 shows the load profile for 16 July 2013, one of the coldest days for the period – temperatures peaked at 15°C and was as low as -1°C. The consumption for that day follows the pattern of Figures 2.5 and 2.6 but the load in the middle of the night is almost 1500 kW higher. This is attributed to the weather at the time and most likely due to the increased heating requirement of the campus.

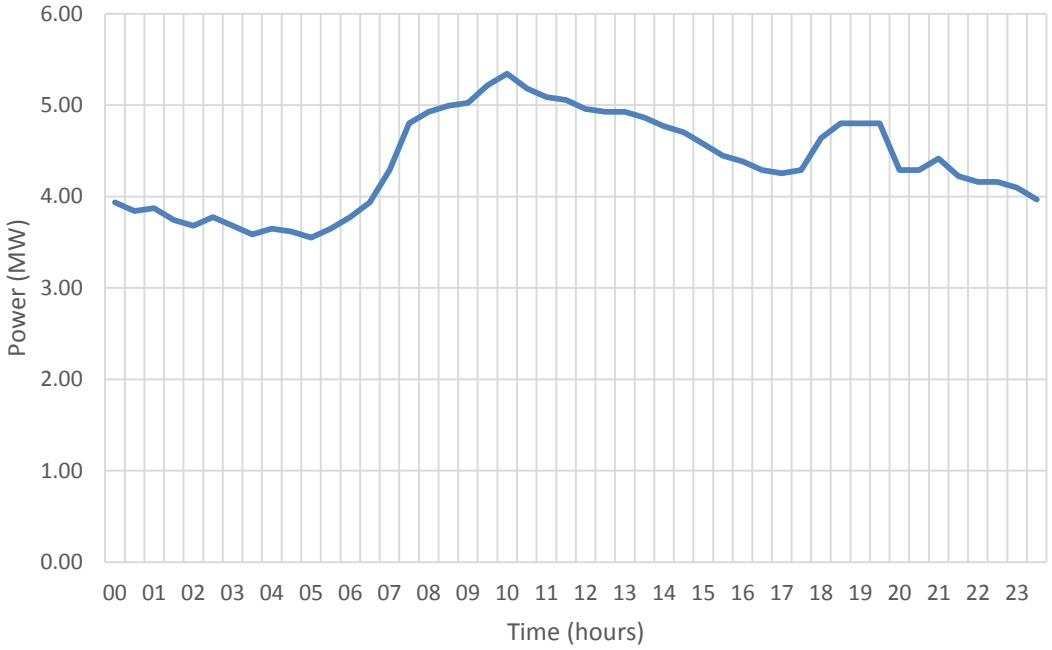



Figure 2. 7: West Campus's load profile for 16/07/2013

From analysing the available data, it is clear that the consumption follows the same pattern while campus is in session. Figure 2.8 shows the load profile for 30 December 2013, campus was closed at this time and the likelihood of the campus residences being full was unlikely. The consumption pattern for this day is relatively flat and does not have as distinct peaks as that found in Figures 2.5, 2.6 and 2.7.

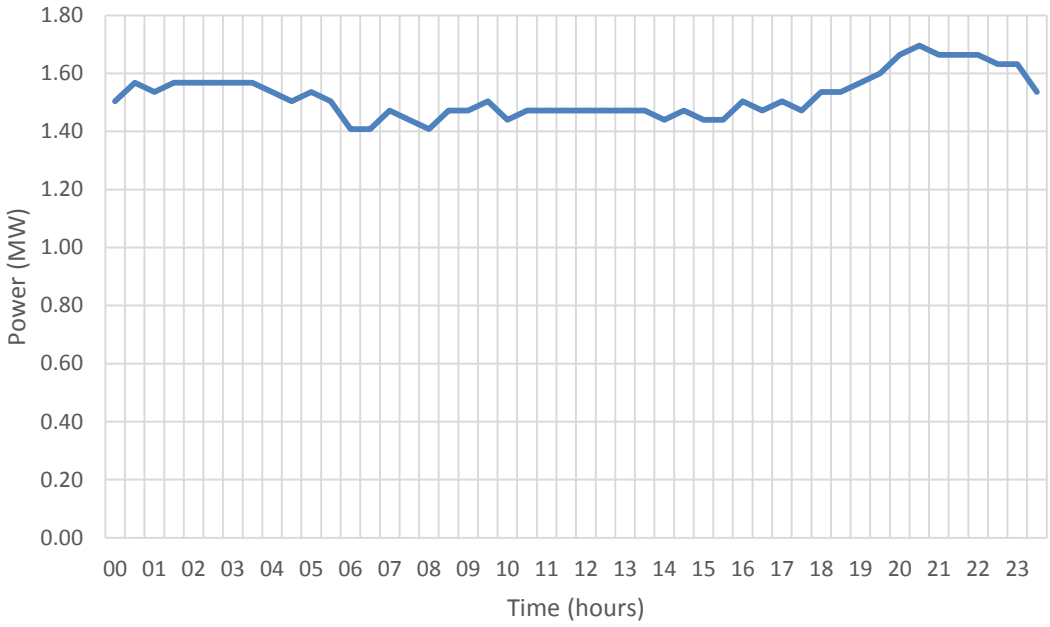



Figure 2. 8: West Campus's load profile for 30/12/2013

The load for the entire month of December 2013 can be seen in Figure 2.9 and shows distinct differences between week day and week night consumption as well as during the weekends. From the 19th, it is evident that the electricity demand on the campus is significantly lower due to the majority of the campus being closed.

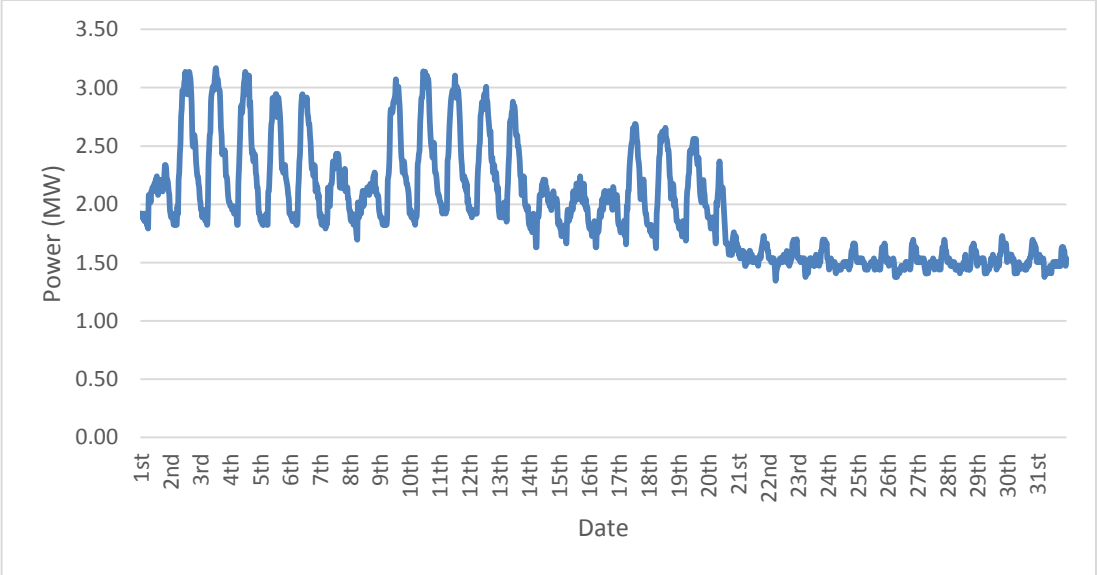



Figure 2. 9: West Campus's load profile for December 2013

By analysing the usage for an entire year on the campus, distinct patterns can be seen:

- In the winter months, consumption increases significantly due to the decrease in temperature and increased heat loads.

- When campus is in session, consumption is higher than when campus is closed.
- There are various study/research breaks, but many of the facilities on campus are still in use although there are no classes.
- During the Christmas/New Year break, the electricity demand is lower.

The load profile for the entire period is shown in Figure 2.10 and is calculated using Equation 2.1.

$$Load\ (MW) = \frac{kW_{max}}{1000} \quad \text{.....[2.1]}$$

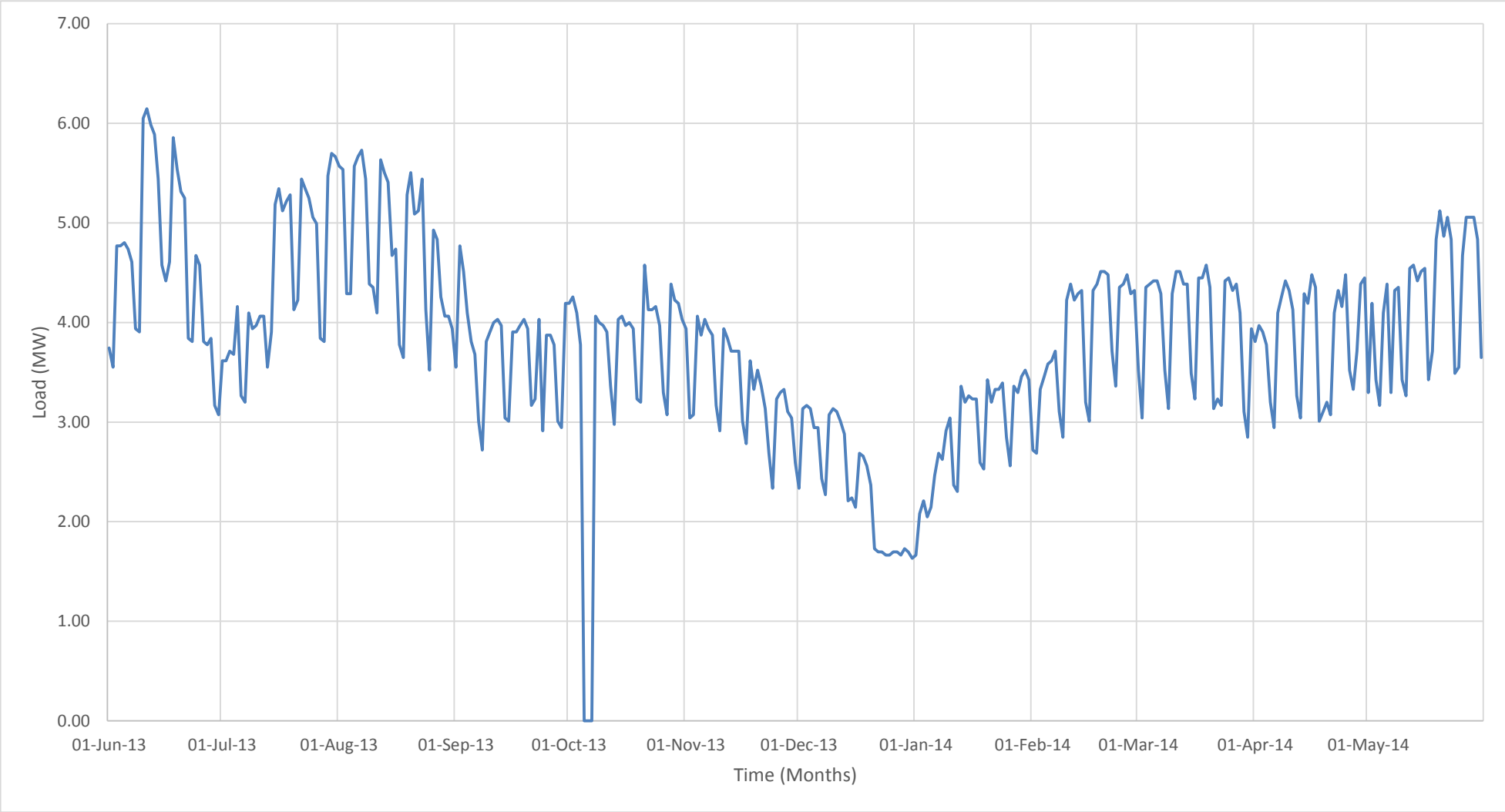



Figure 2. 10: West Campus's load profile for 2013/2014

## 2.3 Available Solar Radiation Data

As mentioned, there are numerous institutes that offer free usage of satellite derived solar databases. For the purpose of this research, SolarGIS's and PVGIS's databases are selected and compared to the University's ground monitored data. These data sets are discussed in the subsequent sections

### 2.3.1 SolarGIS

SolarGIS is an online portal that offers various maps for numerous countries around the world. Solar radiation data is available from 1994 to the present but is not available for free. Data is recorded every 15 – 30 minutes with a resolution of approximately 3 km [57]. South Africa's average GHI map for 1994 – 2003 is available for free and shown in Figure 2.11.

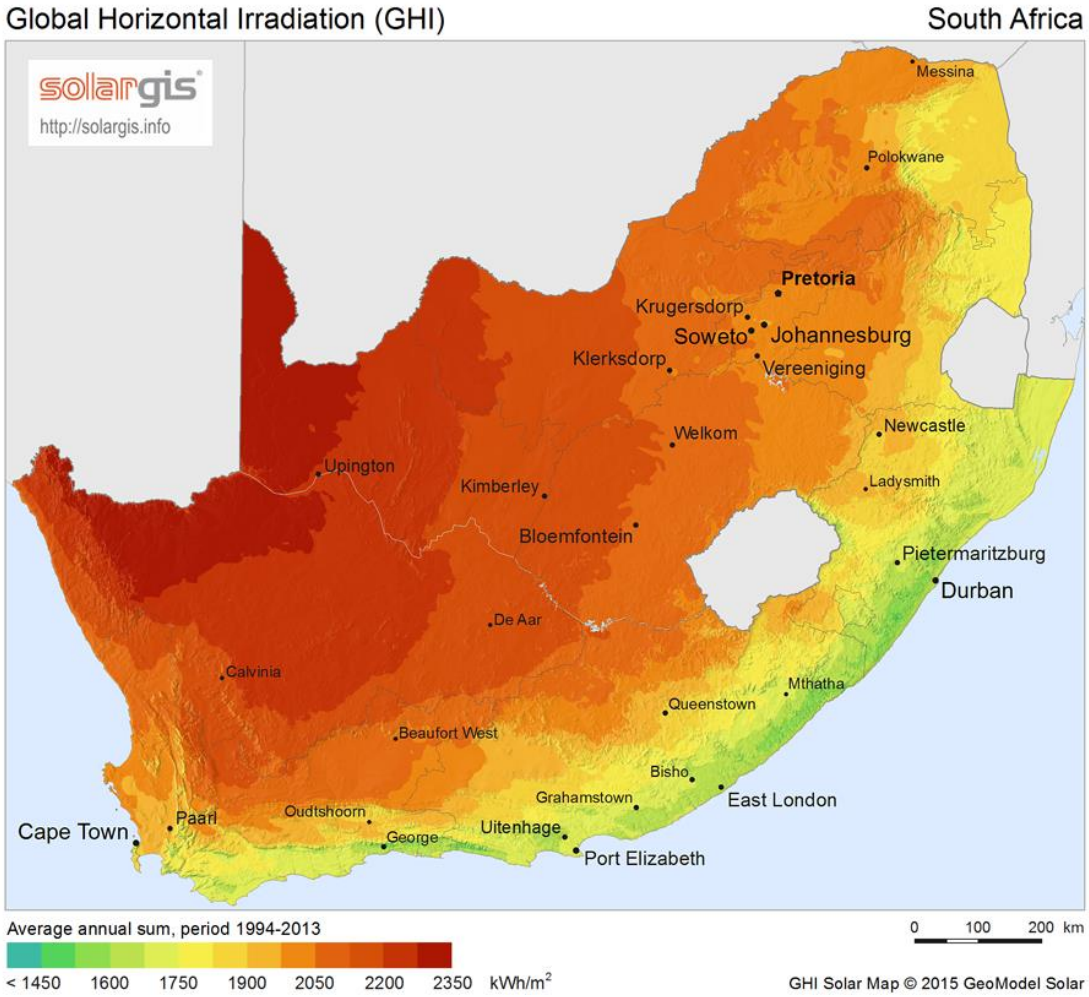



Figure 2. 11: South Africa's global horizontal radiation [58] [1]

[1] Used with permission from SolarGIS © 2015 GeoModel Solar

### 2.3.2 PVGIS

PVGIS is an online solar calculation tool that is run by the European Union's Joint Research Institute. Data is available for Africa, Europe and some parts of Asia. The available data for Africa is collected from 1985 – 2004 [59]. To obtain the data, the latitude and longitude of the campus is required and the available radiation is calculated using a resolution of 30 km x 30 km [59].

### 2.3.3 Wits Data

The University of the Witwatersrand has been measuring solar radiation since 2009 with a Davis solar pyranometer on the Wireless Vantage Pro2™ Plus weather station [37].

Solar radiation is measured every half hour in $W/m^2$ and Figure 2.12 shows the measured radiation for the 2013/2014 period where week 1 is the first week of June 2013. This graph has been created from the data received from the University's School of Education [37]. This period is selected as it corresponds to the period of complete data for the University's electricity data.

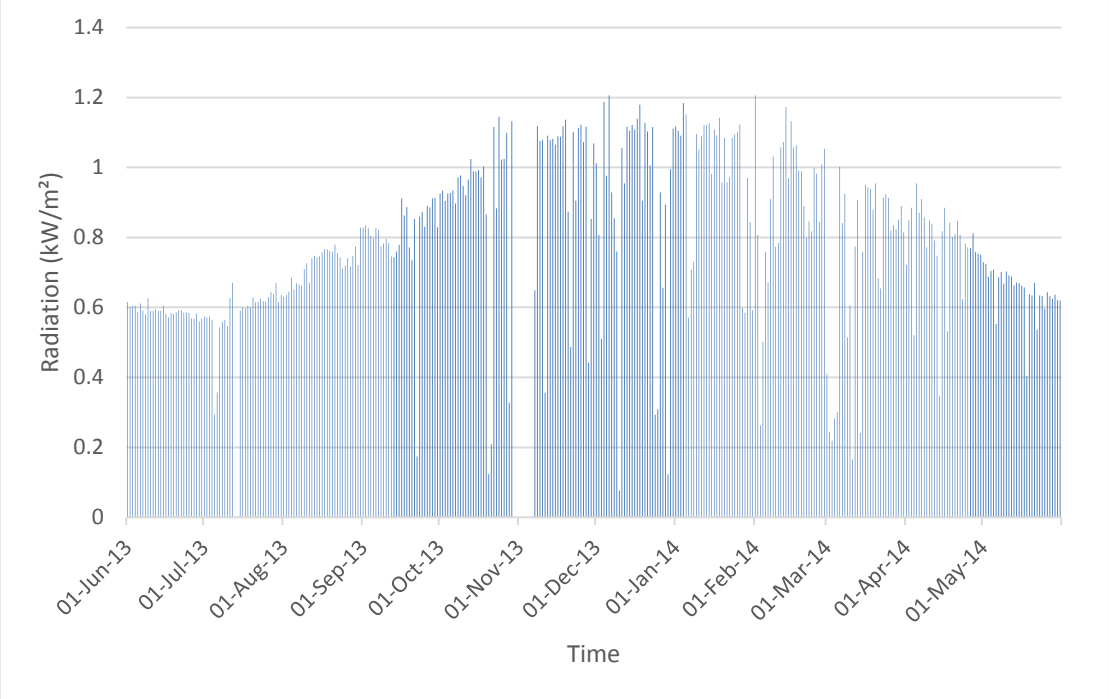



Figure 2. 12: Wits Solar Radiation for 2013/2014

From Figure 2.12 it is evident that the amount of radiation available for harvesting is in the warmer spring and summer months, (September – February). The period of zero radiation in Figure 2.12 is attributed to faulty equipment as no weather data was captured from 15:00 on 29/10/2013 to 10:30 on 07/11/2013.

### 2.3.4 Comparison of data sets

To compare the three data sets, the average daily energy, (in $kWh/m^2\ /\ day$), for the measured Wits data needs to be calculated using Equation 2.2 and adapted from Dekker et al. [14]

$$Monthly\ daily\ average\ energy = \frac{\sum GHI}{1000} \times \frac{1}{xy} \quad \text{[2.2]}$$

Where,

- $x$ = number of intervals per hour
- $y$ = number of days per month

Equation 2.2 is applied to the Wits data set for the selected period. The average daily energy for the period is calculated using Equations 2.3.

$$Yearly\ daily\ average\ energy = \frac{\sum monhly\ daily\ energy}{z} \quad \text{[2.3]}$$

Where,

- $z$ = number of months per period

The average annual sum from the SolarGIS data is read of Figure 2.11 and divided over the selected period. The PVGIS data is extracted from the website's online tool using -26.191, 28.026 as the longitude and latitude for the campus [60]. The three types of data for the campus is presented in Figure 2.13 and illustrates the differences between all the data sets. The supporting data for this graph is attached in Appendix B.

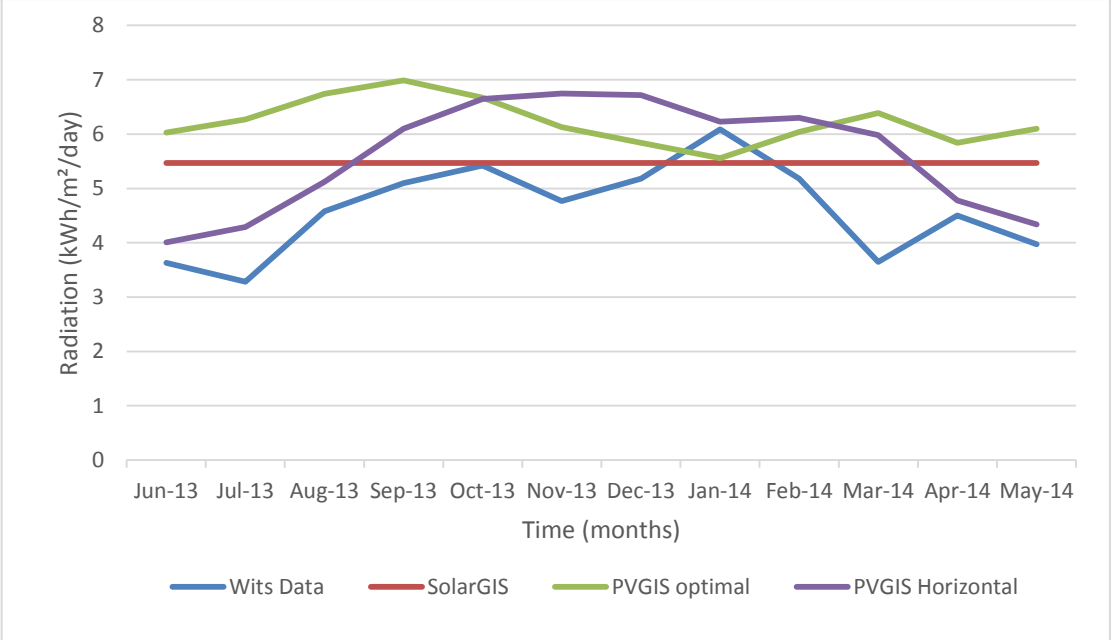



Figure 2. 13: Solar radiation for data sets

## 2.4 Comparison of Load and Wits Radiation Data

Since the actual load and solar radiation data differ by 1 order of magnitude, normalisation is used to investigate the relationship between Wit's radiation data and the load for the milestones presented in Table 2.3 along with the respective normalised values. The normalised curve is presented in Figure 2.14 and the calculations are further explained in Appendix B.

Table 2. 3: Term Schedule for the selected period

| **Activity** | Load (kW) | Normalised Load | Solar Radiation (kW/m²/day) | Normalised Solar Radiation |
|---|---|---|---|---|
| MOY Exams | 6144.00 | 1.00 | 175.78 | 0.33 |
| Winter Break | 4576.00 | 0.74 | 113.60 | 0.21 |
| 3rd Term | 5728.00 | 0.93 | 404.53 | 0.75 |
| Spring Break | 4768.00 | 0.78 | 101.07 | 0.19 |
| 4th Term | 4576.00 | 0.74 | 465.78 | 0.87 |
| EOY Exams | 4384.00 | 0.71 | 238.00 | 0.44 |
| Summer Break | 3520.00 | 0.57 | 537.48 | 1.00 |
| Registration | 3616.00 | 0.59 | 339.60 | 0.63 |
| 1st Term | 4576.00 | 0.74 | 417.97 | 0.78 |
| Autumn Break | 3968.00 | 0.65 | 80.17 | 0.15 |
| 2nd Term | 5120.00 | 0.83 | 399.39 | 0.74 |

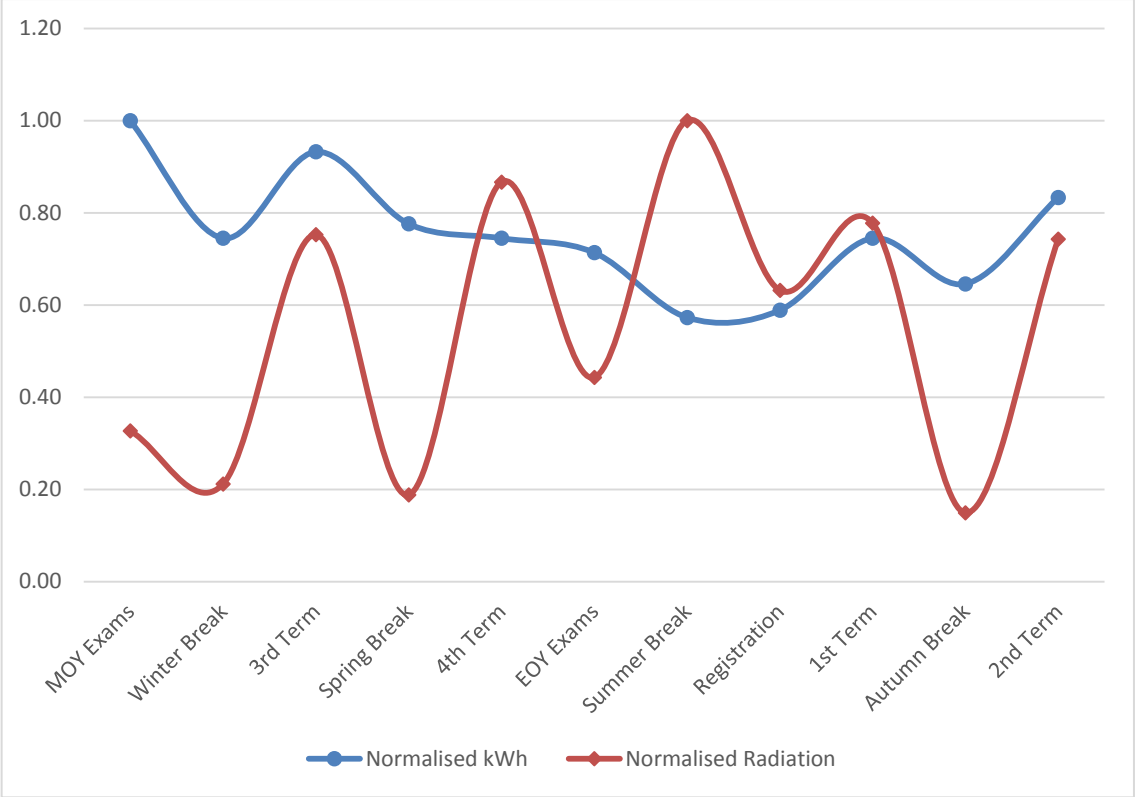



Figure 2. 14: Normalised Data

The low radiation during spring break in Figure 2.13 is attributed to low temperatures and cloud cover due to rainfall. From this figure, it is evident that the available radiation and load have an inverse relationship. Consumption is higher during the winter months and radiation is higher during the summer months when electricity demand is lower.

## 2.5 Determining the Required Yield

The maximum and minimum energy and power for each month in the 2013/2014 period is shown in Figure 2.15, where power relates to real energy by Equation 2.4.

$$E_{kWh} = \int_0^t P_{kW}(t)dt \quad \text{[2.4]}$$

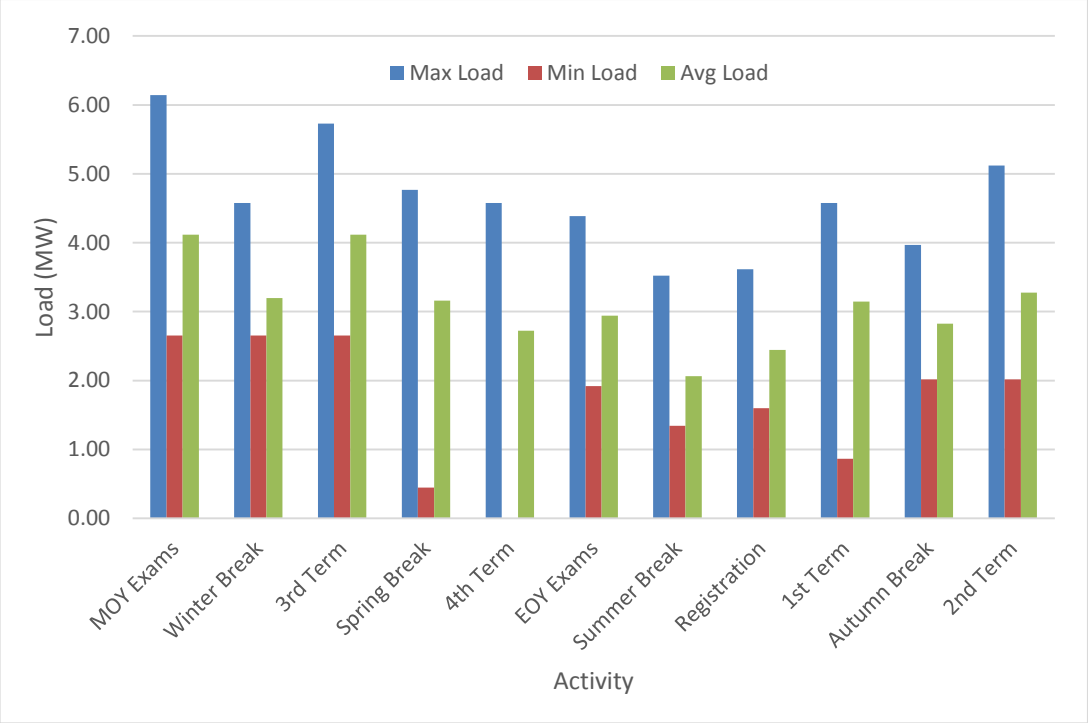


Figure 2. 15: Maximum, minimum and average load for the selected period

The demand clearly drops in December 2013, (summer beak), and slowly begins to pick up again in the months that follow. The recorded zero values for September 2013 and October 2013 are attributed to complete power failures and/or faulty measurement equipment and not because no electricity was utilised on the campus.

To meet the minimum objective, the power yield from the array needs to correspond to the minimum measured power for the period. From Figure 2.8, it is evident that the month with the lowest load profile was in February 2014. But upon further investigation it is found that this value was recorded only for one half hour and the values before and after this time were 600 % larger. This is attributed to errors in measurement and this recorded value is not a true reflection of the load profile at the time. Following this, it is found that the month with the lowest load is December 2013 and found to be 1344 kW.

The electricity demand on the campus is the highest when the University is open and in session. So the average load during these times is found to be 3252 kW and 5 % higher than the entire period's average of 3084 kW. This is selected as the basis for the second option because the University will utilise more self-generated electricity than utility generated and this option could be more financially feasibly as the price of coal generated electricity continues to rise and if selling the excess generated power to the utility becomes a possibility.

The maximum load for the period – 6144 kW – is chosen as the basis for the third option and assumes that over generation and start-up capital is not a limitation.

# 3 DESIGN CONSIDERATIONS

The size of the solar array is determined by analysing the load of the campus as discussed in Section 2. The size of the solar array must be calculated to determine what the cost of the system would be as set out in the objectives of this research. Under real conditions, a solar panel may not perform as well as when tested during the manufacturing process. These losses need to be factored into the final sizing of the array to ensure that the array's output is not over estimated. Solar panels and inverters make up the largest portion of the solar array. The quantity of these items are necessary to calculate the minimum space the array will cover and the area covered is required to calculate the output power of the array.

## 3.1 Losses

All panels are tested under standard test conditions, the output of a solar panel in real conditions will may be less than that achieved under standard conditions. Expected losses were discussed in Section 1.4.2 and are summarised in Table 3.1. Equation 3.1 is used to calculate the total overall performance ratio of the system.

Table 3. 1: Summary of losses

| **Inefficiency** | **Efficiency ($\eta$)** |
|---|---|
| Production Tolerance | 0.95 |
| Temperature | 0.89 |
| Dirt | 0.93 |
| Component Mismatch | 0.95 |
| Conversion Losses | 0.90 |
| **Total** | **0.672** |

$$\eta = \eta_{production} \times \eta_{temp} \times \eta_{dirt} \times \eta_{mismatch} \times \eta_{conversion} \quad \text{[3.1]}$$

To account for these losses, the size of the solar array will be increased by 48 %.

## 3.2 Panels & Inverters

As this is a theoretical design, aimed only at investigating the impact of a suitable sized solar array, the level of design detail is limited to the amount of panels and inverters required to make up the array as well as the installation space required. A 310 panel is selected to calculate the number of photovoltaic panels required. The number of panels is then calculated using Equation 3.2.

$$Number\ of\ panels = \left(\frac{solar\ array\ (kW)}{0.31\ kW}\right) \quad \text{.....[3.2]}$$

Where,

$$solar\ array\ (kW) = P_L \times (1 + total\ losses) = P_L \times 1.48$$

The size of the solar array above takes into account the losses discussed in Section 3.1. The output of the solar array will still be determined using $P_L$, the 48 % increase in size of the solar array merely effects the price of the system and the economic analysis.

The number of inverters is given by Equation 3.3 [22]. Where 2.2 is the power that an inverter can tolerate. Several grid tied inverters with varying power tolerances are available. 2.5 kW inverters are readily available and selected for the purpose of this research. Since this is under standard test conditions an array input power of 2200 W is chosen, this size will also build a slight buffer into the system so a quick future expansion can be undertaken.

$$Number\ of\ inverters = \left(\frac{solar\ array\ (kW)}{2.2}\right) \quad \text{.....[3.3]}$$

To determine the amount of installation space required, the size of the solar panel is required. Three manufacturers of 310 W panels and their corresponding area are presented in Table 3.2

Table 3. 2: Summary of 310 W panel area

| **Manufacturer** | **Area ($m^2$)** |
|---|---|
| Trina Solar [61] | 1.84 |
| Sunpower [62] | 1.63 |
| Canadian Solar [63] | 1.91 |
| **Average Area** | **1.79** |

The average area from Table 3.2 is used in Equation 3.4 to determine the minimum space required.

$$Minimum\ space\ required = number\ of\ panels \times 1.79\ m^2 \quad \text{.....[3.4]}$$

Note that Equation 3.4 does not make provision for additional space for walkways in between the solar array. Normally, panels will need to be installed to ensure access for maintenance and cleaning purposes. From the author's previous experience with the Trina 310 W panel, a minimum spacing of 600 mm between clusters on panels laid out in rows of 4 is sufficient for these purposes.

### 3.2.1 Panel Efficiency

The efficiency of a photovoltaic panel is defined by Equation 3.5 [50]

$$\eta_{PV} = \frac{P_{PV}}{A_{PV}} \quad \text{[3.5]}$$

Where

- $P_{PV}$ is the maximum power that the selected panel is capable of producing
- $A_{PV}$ is the area of the selected panel in m²

Using the values discussed in Section 3.1, it is found that the efficiency of the selected panel is 16.8 %.

## 3.3 Calculating the Array Output

The required yield forms a starting point for designing the solar array, Equation 3.6 is used to determine the final array size

$$Solar\ Array\ (kW) = yield + \eta(\%) \quad \text{[3.6]}$$

Where,

- $\eta(\%)$ is the value determined in Section 3.2

The output of the solar panel in kW is then determined using Equation 3.7 [64]:

$$P_{out} = \eta_{PV} S_{rad} A_{array} \eta \quad \text{[3.7]}$$

Where,

- $\eta_{PV}$ is the value determined in Section 3.1.1
- $S_{rad}$ is solar radiation in $kW/m^2$
- $A_{array}$ is the total area of the array in $m^2$
- $\eta$ is the performance ratio calculated in Section 3.2

The usable electricity in kWh is calculated by integrating Equation 3.6 over time as shown in Equation 2.1.

The nett power and energy are calculated using equations 3.8 and 3.9.

$$kW_{NETT} = kW_{measured} - kW_{array} \quad \text{.....[3.8]}$$

$$kWh_{NETT} = kWh_{measured} - kWh_{array} \quad \text{.....[3.9]}$$

The adapted power triangle for the system is presented in Figure 3.1 and adapted from Matsch & Morgan [54].

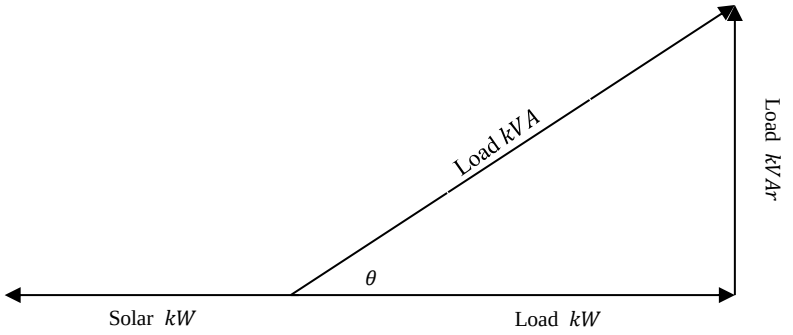



Figure 3. 1: Power triangle for the system

The equation for nett apparent power is calculated from the triangle above and shown by Equation 3.10.

$$kVA_{NETT} = \sqrt{(kW_{nett})^2 + kVAr^2} \quad \text{.....[3.10]}$$

# 4 FINANCIAL CONSIDERATIONS

Once the minimum output of the solar array is established and the losses of the system are incorporated into the final size as discussed in Sections 2 and 3, the system can be costed to ascertain its feasibility. The estimated savings are based on the solar array's potential yield and calculated using the campus's tariffs for the selected period. The Net Present Value, (NPV), method is used to calculate the amount of years that the system will use to pay itself off and start earning revenue for the University. Main inputs into the equation are savings from the solar array output, tax benefits, carbon offsets, maintenance costs of the system and revenue from feed-in power. Following this, the financial feasibility of the array can be determined as set out in the objectives of this research.

## 4.1 Estimated Start-up Capital

The cost per kW, (ZAR/kW), is calculated by taking the average pricing from seven different vendors for a recently tendered 200 kW system and includes inverters, labour, fixing and sundries [65]. This average amounts to R 18 375.39 per kW, the total cost of the final system can therefore be calculated using Equation 4.1.

$$Capital\ required = \ solar\ array\ (kW) \times 18375.39 \quad \text{[4.1]}$$

Note: a copy of this price list is attached in Appendix C but the vendors names have been removed as this information is private and not relevant.

## 4.2 Estimated Savings

The cost of real energy and peak demand per month for the 2013/2014 period is presented in Table 4.1 [53]. These tariffs are later used to calculate the cost of consumption with and without the impact of the solar array.

Table 4. 1: Electricity tariff costs

| **Month** | **Real Energy** | **Peak Demand** |
|---|---|---|
| | $\boldsymbol{kWh}$ | $\boldsymbol{kVA}$ |
| June 2013 | R 0.8780 | R 198.37 |
| July 2013 | R 1.0263 | R 161.82 |
| August 2013 | R 1.0263 | R 161.82 |
| September 13 | R 0.7509 | R 154.10 |
| October 13 | R 0.7509 | R 154.10 |
| November 13 | R 0.7509 | R 154.10 |
| December 13 | R 0.7509 | R 154.10 |
| January 2014 | R 0.7509 | R 154.10 |
| February 2014 | R 0.7509 | R 154.10 |
| March 2014 | R 0.7509 | R 154.10 |
| April 2014 | R 0.7509 | R 154.10 |
| May 2014 | R 1.0263 | R 161.82 |
| **Average** | **R 0.83** | **R 159.70** |

Real energy costs are calculated by adding a complete month's usage in $kWh$ and then multiplying it by the tariff for the month in question as shown by Equation 4.2

$$Real\ Energy\ Cost = kWh_{month} \times Tariff_{month} \quad \text{[4.2]}$$

The energy saving costs come from the power produced from the solar array, since any energy the array produces is considered "clean" and are calculated in the same manner.

The peak demand costs are calculated using Equation 4.3. In this case, the apparent power is measured every half hour just like real energy is but only the maximum value is used to determine peak demand costs for the month.

$$Peak\ Demand\ Cost = MAX\ kVA_{month} \times Tariff_{month} \quad \text{[4.3]}$$

The peak demand savings are calculated by subtracting the peak demand cost with the solar array's impact on the load from the original load's peak demand cost without the solar array's impact.

Real energy and peak demand savings will also fluctuate as the impact of the array can be influenced by the amount of cloud cover. The higher the cloud cover, the less impact the solar array will have on peak demand.

## 4.3 Economic Viability

In spite of the environmental benefits, capital is still required to install the system and at R 18 375.39 per kW for a complete system – a large amount of capital is required. To determine whether a suitable sized solar array will yield a return on the investment made, the payback of the system is calculated and is the period it takes to recover the initial capital investment for the system. A simple payback calculation only takes the invested capital and savings into account, (calculated in the previous section and including inefficiencies). This is not a true reflection of the actual picture, maintenance and degradation of the panels that form the solar array need to be added. Other items to consider are carbon taxes and offsets as well as tax incentives. Table 4.2 summarises the variables used to calculate the payback of the suitably sized solar array and Appendix C details the reasoning behind these variables.

Table 4. 2: Economic variables

| **Variable** | **Value** | **Unit** |
|---|---|---|
| Average kVA tariff | 159.70 | ZAR/kVA |
| Average kWh Tariff | 0.83 | c/kWh |
| Feed-in Tariff | 0 | c/kWh |
| Panel Price per kW | 18 375.39 | ZAR |
| WACC | 7.70% | % |
| Electricity Increase (year 2014 - ) | 12.28% | % |
| Estimated Inflation | 6.10% | % |
| PV panel derating slope | 0.80% | % |
| Carbon Tax Rate (from January 2015) | 0.048 | ZAR/kg |
| Carbon Tax Rate Annual Increase (2016 - ) | 10% | % |
| Carbon Offset Rate | 0.080 | ZAR/kg |
| Tax Incentive Rate | 0 | c/kWh |
| $CO_2$ emission (PV) | 0 | kg/kWh |
| $CO_2$ emission (SA coal) | 1.13 | kg/kWh |
| Maintenance for PV (monthly) | -1 000.00 | ZAR |
| Total Capital Outlay | 36 550 852 | ZAR |
| PV Panel output ratio after 25 years | 80% | % |
| Install Date (yy/mm/dd) | Jun-15 | |
| Estimated Lifespan | 25 | years |

The NPV method is used because it gives an accurate description of the future value of money in today's context, the final equation used for the payback calculation is given in Equation 4.4.

$$\sum_{i=1}^{n} \frac{(savings\ from\ solar\ output + tax\ benefits + feed-in + carbon\ offsets - maintenance\ costs)_i}{(1+WACC)^i} \ldots [4.4]$$

Where,

- n = number of years (0 to 25)
- WACC = weighted average cost of capital

Tax incentives and feed-in tariffs are not implemented yet [27 & 66], however they are considered in the payback calculations in the critical analysis section of this report.

# 5 RESULTS & ANALYSIS

This chapter summarises the results found during this research. The time when the solar radiaiton is high does not correlate with the campus's period of high demand but to meet the minimum objective, the selected array cannot generate excess power as exporting electricity to the grid is not a possiblity at this stage. The second part of the research invesitgates the outcome if selling back to the grid was possible as discussed in the preceeding sections. Two alternative options are explored:

- The first option is to reduce the campus's dependancy on utility provided electricity so this array's size is based on the campus's average electricity load when campus is in session.
- The second option assumes that over generation of electricity and capital expenditure are not limitations, so the array's size is based on the campus's maximum load for the period.

Section 5.1, 5.2 and 5.3 present the results of the research for the three options discussed in Section in 2.5. The estimated financial and environmental impact are discussed in Section 5.4 and 5.5 respectively. Section 5.6 compares the three mentioned available solar radiation data sets. For the purpose fo this research, the following variables were fixed:

- Cloud cover
- Tax incentives
- Carbon tax
- Carbon offsets
- Utility supplied electricity costs
- Losses
- Feed-in tariff costs

Start-up costs, tax incentives, carbon tax, carbon offsets and the cost of electricity are further discussed in Appendix C. Inefficiencies are discussed in Section 3 and electricity costs are discussed in Section 4.

Sections 5.8 – 5.13 explores the design and financial impact of changing these variables and Section 5.14 explores the effect of changing a combination of variables.

## 5.1 Final Array Size

The amount of solar radiation available per milestone in the University's 2013/2014 calendar is shown in Figure 5.1 and Figure 5.2 illustrates the total radiation available per month – where the correlation with the seasons of South Africa is clearly noticeable.

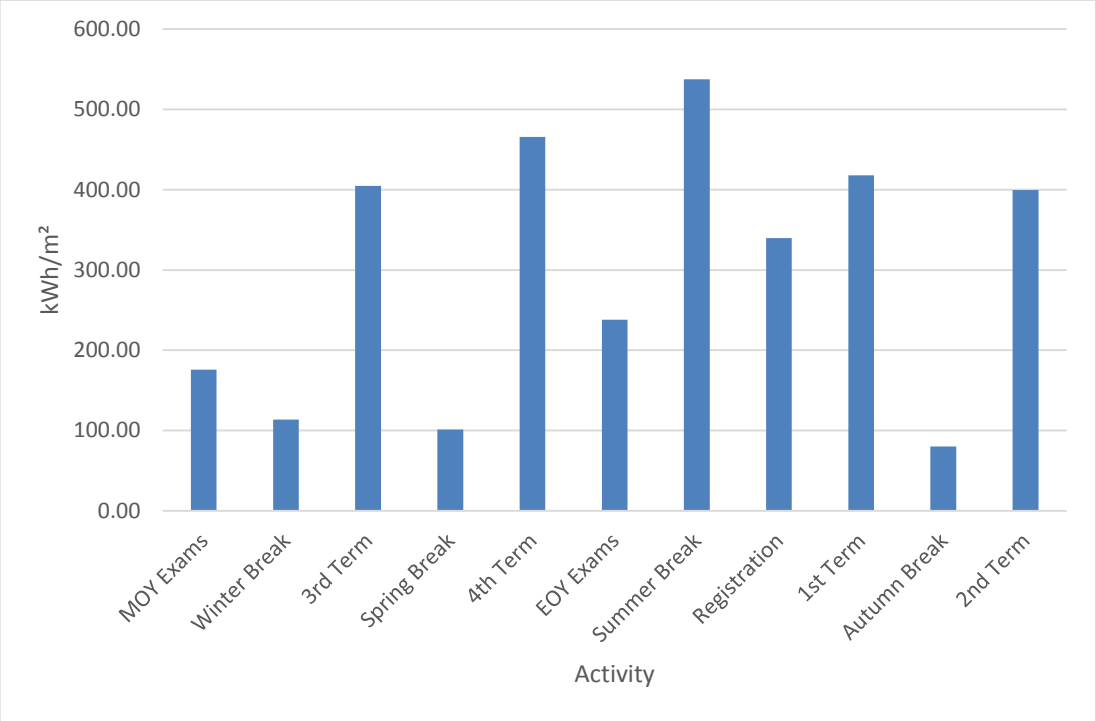



Figure 5. 1: Total available solar radiation per activity

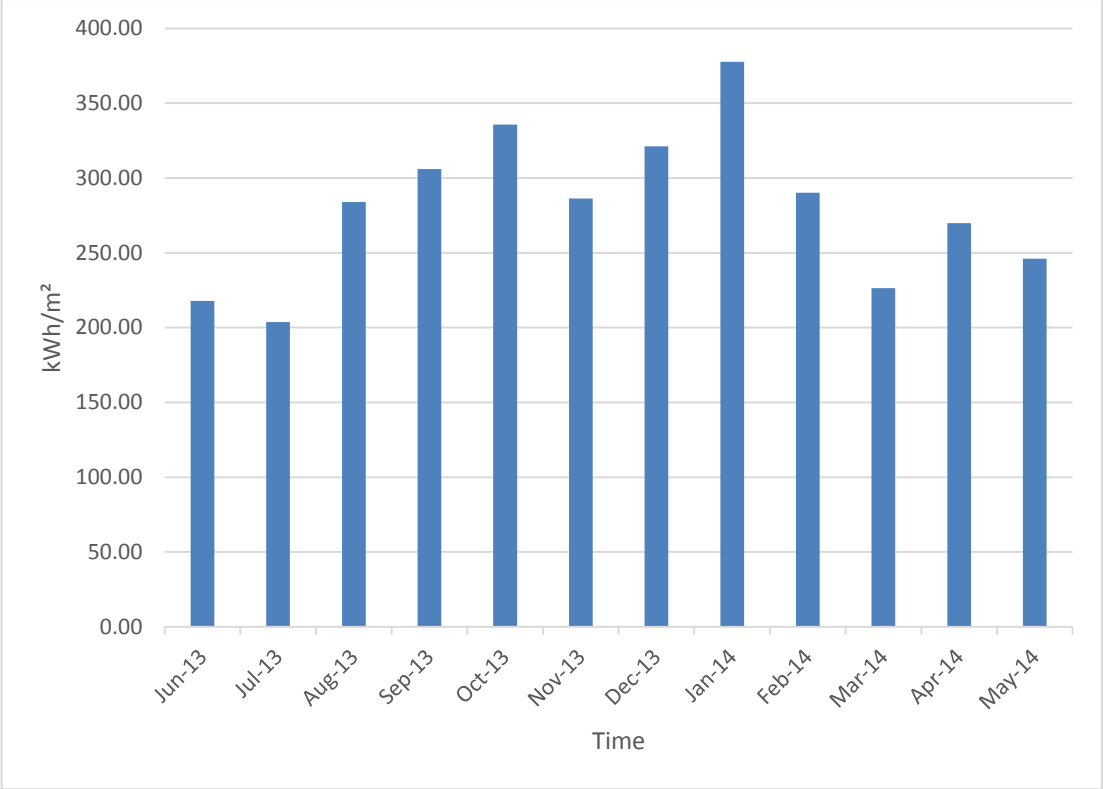


Figure 5. 2: Total available solar radiation per month

To meet the minimum objective, the first option for the solar array size needs to yield a maximum of 1344 kW. The second option needs to yield a maximum of 3252 kW as this is based on the campus's average consumption when campus is in session. This option is explored to determine if the campus's dependency on the utility can be reduced. The third option is based on the campus's maximum load and is explored to determine the impact if over generation and capital are not limiting factors. The solar array size for each option is based on the required yield as discussed in Section 2.5. Equations 3.1, 3.4 and 3.6 is used to calculate the final array sizes and is presented in Table 5.1.

Table 5. 1: Final array size

| Option | Yield (kW) | Array Size (kW) | Array Size (m²) |
|---|---|---|---|
| 1 | 1344 | 1989 | 11486 |
| 2 | 3252 | 4813 | 27791 |
| 3 | 6144 | 9093 | 52505 |

## 5.2 Solar Array Output

The amount of radiation in W/m² is converted to kW/m² by dividing the first value by 1000. The potential power that the array can produce from the available radiation is calculated using Equation 3.7 and the amount of electricity that this translates to is calculated using Equation 2.2. The final nett values are calculated using Equations 3.8 – 3.10. Figure 5.3 graphically shows these steps.

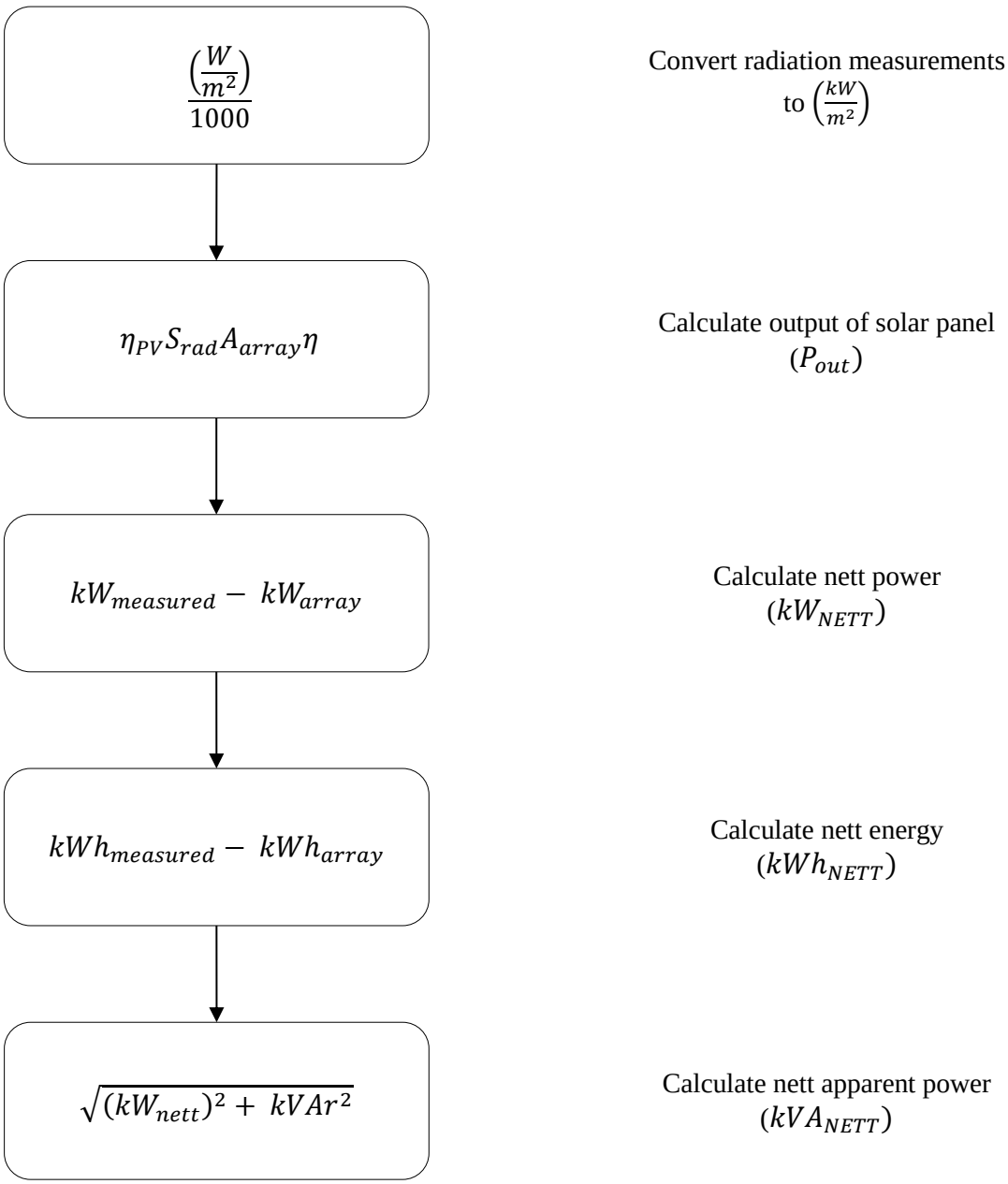


Figure 5. 3: Solar Array Output Methodology

Each day is made up of 48 readings. To calculate the daily loads, the following steps are applied to the readings:

- Total consumed and reactive energy in kWh and kVArh respectively is summed
- The load is determined by calculating the maximum kW recorded
- The daily peak demand is calculated by determining the maximum kVA recorded

The corresponding solar radiation, solar energy, nett energy, nett power and nett peak demand are calculated in the same manner. The monthly loads are calculated by following the above

mentioned steps for each month in the period. The monthly loads for each array size are presented in Figure 5.4 in comparison to the measured load of the campus.

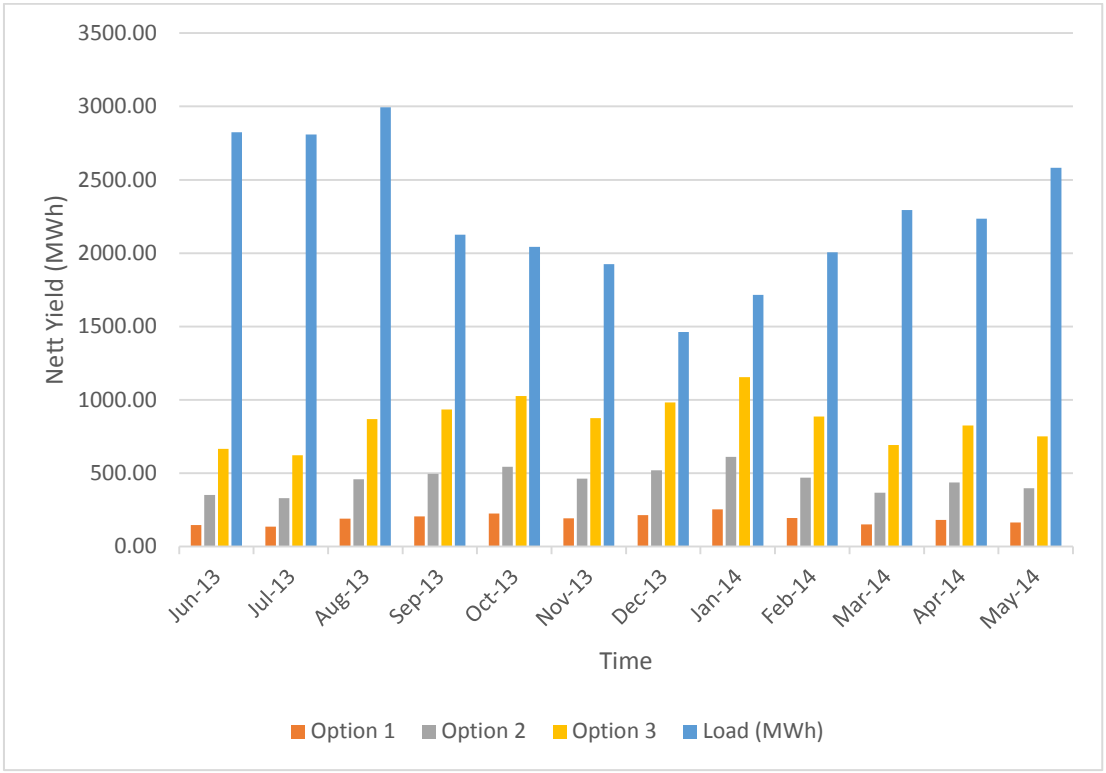



Figure 5. 4: Solar Yield for three Options

From Figure 5.4, the sum of each array's output does not exceed the load of the campus. However, the half hourly power output for each array is shown on Figures 5.5 – 5.7 below and shows over generation for options 2 and 3 during the summer break in December when the activities on campus are at their minimum for the period. The peak demand for each array is shown graphically in Figure 5.8.

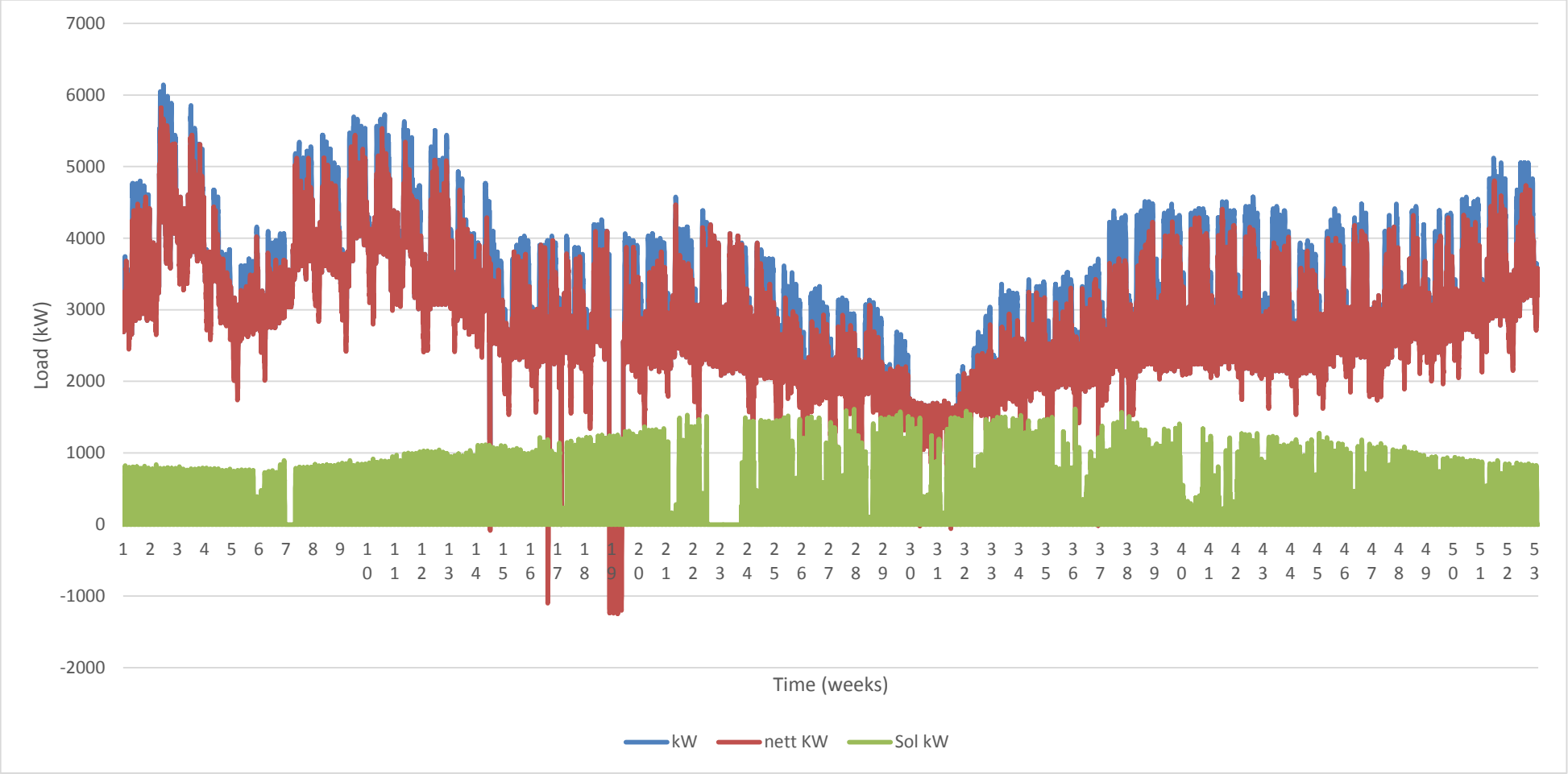


Figure 5. 5: Load and Solar output for Option 1

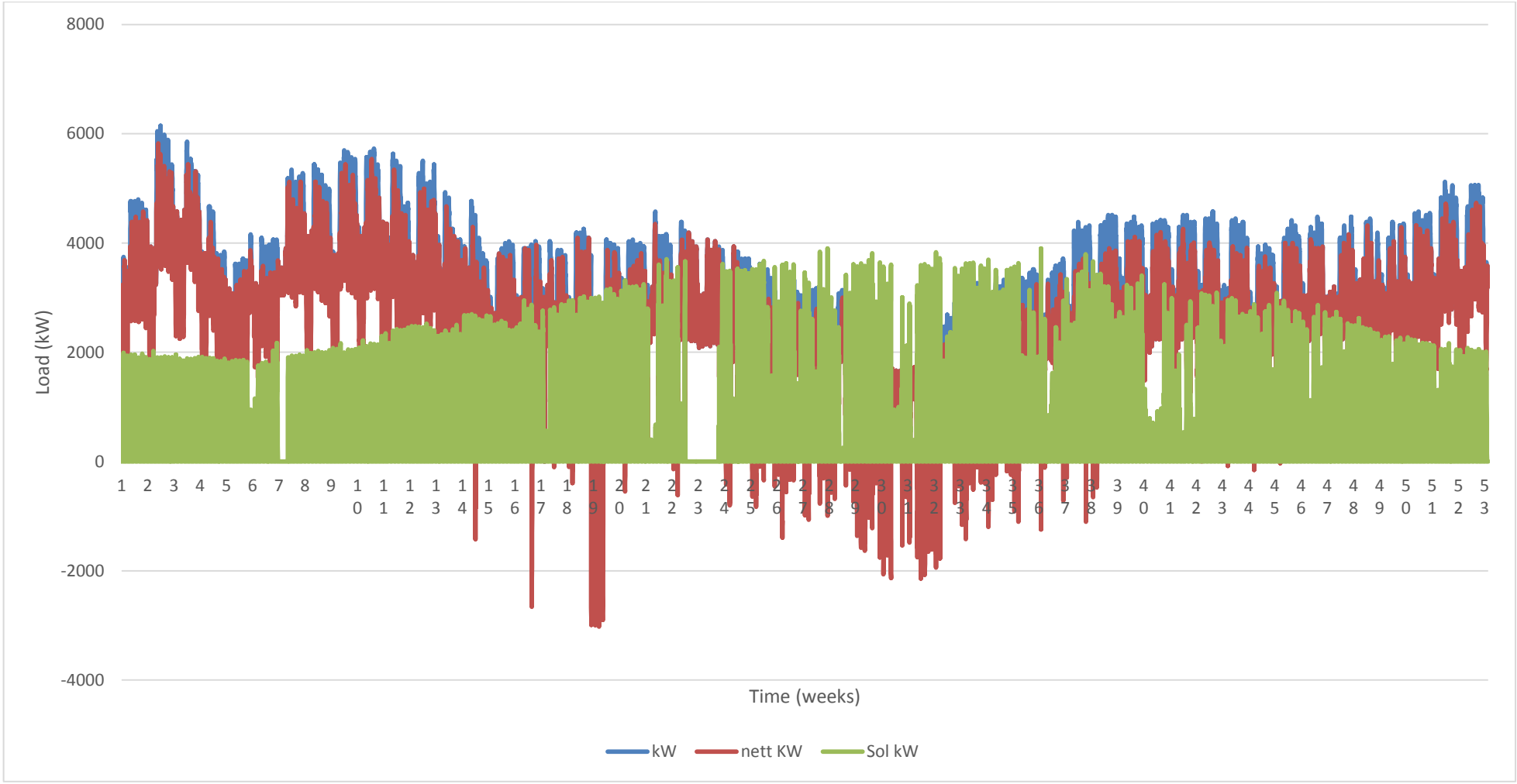



Figure 5. 6: Load and Solar output for Option 2

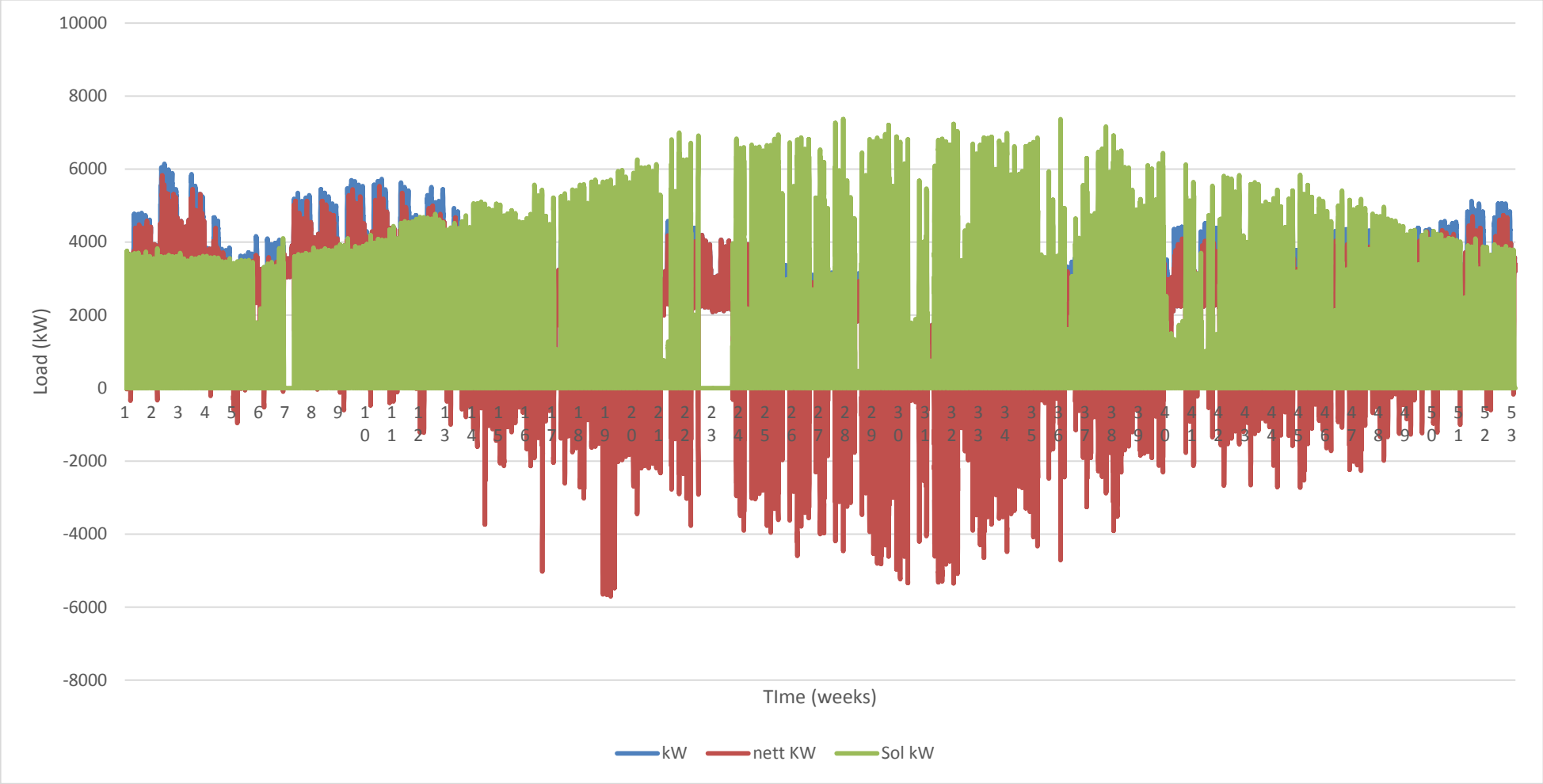



Figure 5. 7: Load and Solar output for Option 3

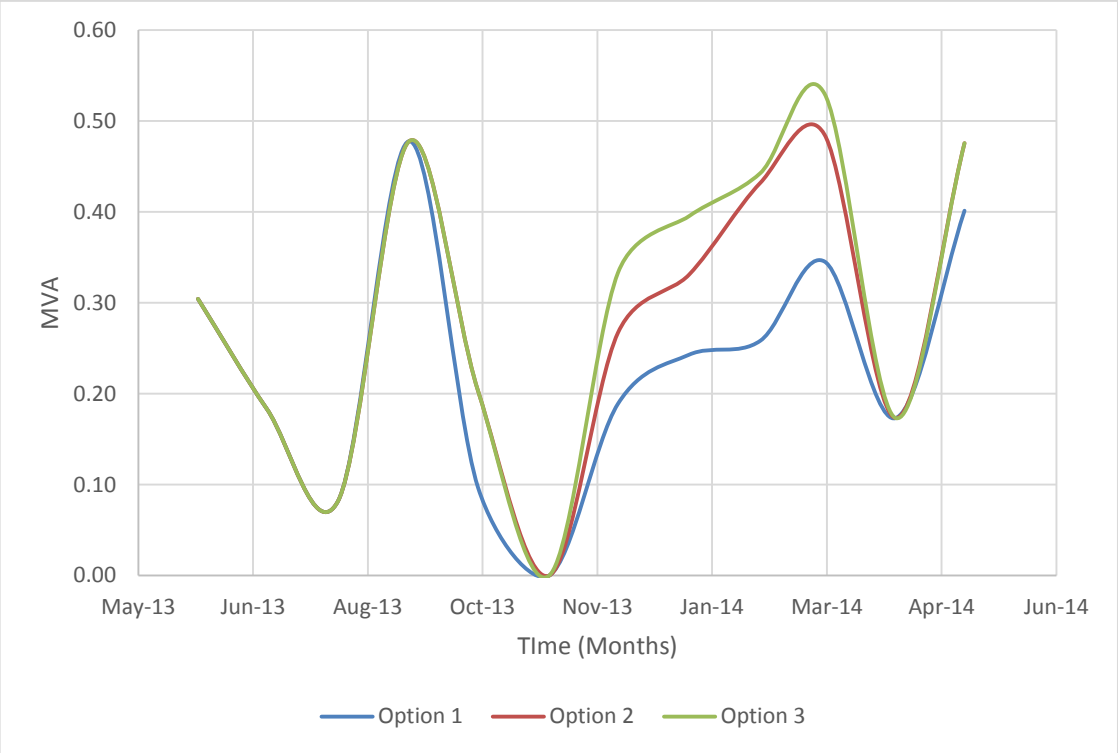


Figure 5. 8: Peak Demand Savings per Option

## 5.3 System Design

Equations 3.2 – 3.4 are used to calculate the basic system design as discussed in Section 3 and is presented in Table 5.2.

Table 5. 2: Summary of each options system design

| | Option 1 | Option 2 | Option 3 | Units |
|---|---|---|---|---|
| **Base Load** | 1344 | 3252 | 6144 | kW |
| **Actual Solar Array Size (with inefficiencies)** | 1989 | 4813 | 9093 | kW |
| **Number of Panels Required** | 6417 | 15526 | 29333 | No |
| **Number of Inverters required** | 904 | 2188 | 4133 | No |
| **Minimum space required** | 11486 | 27791 | 52505 | $m^2$ |

## 5.4 Estimated Cost and Savings

The estimated cost and savings for each of the arrays is presented in Table 5.3 and calculated using Equations 3.11 – 3.14. The corrsponding NPV graphs for the three options is attached in Appendix D.

Table 5. 3: Capital costs, savings and payback

| | Option 1 | Option 2 | Option 3 | Units |
|---|---|---|---|---|
| **Required Capital Investment** | 36.55 | 88.44 | 167.09 | MZAR |
| **Electricity produced (year 1)** | 2248.58 | 5441.13 | 10279.69 | MWh |
| **Savings (year 1)** | 1.87 | 4.52 | 8.53 | MZAR |
| **Amount of peak demand offset (year 1)** | 2.76 | 3.42 | -2.84 | MVA |
| **Peak Demand savings (1 year)** | 0.44 | 0.55 | 0.58 | MZAR |
| **Payback Period** | 9.6 | 10.2 | 10.5 | Years |
| **NPV (year 20)** | 124.31 | 268.89 | 480.07 | MZAR |

The University was billed for a total of 13656 MWh used in the period from May 2013 to June 2014. Table 5.4 compares the total energy produced to the total consumed energy in the period. In this table each array's percentage penetration of the recorded energy for the period is shown as a percentage of the used energy and as expected, the larger the array the higher the penetration.

Using each month's tariffs for kWh and kVA, each array's total savings for the 2013/2014 period is calculated and also displayed in Table 5.4. The total billed costs for kVA and kWh was R 16.7 million and the last column in Table 5.4 presents the total savings as a percentage of this value.

Table 5. 4: Percentage penetration for each option

| **Array Size (kW)** | **Total MWh produced (year 1)** | **% MWh Penetration** | **Savings of total cost (%)** |
|---|---|---|---|
| 1989 | 2249 | 16% | 14% |
| 4813 | 5441 | 40% | 30% |
| 9093 | 10280 | 75% | 55% |

Although the savings increase as the size of the solar array increases, the required capital also increases substantially. These differences are illustrated in Table 5.5 along with the percentage difference for payback. Options 2 and 3 are compared to corresponding values from Option 1 to arrive at each percentage difference that is presented.

Table 5. 5: Percentage differences for each option

| Array Size (kW) | Difference in kW& capital required (%) | Difference in payback (%) | Difference in savings in year 1 (%) |
|---|---|---|---|
| 1989 | | | |
| 4813 | 142% | 6% | 119% |
| 9093 | 357% | 10% | 295% |

As evident in Table 5.5, the payback times for each different array is not very different, but the required capital investment is. As the cost of electricity continues to rise, the payback period will decrease.

## 5.5 Environmental Impact

The impact on the environment decreases as the size of the solar array increases, as less non-renewable resources would be used to provide electricty. This calculation is based on the amount of carbon dioxide emitted if coal was used as a generating source instead of solar. The selected 1989 kW array will save almost 60 kt of carbon dioxide emissions whereas the largest array – 9093 kW – will save approximately 270 kt. Each array's carbon dioxide emission savings are displayed in Figure 5.9 below and includes all emission savings over an assumed 25 year lifespan.

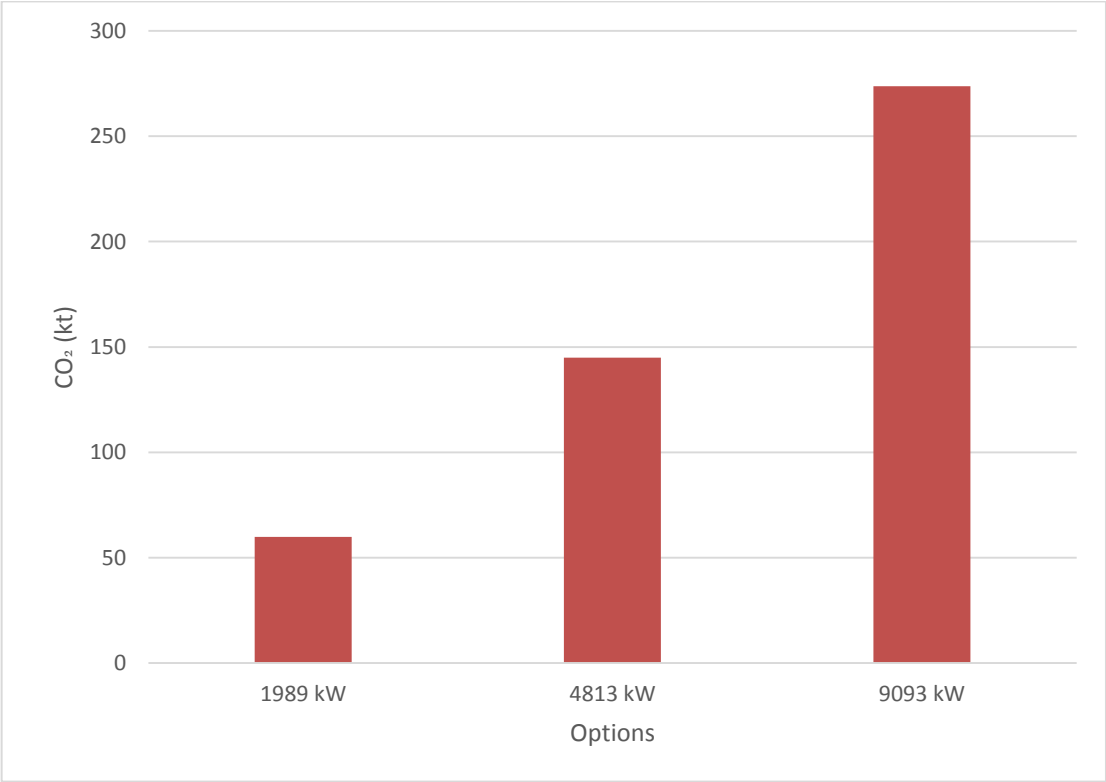



Figure 5. 9: Total $CO_2$ emission savings for each array

## 5.6 Comparing Solar Radiation Data

The SolarGIS, PVGIS and Wits solar radiation data were compared in Section 2.3.4. The graph illustrating the difference in the three types of data for the campus is copied in Figure 5.10 for ease of reference.

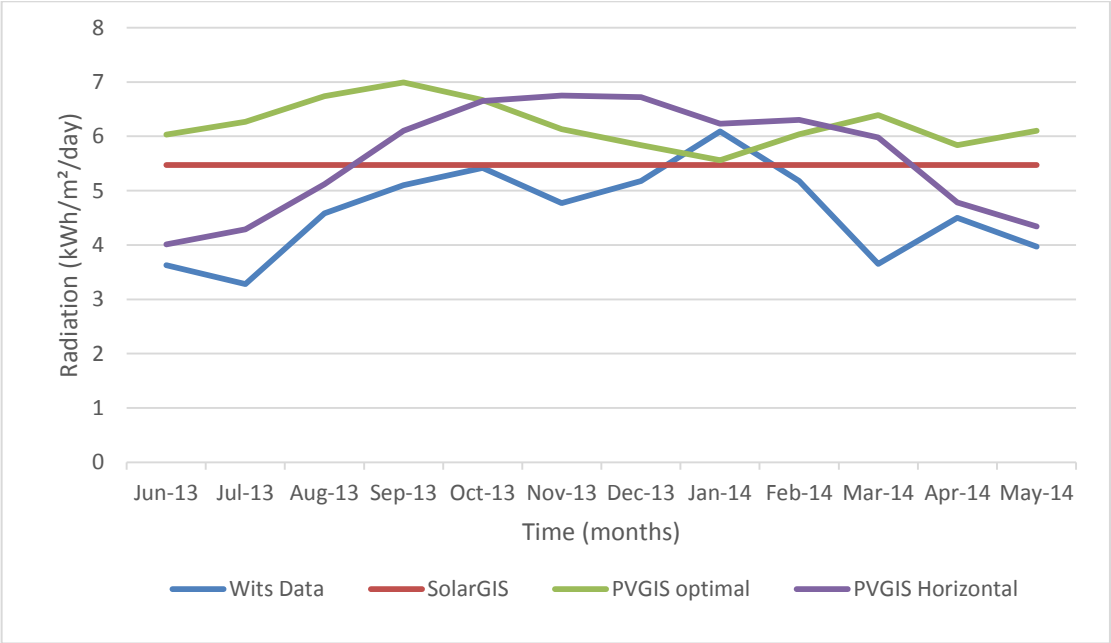



Figure 5. 10: Solar radiation for data sets

To calculate the deviation between the satellite derived data and the ground monitored Wits data, the mean bias error, (MBE), is calculated using Equations 5.1 and 5.2 [67], the results of which are shown in Table 5.6.

$$MBE = \left(\sum_{n=1}^{y} R_{sat}(n) - R_{wits}(n)\right) \times \frac{1}{y} \quad \text{.....[5.1]}$$

$$\%\, MBE = \frac{MBE - average\ for\ wits\ data}{average\ for\ wits\ data} \times 100 \quad \text{.....[5.2]}$$

Table 5. 6: Mean Bias Error

| | Wits Data | SolarGIS | PVGIS – optimal | PVGIS – horizontal |
|---|---|---|---|---|
| MBE | | 0.86 | 1.60 | 0.99 |
| % MBE | | 19 % | 35 % | 21 % |

From the calculations results in Table 5.6, a positive mean bias error is found which concludes that all the satellite derived data sets overestimates the available solar radiation on the campus.

The SolarGIS data is the dataset with the smallest mean bias error and therefore the closest to the Wits Data. But from Figure 5.10, it is evident that the PVGIS-horizontal data follows the same pattern as the Wits Data though the mean bias error is slightly larger.

To investigate the true impact of this error, the satellite derived data is used to design a system for Option 1 selected above. A summary of the system architecture and payback is presented in Table 5.7.

Table 5. 7: System Design and Payback

| | Wits Data | SolarGIS | PVGIS – optimal | PVGIS – horizontal | Units |
|---|---|---|---|---|---|
| **Actual Solar Array Size (with inefficiencies)** | 1989.00 | 2359 | 2681 | 2417 | kW |
| **Number of Panels Required** | 6417 | 7609 | 8648 | 7798 | No |
| **Number of Inverters required** | 904 | 1072 | 1219 | 1099 | No |
| **Minimum space required** | 11486 | 13620 | 15479 | 13958 | $m^2$ |
| **Required Capital Investment** | 36.55 | 43.33 | 49.26 | 44.42 | MZAR |
| **Payback Period** | 9.6 | 10.7 | 11.6 | 10.8 | Years |

## 5.7 Solar Array Size

The main research objective is structured around designing a solar array using historical data based on the University's West Campus so that no excess power is generated. Two further options are explored and are based on the average load when campus is in session and the maximum load measured in the selected period. Table 5.8 summarises these options, corresponding solar array size, the date/time when the load was recorded and the solar radiation at that time.

Table 5. 8: Summary of selected options

| Option | Occurrence | Load (kW) | Solar Array Size (kW) | Solar Radiation ($kW/m^2$) |
|---|---|---|---|---|
| 1 | 22/12/2013, 06:00 | 1344 | 1989 | 0.065 |
| 2 | N/A | 3252 | 4813 | 0.97 (AVG) |
| 3 | 11/06/2013, 9:30 | 6144 | 9093 | 0.37 |

From Table 5.8, it is evident that the solar radiation available at the time of the lowest recorded load is quite low. This is significant because the selected solar array will not yield 1344 kW at this data and time with this amount of radiation so the probability of excess power being generated is very low. Figure 5.11 shows the half hourly solar output for weeks 23 – 39 for option 1, (the entire period is shown in Figure 5.4).

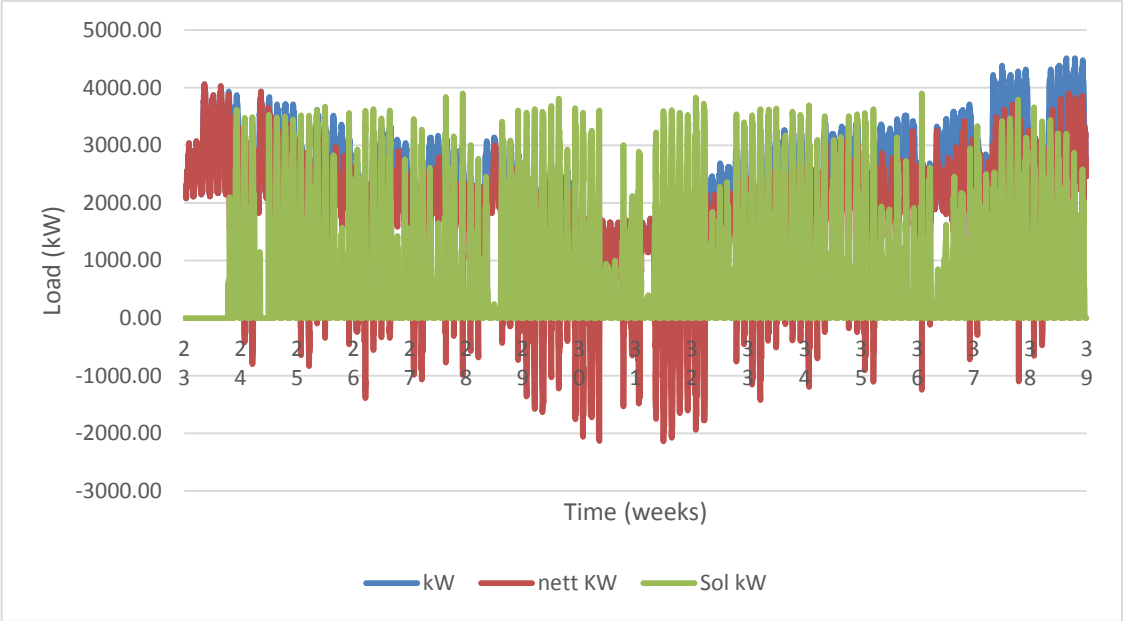



Figure 5. 11: Load and solar output for Option 1 (week 23 – 39)

To optimise the output of a solar array, the size of the array needs to be sized according to the load on the campus when the maximum solar radiation is recorded. The maximum solar radiation for each month in the period is illustrated in Figure 5.12.

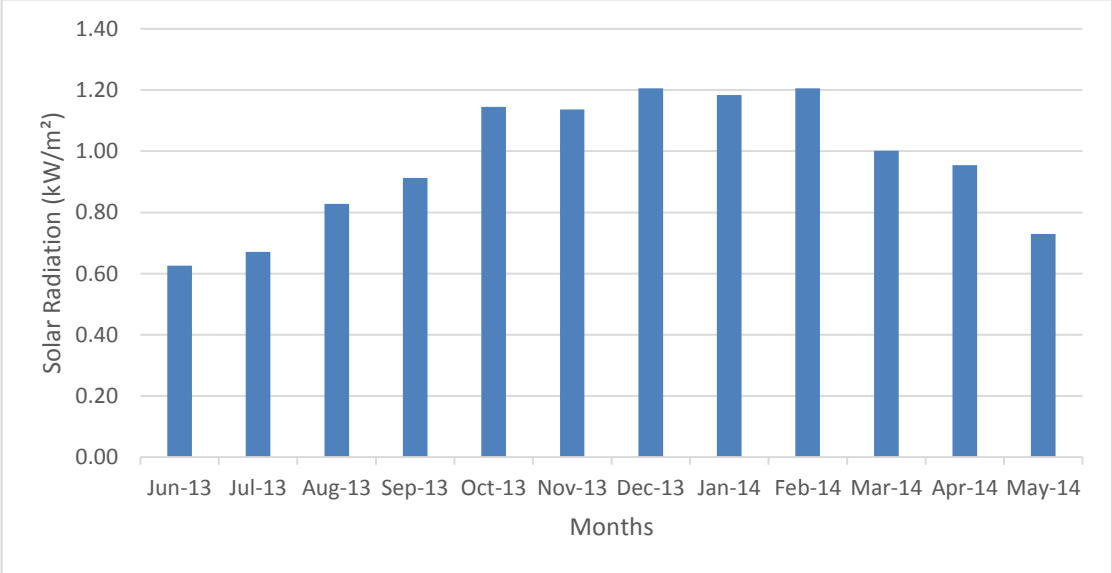



Figure 5. 12: Maximum recorded solar radiation

December 2013 and February 2014 recorded the maximum solar radiation for the period, the load and date/time when this occurred is displayed in Table 5.9.

Table 5. 9: Highest Radiation's load and occurrence

| Occurrence | Load (kW) | Solar Radiation (kW/m²) |
|---|---|---|
| 01/02/2014, 13:30 | 2656 | 1.21 |
| 06/12/2013, 13:30 | 2912 | 1.21 |

Applying Equations 3.2 – 3.10 and using the load in Table 5.9 results in a solar array size of 3931 kW and 4310 kW respectively. Figures 5.13 and 5.14 show the half hourly solar output for both arrays.

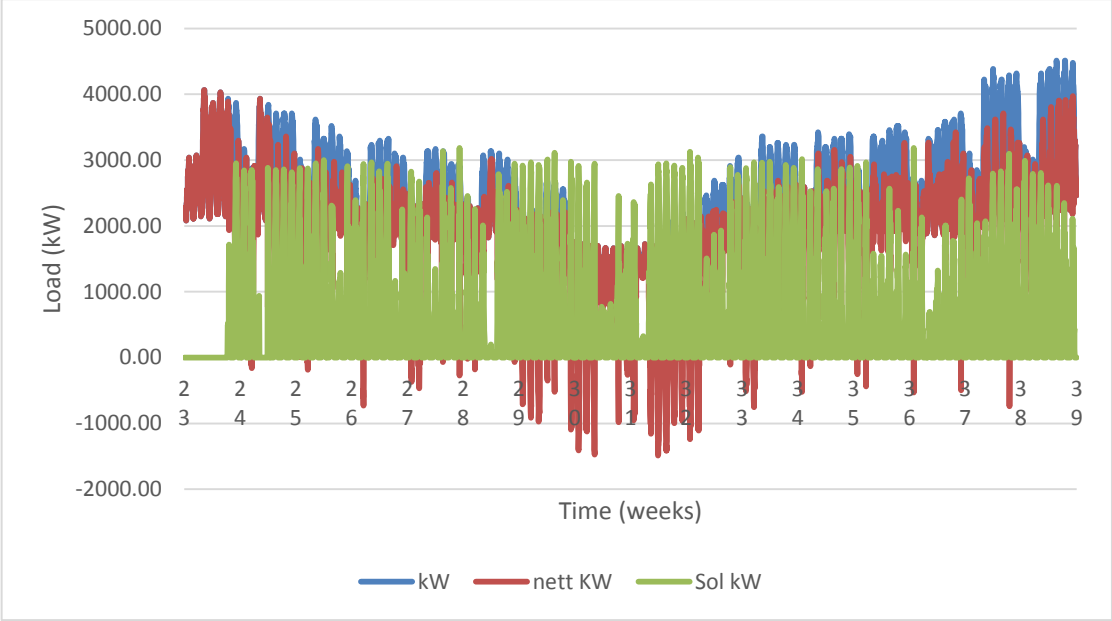



Figure 5. 13: Load and solar output for 3931 kW array (week 23 – 39)

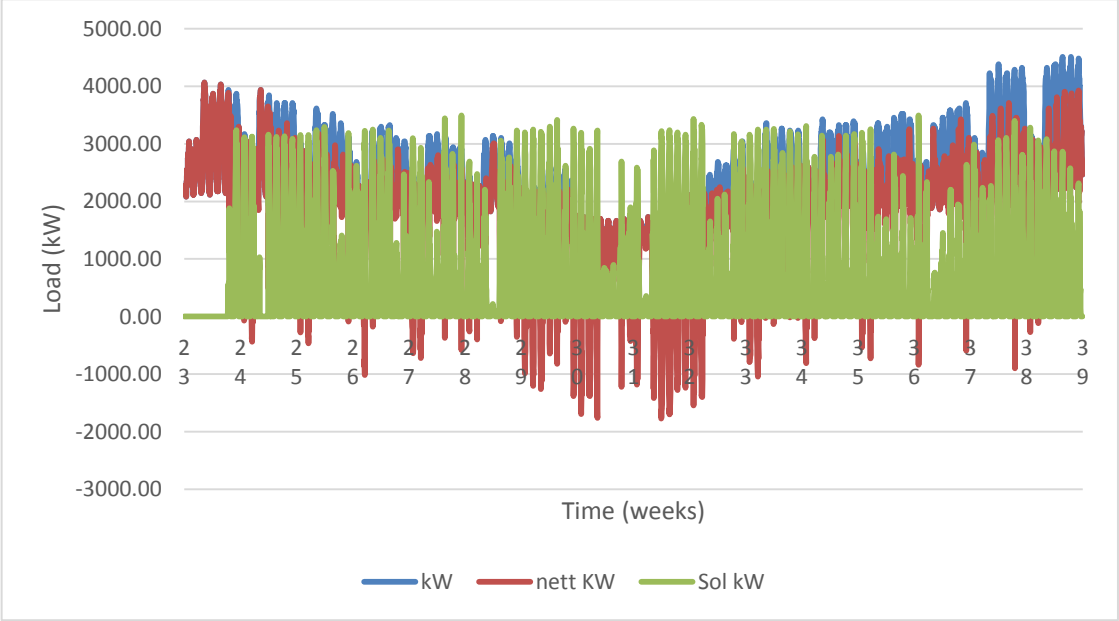



Figure 5. 14: Load and solar output for 4310 kW array (week 23 – 39)

Over generation can be seen when comparing Figures 5.12 and 5.13 to Figure 5.10. Option 2 – the 4813 kW array – is 22% and 12 % larger than the 3931 kW and 4310 kW arrays respectively. This option is based on the average load when campus is in session and will be a more viable option if feeding excess generated electricity back into the grid was not an issue.

## 5.8 Cloud Cover

The methodology used to calculate the electricity cost savings is explained in Section 4. Producing power from solar resources is depended on the availabilty of that resource and therefore fluctuates. The impact of cloud cover on the results is not taken into account for the initial investigation. To investigate the impact of overcast days on the solar array, the amount of days with recorded rain is extracted from the available weather data. A summary of the rainfall since 2009 is plotted in Figure 5.15.

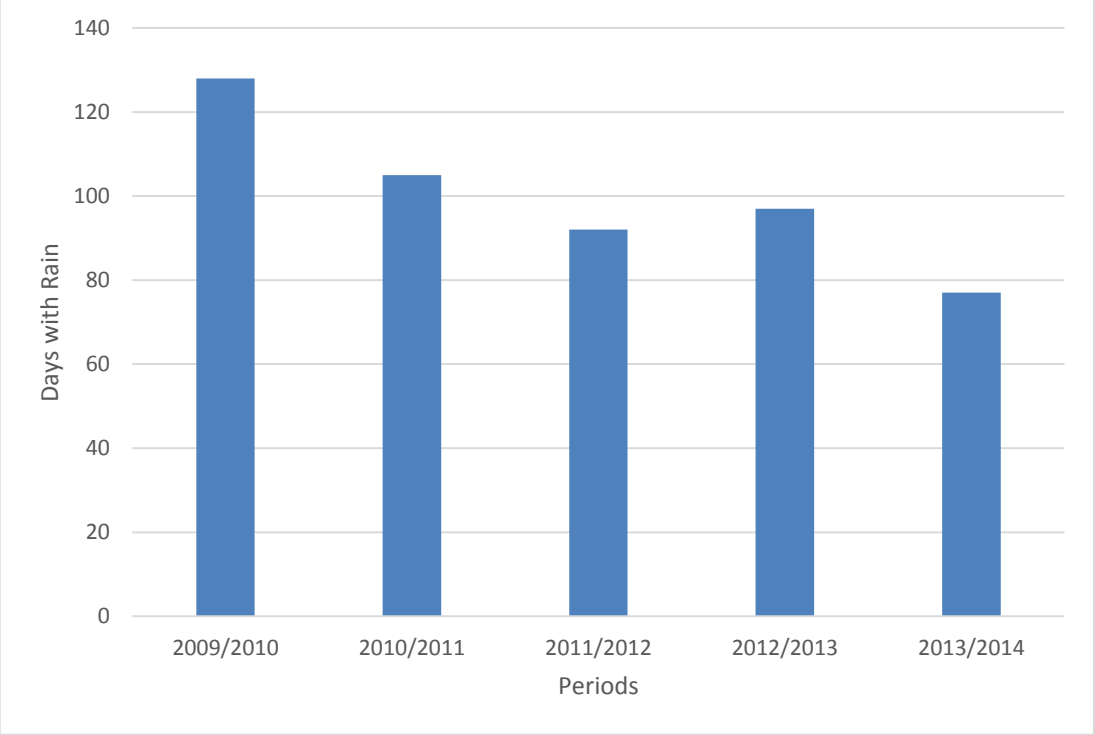



Figure 5. 15: Amount of days with rain

In the 2013/2014 period, 77 days with rain was recorded. Equation 5.5 is used to calculate the percentage change of the selected period's data to the average amount of rainfall days.

$$\Delta = \frac{\beta - \delta}{\beta} \times 100 \quad \text{.....[5.5]}$$

Where,

- $\beta$ is the average amount of rainfall days since 2009
- $\delta$ is the actual recorded days of rainfall for 2013/2014

This results in a 23 % difference, the impact of which on the three options is presented in Table 5.10

Table 5. 10: Effect of changing the number of rain days for year 1

| | **Option 1** | **Option 2** | **Option 3** | **Units** |
|---|---|---|---|---|
| **Required Capital Investment** | 36.55 | 88.44 | 167.09 | MZAR |
| **Electricity produced** | 2248.58 | 5441.13 | 10279.69 | MWh |
| **Electricity produced with rain day compensation** | 1731.40 | 4189.67 | 7915.36 | MWh |
| **Amount of peak demand offset** | 2.76 | 3.42 | -2.84 | MVA |
| **Amount of peak demand offset with rain day compensation** | 2.12 | 2.63 | 2.77 | MVA |
| **Total savings** | 2.31 | 5.06 | 9.11 | MZAR |
| **Total savings with rain compensation** | 1.78 | 3.90 | 7.01 | MZAR |
| **Original Payback Period** | 9.6 | 10.2 | 10.5 | years |
| **Payback Period with rain compensation** | 11.33 | 12.00 | 12.33 | years |

The average amount of rainfall days since 2009 has been 100 but is decreasing with each passing year. If this trend is to continue, then the results presented in Section 5 will form a good basis for the years to come. If not, the output of each option will need to be adjust to accommodate the additional rain days.

## 5.9 Tax Incentives

In 2009, South Africa began the process of legislating a tax incentive for energy efficiency programmes/investments. In November 2013 – the 12L regulation for the allowance of energy efficiency savings was implemented [68] unfortunately the regulation excludes savings yielded from using renewable energy resources. The tax incentive amounts to R 0.45 per approved kWh [30] and is applied to the calculations for the options to determine what its impact would be if it was possible to claim this incentive. A summary of the change in each array's payback is presented in Table 5.11.

Table 5. 11: Effect of Changing the Tax Incentive Rate

| | | New Payback Period | |
|---|---|---|---|
| **Array Size (kW)** | **Original Payback Period (years)** | **Years** | |
| 1989 | 9.6 | 8.3 | -13% |
| 4813 | 10.2 | 8.7 | -14% |
| 9093 | 10.5 | 8.9 | -15% |

From Table 5.11, it is evident that the effect of changing the tax incentive rate only has an average of 14 % for all three options.

## 5.10 Carbon Taxes and Offsets

The proposed maximum carbon tax payable per ton of emitted carbon dioxide is R 120 [27]. To ease economic burdens, a 60 % tax free threshold is also applied and carbon dioxide emitters can apply for lenancies that can result in a 90 % tax relief. for the purpose of this reasech, a 60 % lenancy was applied and resulted in a carbon tax of R 48 per ton. Applying the full tax of R 120 and R 12 to investigate the effects of a 0 % and 90 % tax relief are investigated, the results of which are presented in Table 5.12.

Table 5. 12: Effect of Changing the Carbon Tax Rate

| | | New Payback Period for 0% tax relief | | New Payback Period for 90% tax relief | |
|---|---|---|---|---|---|
| **Array Size (kW)** | **Original Payback Period (years)** | **Years** | | **Years** | |
| 1989 | 9.6 | 9.3 | -3% | 9.8 | 2% |
| 4813 | 10.2 | 9.8 | -4% | 10.3 | 1% |
| 9093 | 10.5 | 10.2 | -3% | 10.7 | 2% |

Carbon emitters can also purchase carbon offsets to further reduce the amount of tax payable, the price of these offsets is uncertain at this stage but R 80 per ton is used in the calculations as this is being used by Promethium carbon for their calculations [28] and is 67 % of the above mentioned carbon tax rate. Adjusting the offset rate to 90 % and 100 % of the tax rate is explored even though the likely hood of this happening is unfavourable, the calculations of which is presented in Table 5.13.

Table 5. 13: Effect of Changing the Carbon Offset Rate

| | | New Payback Period for 90% offset | | New Payback Period for 100% Offset | |
|---|---|---|---|---|---|
| **Array Size (kW)** | **Original Payback Period (years)** | **Years** | | **Years** | |
| 1989 | 9.6 | 9.5 | -1% | 9.4 | -2% |
| 4813 | 10.2 | 10.1 | -1% | 10 | -2% |
| 9093 | 10.5 | 10.3 | -2% | 10.3 | -2% |

From Tables 5.12 and 5.13, it is evident that the impact of the full carbon tax of R 120/ton is not significantly larger and almost negligible. This is also the conclusion drawn from the effect of the 90 % tax relief and offsets.

## 5.11 Electricity and Start-up Costs

The average electricity tariff increase in South Africa per annum is illustrated in Figure 5.16 [69].

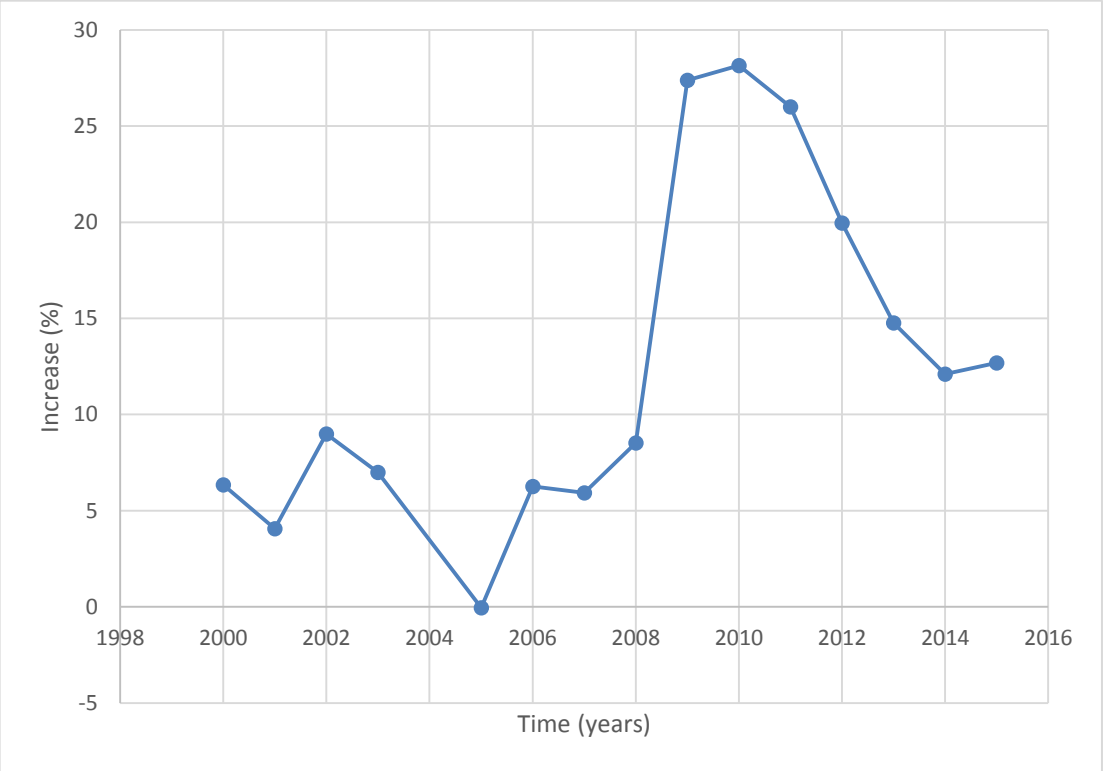



Figure 5. 16: Average Electricity Price Increase/Decrease Since 2000

It is evident that the cost of electricity in South Africa has been decreasing since 2011 as shown in Figure 5.16. The average tariff increase since 2000 – 12.54 % – was used in the payback calculations. The average tariff increase since the black outs for 2008 has been almost 20 % and NERSA has recently declined Eskom's 25.3 % for the next period. The impact of these two tariffs increase on the three options are investigated and presented in Table 5.14.

Table 5. 14: Effect of Changing the Electricity Tariff Increases

| | | New Payback Period for 20 % increase | | New Payback Period for 25.3 % increase | |
|---|---|---|---|---|---|
| **Array Size (kW)** | **Original Payback Period (years)** | **Years** | | **Years** | |
| 1989 | 9.6 | 8.1 | -15% | 7.3 | -24% |
| 4813 | 10.2 | 8.5 | -16% | 7.7 | -24% |
| 9093 | 10.5 | 8.7 | -17% | 7.9 | -25% |

Table 5.14 demonstrates that the effect of electricity price increases is inversely proportional to the payback period. As the cost of electricity increases, the economic feasibility of the solar array becomes more viable.

The required capital investment per kW amounts to R 18 375.39 and is based on previous projects. The start-up capital required to procure and install a solar array is decreasing with grid parity on the horizon [49]. Table 5.15 presents the summary of investigating the impact of reducing the cost per kW for the three options. The decreasing payback for Option 1 is shown in Figure 5.17.

Table 5. 15: Effect of Changing the Cost per kW

| | | **New Payback Period for R 17 375.39/kW** | | **New Payback Period for R 14 375.39/kW** | |
|---|---|---|---|---|---|
| **Array Size (kW)** | **Original Payback Period (years)** | **Years** | | **Years** | |
| 1989 | 9.6 | 9.3 | -3% | 8.2 | -14% |
| 4813 | 10.2 | 9.8 | -4% | 8.7 | -14% |
| 9093 | 10.5 | 10.1 | -4% | 8.9 | -15% |

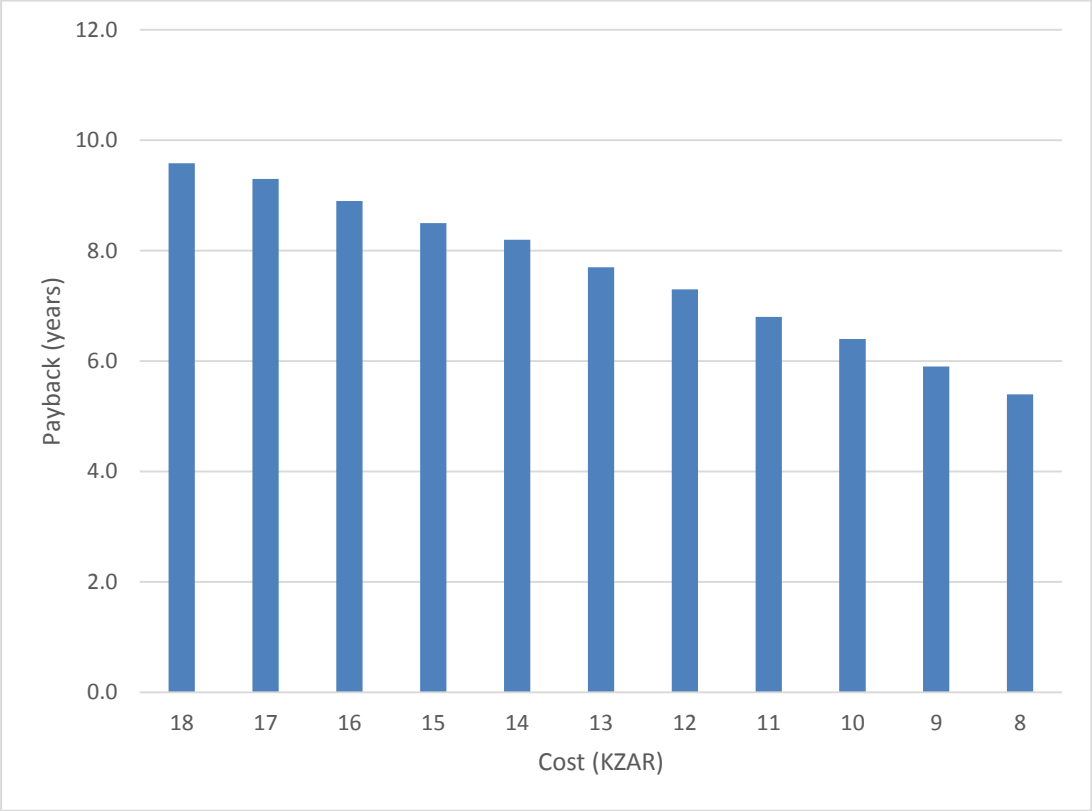



Figure 5. 17: Comparison of cost per kW and payback

From Table 5.15 and Figure 5.17, it is evident that the payback and cost of a system are directly proportional.

## 5.12 Losses

The inefficiencies of the system are explained in Section 1.2.2 and certain assumptions were made to calculate the performance ratio of 0.672. The selected factors for the dirt and component mismatch are kept the same as the losses associated with these factors are low. The balance of the factors are adjusted as follows:

- Production tolerance. It was initially assumed that the solar panel will produce less that the stated output. Changing this assumption to a 100 % output per panel changes the efficiency of this factor from 0.95 to 0.97

- Temperature. As discussed, high ambient temperatures impact the array's output and a 0.89 efficiency factor is used. This approximation is based on temperatures rising higher than 50°C [26]. Johannesburg's maximum recorded temperature between 1961 – 2002 has been between 26°C and 28°C according to Statistics South Africa [70] so this factor has been changed to 0.95 for analysis purposes

- Conversion losses are assumed to be 10 %. As technology advances and efficiency increases, these losses may decrease to 5 % which will result in an efficiency factor of 0.95

Applying these factors results in a system efficiency of 0.797 which is 19 % better than the initial calculation of 0.672. To account for these revised losses, the size of the solar array will have to be increased by 25% instead of the initial 48 % calculated in Section 3.2. A summary of the impact of these changes on the solar array size and payback period is presented in Table 5.16.

Table 5. 16: Effect of adjusting contributing inefficiencies

| Original Array Size (kW) | New Array Size (kW) | Original Payback Period (years) | New Payback Period (years) |
|---|---|---|---|
| 1989 | 1680 | 9.6 | 8.6 |
| 4813 | 4065 | 10.2 | 9.1 |
| 9093 | 7680 | 10.5 | 9.4 |

Adjusting the inefficiencies as mentioned results in a 10 % reduction in solar array size and payback period as can be seen in Table 5.16.

## 5.13 Feed-in Tariffs

From 2009 – 2011, NERSA developed the REFIT policy that has since been terminated in favour of the REIPPPP. The tariff for every kWh fed back into the grid in 2011 and 2009 was R 2.31 and R 3.94 respectively [66]. Other countries, such as America, also offer to credit consumers with the full rate per kWh for each kWh produced by their solar installation [71]. This concept is known as net metering and is also explored. Figures 5.18 – 5.20 show the total energy produced by each array, the consumption on west campus and the nett energy for each option for the selected period.

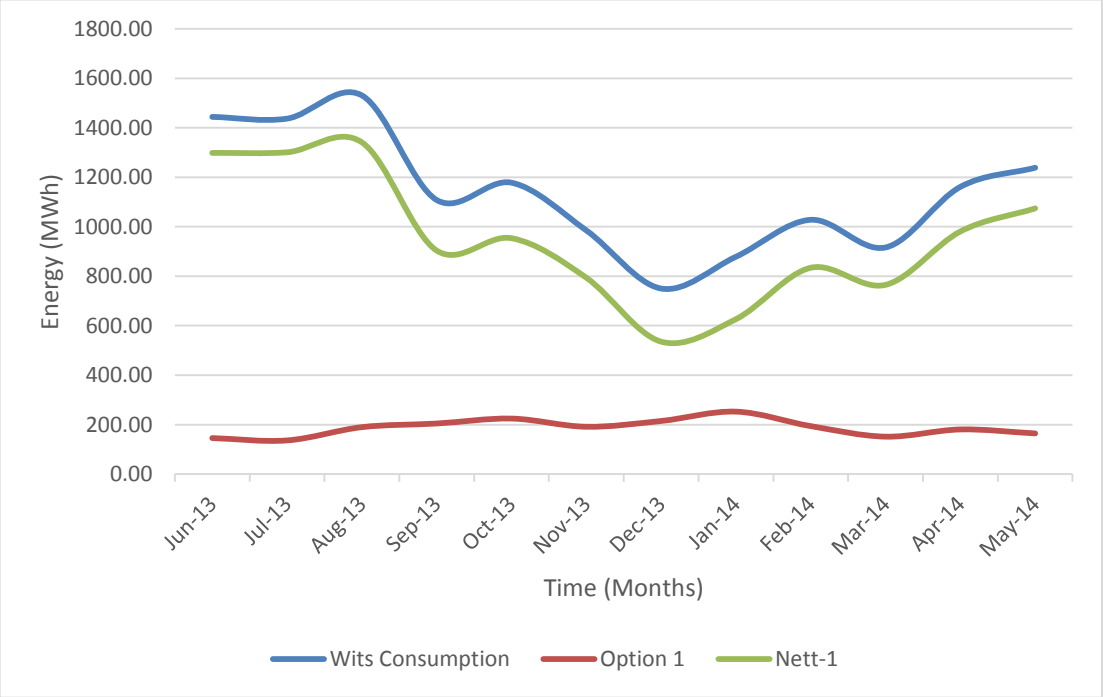



Figure 5. 18: Consumption, solar yield and nett energy for Option 1

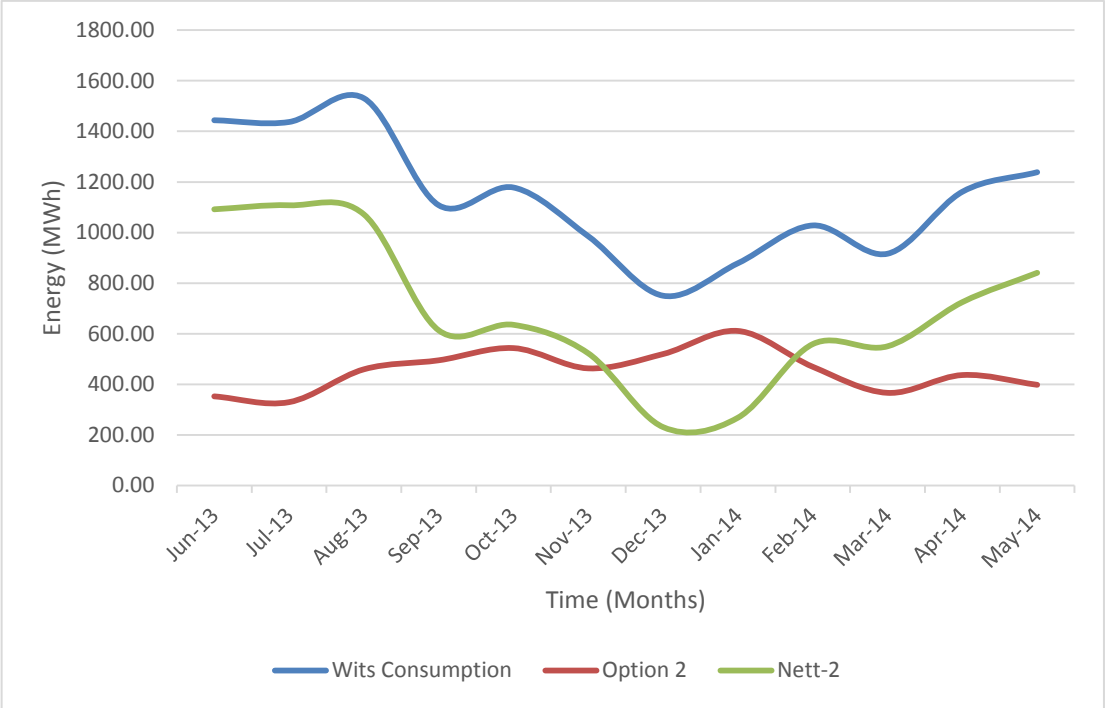



Figure 5. 19: Consumption, solar yield and nett energy for Option 2

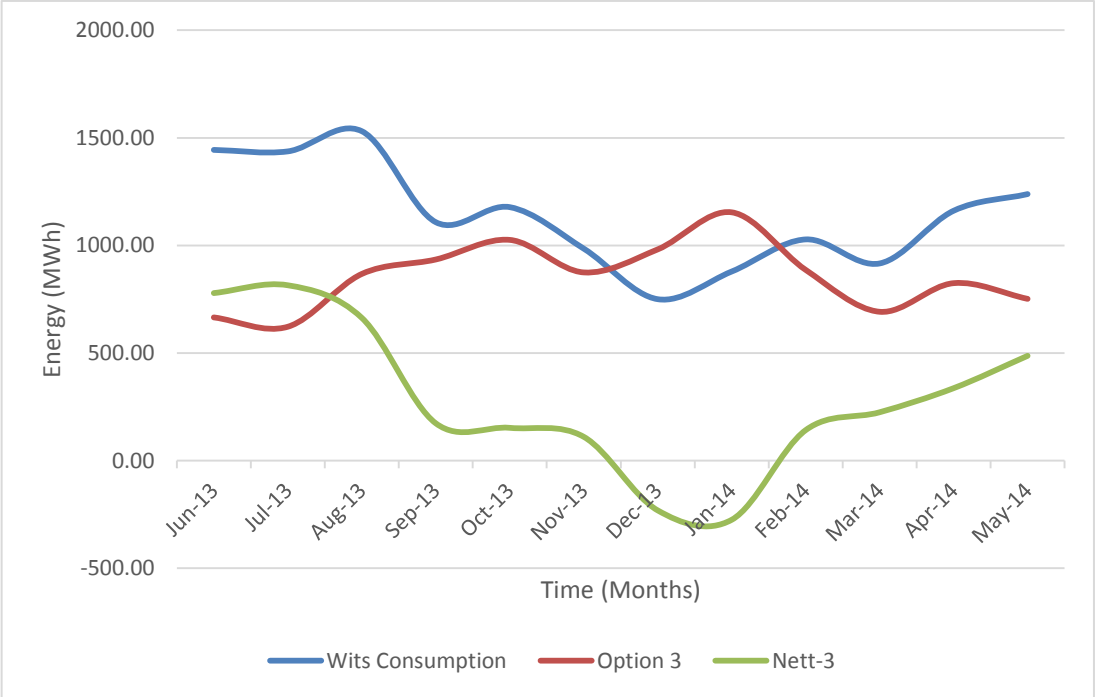



Figure 5. 20: Consumption, solar yield and nett energy for Option 3

From Figures 5.18 – 5.20, the third option is the only array that results in over generation in December 2013 and January 2014. Options 1 and 2 generate electricity that is used by the campus, however the total energy consumed per month does not exceed the demand on campus.

The total feed-in capacity for this array is 507 MWh. Table 5.17 summarises the impact of feeding back this excess electricity back into the grid under various tariffs.

Table 5. 17: Effect of Feed-in Tariffs

| | | New Payback Period for net metering | | New Payback Period for R2.31/kWh | | New Payback Period for R3.94/kWh | |
|---|---|---|---|---|---|---|---|
| **Array Size (kW)** | **Original Payback Period (years)** | **Years** | | **Years** | | **Years** | |
| 9093 | 10.5 | 10.3 | -2% | 9.7 | -8% | 9.3 | -11% |

As the feed-in tariff increases, the payback period of the solar array decreases. Similar results were found with electricity cost increases and start-up cost reduction.

## 5.14 Combining Variables

Sections 5.8 – 5.13 investigated the effect of adjusting the fixed variables that formed a basis for this research and looked at each variable in isolation. The following variables are applied to determine the impact on the payback period, the results of which are presented in Table 5.18.

- Tax incentive rate of R 0.45 per approved kWh
- Full carbon tax of R 120 per ton
- Carbon offset rate stays fixed at R 80 per ton
- Electricity price increase increased to 20 %
- R 1000 reduction in the price per kW
- Performance ratio of 0.797

Table 5. 18: Effect of changing several variables

| | | New Payback Period | |
|---|---|---|---|
| **Array Size (kW)** | **Original Payback Period (years)** | **Years** | **Percentage** |
| 1989 | 9.6 | 6.1 | -36% |
| 4813 | 10.2 | 6.3 | -38% |
| 9093 | 10.5 | 6.5 | -38% |

Table 5.18 demonstrates that changing multiple variables can have a positive impact on the payback of each of the options. This can make investing and installing a solar array more lucrative. Applying a feed-in tariff of R 2.31/kWh and R 3.94/kWh for the third array and applying the above mentioned variables reduces the payback period in Table 5.18 to 6.3 and 5.9 years respectively for option 3.

# 6 CONCLUSION & RECOMMENDATIONS

It is known that South Africa currently generates almost all of its electricity with non-renewable resources – the largest of which is coal. These energy choices make South Africa the 12th largest contributor to carbon emissions which in turn effects the climate negatively. In addition to aiding global warming, non-renewable resources are slowly being depleted and as resources dwindle, the price of energy and electricity are increasing. The electricity price increase is evident in Eskom's 20 % average annual increases experienced in the past. One solution to this growing problem is to supplement daytime electricity consumption with electricity generation from renewable resources. Since South Africa has an abundance of solar resources – this makes solar generated electricity a viable technology to investigate. Solar electricity is generated by technologies such as photovoltaics, solar ponds and concentrated solar power plants that convert the sun's solar radiation into electricity. To determine the expected yield, the amount of solar radiation available is required. This information is area specific and measured using specialised instruments or by analysing satellite derived photographs. Photovoltaics are the most popular solar technology in use today due to the amount of space required for the installation when compared to other solar technologies. A photovoltaic solar system can be grid tied or off-grid. Grid-tied arrays are generally more feasible for consumers who require large amount of electricity during the day as they can use almost all of the solar generated electricity. Grid-tied solar arrays also do not have battery storage which make them less expensive. Three of the largest reasons for the lack of use of grid-tied solar arrays are:

1. High capital costs. Solar array installations are generally quite expensive and consumers are not used to "paying off" electrical equipment.
2. Irregular resource. Since solar is a natural resource, constant electricity generation is not guaranteed and dependent on fluctuating weather patterns.
3. Selling back to the grid. At this juncture, consumers cannot sell excess power back to the grid easily. This makes the feasibility of solar arrays weak and difficult to design because consumer usage needs to be close to the power generated from the solar array.

Currently, there is no specific legislation for the selling of solar generated electricity back to the grid. Carbon taxes are in the process of being implemented but are quite lenient towards non-renewable generated power as this is mainly used in South Africa. Tax incentives were implemented in 2013 but no other rebates are available to consumers wanting to install a solar array. Although feed-in tariffs have been drafted by NERSA, many of municipalities are not

open to accepting power generated from solar, because selling coal generated electricity to consumers forms the backbone of their budget structure and income.

This research investigates the design of a solar array for the University of the Witwatersrand's west campus in Johannesburg using historical solar radiation data that is specific to this site. The availability of accurate solar radiation data is limited as the instruments required for these measurements are expensive. Several free solar radiation databases are available and the accuracy of this data is also explored. West Campus is a perfect example of a mixed use facility as it is also home to lecture venues, laboratories, night time lecture venues, sports facilities and residences for students so electricity is used 24 hours a day. The array has to be sized for the load of the campus as selling power back to the utility is not an option as yet.
The problem is formally defined in the introduction along with the scope of works, success criteria, assumptions and limitations. Following this, the research significance is explored and covers global warming, electricity security and consumer education. The introduction is concluded with a review of the current methods and an overview of the methodology used in the research process.

To determine the size of the array, the University's consumption is discussed and analysed. Since West Campus is a large consumer, they are billed for real power, peak demand and reactive power; as well as other items such as connection fees, levies and sundry charges. The reactive component is relatively small and is left out of the analysis as the associated costs are quite small in comparison to the costs of real power and peak demand. The other items are also excluded as their method of calculation is difficult to estimate along with the effect of a solar array on them. Analysis of consumption patterns for West Campus finds that consumption is at its highest when campus is in full session and during the day. The demand on campus at night is still high and is attributed to residences on the campus and other night time activities such as classes and events. A substantial increase in demand in general is also noticeable in the colder winter months. Another substantial decrease in electricity demand is noticeable in the December/January break when campus is mostly closed. Analysis of the received solar radiation data shows that the summer months offer the highest amount of radiation available for harvesting. This unfortunately coincides with the campus's quietest period. This analysis forms a basis for sizing the solar array and three options are explored:

- 1989 kW. This option meets the minimum objective of the research and will yield a maximum of 1344 kW.

- 4813 kW. This option is based on the campus's average consumption when campus is opened and is more in line with the campus's electricity demands. This option will yield a maximum of 3253 kW.
- 9093 kW. This option is explored to determine what the benefits/detriments would be if selling power back to the utility was an option and is equivalent to the maximum load in the selected period. This option will yield a maximum of 6144 kW and is explored to determine what the benefits would be if capital and feeding back into the grid was not an issue.

The above mentioned array sizes also include system losses which are calculated to be 48 %. The design of the hypothetical system is discussed and includes the number of panels, inverters and total space required. The capital required to provide all necessary equipment is calculated to be R 18 375.39 per kW and is based on recent tendered prices. A summary of each array's system design and space required is presented in Table 6.1.

Table 6. 1: Summary of space and equipment required for solar arrays

| **Option** | **Max Yield (kW)** | **Array Size (kW)** | **Space Required ($m^2$)** | **Inverters** | **Panels (310 W)** |
|---|---|---|---|---|---|
| **1** | 1344 | 1989 | 11486 | 904 | 6417 |
| **2** | 3252 | 4813 | 27791 | 2188 | 15526 |
| **3** | 6144 | 9093 | 52505 | 4133 | 29333 |

Savings for the system is calculated using the period's electricity tariffs. The economic viability is also explored and includes carbon taxes and the selling of carbon offsets. Table 6.2 shows a summary of the cost, savings and payback.

Table 6. 2: Summary of costs and savings, (year 1), for three options

| **Option** | **Size (kW)** | **Payback** | **Cost (MZAR)** | **Savings (MZAR)** |
|---|---|---|---|---|
| **1** | 1344 | 9.6 | 36.55 | 2.3 |
| **2** | 3252 | 10.2 | 88.44 | 5.1 |
| **3** | 6144 | 10.5 | 167.09 | 9.1 |

Option 2 results in a solar array increase of 142 % over option 1, this results in a 119 % increase in electricity cost savings and a 6 % increase in the payback period. Option 3's array is 357 % larger than Option 1's array and translates to a 295 % increase in electricity cost savings and an 9 % increase in the payback period when compared to Option 1.

Comparing several satellite derived data sets to the ground monitored data found that the satellite derived radiation data was an average of 25 % higher. For the purpose of this research, it is found that ground monitoried data is more accurate than satellite derived data as the payback period is less and therefore better suited to design the solar array for the campus.

To determine the output and payback of the system, several variables are fixed:

- **The size of the array**. The sizes of the arrays are selected to meet the minimum and additional objectives of this research.
- **Cloud cover**. The impact of real energy and peak demand savings can decrease if the amount of cloud cover increases. Cloud cover was not taken into consideration in the initial calculations.
- **Tax incentives**. Tax incentives are currently not offered for the use of solar energy so this is excluded in the initial calculations.
- **Carbon Tax.** The proposed carbon tax on non-renewable resources has a built-in tax threshold of 60 % and users can increase the discount to up to 90 %.
- **Carbon offsets**. Carbon offsets can be purchased by carbon emitters, though the rate is not fixed as yet. A conservative estimate is used in the calculations.
- **Cost of Electricity**. The cost of electricity used in the calculations is determined from Eskom's average price increase since 2000.
- **Start-up Costs**. These costs are based on previous projects.
- **Losses**. Various loss factors contributing to the inefficiency of the system – from the panel and the environment – are applied to the calculations.
- **Feed-in Tariffs**. These tariffs have been officially terminated in favour of the REIPPPP.

Adjusting these variables yields the following major findings:

- The amount of rain days in the 2013/2014 period is 23 % lower than the average from 2009. This will impact the design if the average stays the same or increases
- Applying the tax incentive of R 0.45 per kWh has a positive effect on the payback period for all three options with an average reduction of 14 %
- Applying the full carbon tax of R 120 per ton instead of R 48 per ton also has a positive effect on all three options and reduces the payback periods by an average of 2 %
- Adjusting the carbon offset rate to between 80 – 90 % of the full carbon tax has a smaller average impact on the payback periods of 1 %

- Increasing the electricity tariffs from 12.54 % has the largest average impact of all the adjusted variable:
    - 16 % reduction in payback periods for a tariff increase of 20 % per annum
    - 24 % reduction in payback periods for a tariff increase of 25.3 % per annum
- Reducing the cost per kW by R 1000 improves the payback period by 6 %
- Improving the efficiency of the system by 19 % reduces the array size and payback period by 10 %
- Feed in tariffs can be beneficial to the campus – depending on the tariff structure and amount of excess power fed back into the grid
- Combining variables such as tax incentive rates, carbon tax, electricity price increase, losses and reduction in start up capital can improve the payback period by 36 %
- The ground monitored data is measured using a single pyranometer so the data cannot be validated as explained in Section 1.
- The capital required for the system is based on small installaitons that are less than 1 MW. PV installations over 1 MW can become cheaper due to the volume of equipment required for the installation

The impact on the above mentioned variables on the payback are presented in Table 6.3.

Table 6. 3: Impact of changing variables

| **Array Size (kW)** | **Original Payback Period (years)** | **Tax Incentive** | **Carbon Tax** | **Tariff Increase** | **Reduced Capital** | **Losses** | **Combined** |
|---|---|---|---|---|---|---|---|
| 1989 | 9.6 | -13% | -3% | -15% | -3% | -10 % | -36% |
| 4813 | 10.2 | -14% | -4% | -16% | -3% | -10 % | -38% |
| 9093 | 10.5 | -15% | -3% | -17% | -3% | -10 % | -38% |

This research demonstrates that ground monitored data is 25 % more accurate than satellite derived data. It also demonstrates that installing a suitably sized array can have a significant impact on electricity costs and reduce the strain on the environment.

It is suggested that a minimum array size of 1989 kW be installed on the University of the Witwatersrand's West Campus if the space required for the installation is available. This solar array will produce a maximum of 1344 kW during the months with high solar radiation readings – December and January – when the campus is the least busy.

The maximum output from the array is well below the minimum measured power recorded for the period and the calculated average. Producing any more power than this may possibly result in over generation and since the University cannot sell excess electricity back to the grid, this is not a viable option.

South Africa has committed to reduce carbon emissions by 42 % by 2025, but only 9 % renewable energy penetration by 2030 has been mapped out in the REIPPPP and more money is currently being spent on new coal generating power plants – Medupi (4764 MW) and Kusile (4800 MW). To ensure that South Africa reduces its impact on the environment, the uptake of solar and other renewable resources for electricity generation needs to be promoted. In light of the environmental impacts from the continuous use of coal as South Africa's primary source for electricity generation and to ensure security of supply, South Africa needs to promote the uptake of solar photovoltaics. To achieve this, the following recommendations are made:

- Adjust carbon taxes to make coal a less viable choice
- Increase the tax benefits associated with renewable generation
- Study Germany's model for the uptake of solar arrays and possibly offer other incentives to consumers
- Explore the municipal budget structure to make it less dependent on electricity sales
- Investigate and monitor current and future capacity of the electricity network to ensure that it can handle additional fluctuating capacity.

In addition to the items above, clear legislation needs to be drafted for the implementation of renewable resources and implemented across the country. The current capacity of the grid needs to be investigated and monitored to ensure that it can handle additional capacity generated from renewable resources. If legislation were to change in favour of renewable resources over non-renewable resources, and if the University has additional capital and space then it will benefit them to install a larger array as the payback periods are not significantly larger. The return on investment for the system will decrease as the price of coal generated electricity increases.

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# A BILLING INFORMATION

The University of the Witwatersrand spent almost R 20 million on electricity for its West Campus from June 2013 to May 2014. Table A.1 summaries the entire cost for this period, as received from the School of Electrical and Information Engineering [53].

Table A. 1: Total Electricity Costs for June 2013 – May 2014

| | **Cost (R )** |
|---|---|
| **Cost per annum** | R 17 393 178.75 |
| **Average cost per month** | R 1 449 431.56 |
| **Average cost per day** | R 47 652.54 |

The University is considered a large consumer and is billed for three components of electricity:

- Real energy in kWh
- Peak Demand in kVA
- Reactive energy in kVArh

Peak demand is the highest recorded amount of apparent power, (kVA), measured in a month. The utility measures electricity consumption every half hour at the main incomer to West Campus. The real and reactive energy components are summed for the month, multiplied by the appropriate tariff and added to the bill. The peak demand is also measured every half hour, but only the highest recorded amount for the month in question is multiplied by the peak demand tariff and added to the bill. Costs associated with real energy, peak demand and reactive energy are presented in Tables A.2, A.3 and A.4 respectively.

Table A. 2: Total Real Energy Costs for June 2013 – May 2014

| | **Cost (R )** |
|---|---|
| **Cost per annum** | R 11 596 303.09 |
| **Average cost per month** | R 966 358.59 |
| **Average cost per day** | R 31 770.69 |

Table A. 3: Total Peak Demand Costs for June 2013 – May 2014

| | **Cost (R )** |
|---|---|
| **Cost per annum** | R 5 104 071.08 |
| **Average cost per month** | R 425 339.26 |
| **Average cost per day** | R 13 983.76 |

Table A. 4: Total Reactive Energy Costs for June 2013 – May 2014

| | **Cost (R )** |
|---|---|
| **Cost per annum** | R 177 753.20 |
| **Average cost per month** | R 14 812.77 |
| **Average cost per day** | R 487.00 |

The average tariffs for these costs for the period in question were:

- R 0.83 per kWh
- R 159.72 per kVA
- R 0.14 per kVArh

In addition to this, the University also pays a fixed service charge for the connection to West Campus, a sundry amount that varies every month and a demand side management levy that is based on peak demand usage. The costs associated with the demand side management levy, service charge and sundry charges are summarised in Table A.5

Table A. 5: Total other costs for June 2013 – May 2014

| | **Cost (R )** |
|---|---|
| **Cost per annum** | R 515 051.38 |
| **Average cost per month** | R 42 920.95 |
| **Average cost per day** | R 1 411.10 |

The total cost per month for each component is presented in Tables A.6 – A.9 with a final total per month in Table A.10

Table A. 6: kWh cost per month

| **Month** | **kWh** | **R/kWh** | **Total kWh Cost** |
|---|---|---|---|
| June 2013 | 1 444 000.00 | R 0.8780 | R 1 267 832.00 |
| July 2013 | 1 437 000.00 | R 1.0263 | R 1 474 793.10 |
| August 2013 | 1 531 000.00 | R 1.0263 | R 1 571 265.30 |
| September 2013 | 1 108 000.00 | R 0.7509 | R 831 997.20 |
| October 2013 | 1 178 000.00 | R 0.7509 | R 884 560.20 |
| November 2013 | 985 213.81 | R 0.7509 | R 739 797.05 |
| December 2013 | 750 092.19 | R 0.7509 | R 563 244.22 |
| January 2014 | 878 694.00 | R 0.7509 | R 659 811.32 |
| February 2014 | 1 028 000.00 | R 0.7509 | R 771 925.20 |
| March 2014 | 916 231.70 | R 0.7509 | R 687 998.38 |
| April 2014 | 1 161 231.30 | R 0.7509 | R 871 968.58 |
| May 2014 | 1 238 537.00 | R 1.0263 | R 1 271 110.52 |

Table A. 7: kVA cost per month

| Month | kVA | R/kVA | Total kVA Cost |
|---|---|---|---|
| June 2013 | 3 200.00 | R 198.3700 | R 634 784.00 |
| July 2013 | 3 000.00 | R 161.8200 | R 485 460.00 |
| August 2013 | 3 000.00 | R 161.8200 | R 485 460.00 |
| September 2013 | 2 500.00 | R 154.1000 | R 385 250.00 |
| October 2013 | 2 453.33 | R 154.1000 | R 378 058.62 |
| November 2013 | 2 453.33 | R 154.1000 | R 378 058.62 |
| December 2013 | 2 453.33 | R 154.1000 | R 378 058.62 |
| January 2014 | 2 453.33 | R 154.1000 | R 378 058.62 |
| February 2014 | 2 500.00 | R 154.1000 | R 385 250.00 |
| March 2014 | 2 600.00 | R 154.1000 | R 400 660.00 |
| April 2014 | 2 453.33 | R 154.1000 | R 378 058.62 |
| May 2014 | 2 700.00 | R 161.8200 | R 436 914.00 |

Table A. 8: kVArh cost per month

| Month | kVArh | R/kVArh | Total kVArh Cost |
|---|---|---|---|
| June 2013 | 0.00 | R 0.1295 | R - |
| July 2013 | 0.00 | R 0.1295 | R - |
| August 2013 | 0.00 | R 0.1295 | R - |
| September 2013 | 103600 | R 0.1390 | R 14 400.40 |
| October 2013 | 147 600.00 | R 0.1390 | R 20 516.40 |
| November 2013 | 174 371.46 | R 0.1390 | R 24 237.63 |
| December 2013 | 142 019.74 | R 0.1390 | R 19 740.74 |
| January 2014 | 192 408.80 | R 0.1390 | R 26 744.82 |
| February 2014 | 194 600.00 | R 0.1390 | R 27 049.40 |
| March 2014 | 123 130.49 | R 0.1390 | R 17 115.14 |
| April 2014 | 135 014.61 | R 0.1390 | R 18 767.03 |
| May 2014 | 66 054.90 | R 0.1390 | R 9 181.63 |

Table A. 9: Other costs per month

| Month | Service Charge | DSM levy | Sundries |
|---|---|---|---|
| June 2013 | R 3 328.31 | R 14 440.00 | R 38 118.89 |
| July 2013 | R 3 328.31 | R 14 370.00 | R 39 271.63 |
| August 2013 | R 3 328.31 | R 15 310.00 | R 41 201.08 |
| September 2013 | R 3 328.31 | R 11 080.00 | R 24 699.52 |
| October 2013 | R 3 328.31 | R 11 780.00 | R 25 729.27 |
| November 2013 | R 3 328.31 | R 10 042.14 | R 22 908.43 |
| December 2013 | R 3 328.31 | R 7 500.92 | R 19 287.44 |
| January 2014 | R 3 328.31 | R 8 786.94 | R 21 358.86 |
| February 2014 | R 3 328.31 | R 10 280.00 | R 23 751.06 |
| March 2014 | R 3 328.31 | R 9 162.32 | R 22 182.04 |
| April 2014 | R 3 328.31 | R 11 612.61 | R 25 442.45 |
| May 2014 | R 3 328.31 | R 12 385.37 | R 34 410.69 |

Table A. 10: Total costs per month

| **Month** | **Total (all charges)** |
|---|---|
| June 2013 | R 1 958 503.20 |
| July 2013 | R 2 017 223.04 |
| August 2013 | R 2 116 564.69 |
| September 2013 | R 1 270 755.43 |
| October 2013 | R 1 323 972.80 |
| November 2013 | R 1 178 372.18 |
| December 2013 | R 991 160.25 |
| January 2014 | R 1 098 088.87 |
| February 2014 | R 1 221 583.97 |
| March 2014 | R 1 140 446.19 |
| April 2014 | R 1 309 177.60 |
| May 2014 | R 1 767 330.52 |

# B DATA ANALYSIS

## B.1 COMPARING DATA SETS

Table B. 1: Various data sets for the campus

| MONTH | Wits Data (kWh/m²/day) | SolarGIS (kWh/m²/day) | PVGIS – optimal (kWh/m²/day) | PVGIS – horizontal (kWh/m²/day) |
|---|---|---|---|---|
| Jun-13 | 3.63 | 5.47 | 6.03 | 4.01 |
| Jul-13 | 3.28 | 5.47 | 6.27 | 4.29 |
| Aug-13 | 4.58 | 5.47 | 6.74 | 5.12 |
| Sep-13 | 5.10 | 5.47 | 6.99 | 6.1 |
| Oct-13 | 5.42 | 5.47 | 6.67 | 6.65 |
| Nov-13 | 4.77 | 5.47 | 6.13 | 6.75 |
| Dec-13 | 5.18 | 5.47 | 5.84 | 6.72 |
| Jan-14 | 6.09 | 5.47 | 5.56 | 6.23 |
| Feb-14 | 5.18 | 5.47 | 6.04 | 6.3 |
| Mar-14 | 3.65 | 5.47 | 6.39 | 5.98 |
| Apr-14 | 4.50 | 5.47 | 5.84 | 4.78 |
| May-14 | 3.97 | 5.47 | 6.1 | 4.34 |
| Average for period | 4.61 | 5.47 | 6.22 | 5.6 |
| Total for period | 1682 | 2000 | 2270 | 2044 |

## B.2 NORMALISATION

Table B.1 summarises the significant periods for the campus along with the maximum recorded load and total recorded radiation for the period and a plot of this data is shown in Figure B.1.

Table B. 2: Significant periods and accompanying data

| **Activity** | Load (kW) | Solar Radiation (kW/m²/day) |
|---|---|---|
| MOY Exams | 6144.00 | 175.78 |
| Winter Break | 4576.00 | 113.60 |
| 3rd Term | 5728.00 | 404.53 |
| Spring Break | 4768.00 | 101.07 |
| 4th Term | 4576.00 | 465.78 |
| EOY Exams | 4384.00 | 238.00 |
| Summer Break | 3520.00 | 537.48 |
| Registration | 3616.00 | 339.60 |
| 1st Term | 4576.00 | 417.97 |
| Autumn Break | 3968.00 | 80.17 |
| 2nd Term | 5120.00 | 399.39 |

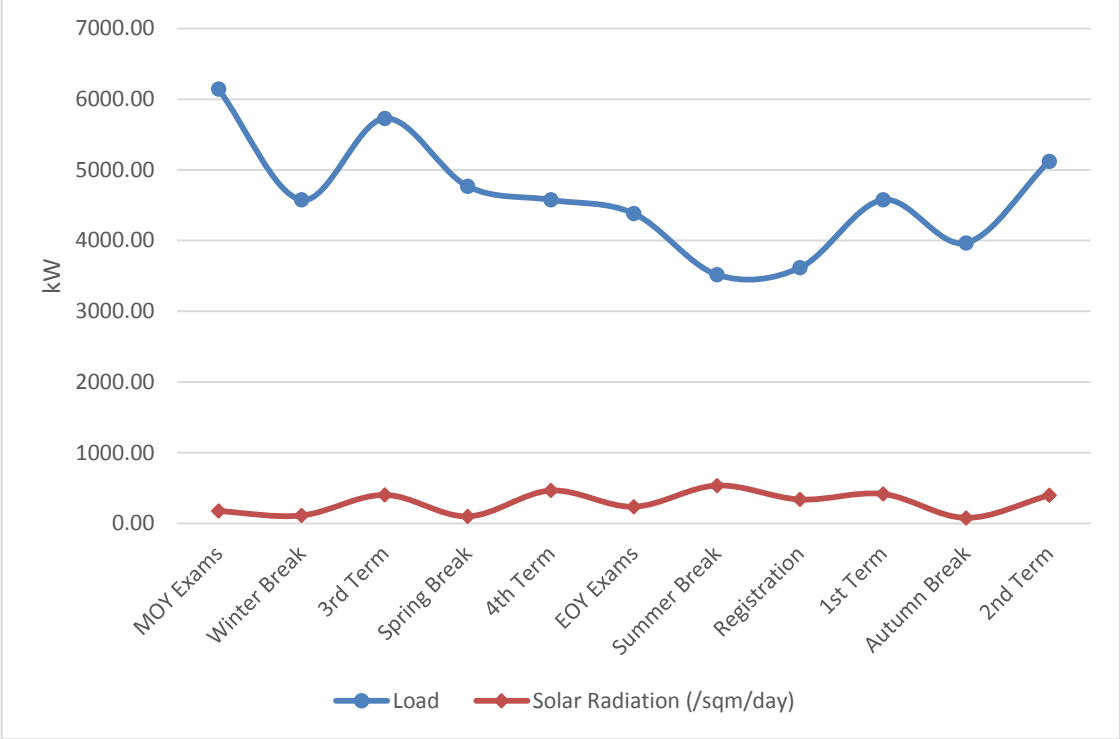


Figure B. 1: Load profile and available radiation

Since the load for West Campus differs by an order of magnitude to the solar radiation in most instances – both sets of data need to be normalised for analysis to continue. To achieve this the maximum recorded value for power and radiation is chosen as base quantities – as shown in Equations B3 and B4. The normalised values for the data from Table B.1 is presented in Table B.2 and illustrated in Figure B.2.

$$P_{PU} = \frac{kW}{kW_{max}} \quad \text{[B3]}$$

$$Sol_{PU} = \frac{{}^{kW}/_{m^2}}{{}^{kW}/_{m^2{}_{max}}} \quad \text{[B4]}$$

Where,

- $kW_{max} = 6144$
- ${}^{kW}/_{m^2{}_{max}} = 537.48$

Table B. 3: Normalised data

| **Activity** | Normalised Load | Normalised Solar Radiation |
|---|---|---|
| MOY Exams | 1.00 | 0.33 |
| Winter Break | 0.74 | 0.21 |
| 3rd Term | 0.93 | 0.75 |

| | | |
|---|---|---|
| Spring Break | 0.78 | 0.19 |
| 4th Term | 0.74 | 0.87 |
| EOY Exams | 0.71 | 0.44 |
| Summer Break | 0.57 | 1.00 |
| Registration | 0.59 | 0.63 |
| 1st Term | 0.74 | 0.78 |
| Autumn Break | 0.65 | 0.15 |
| 2nd Term | 0.83 | 0.74 |

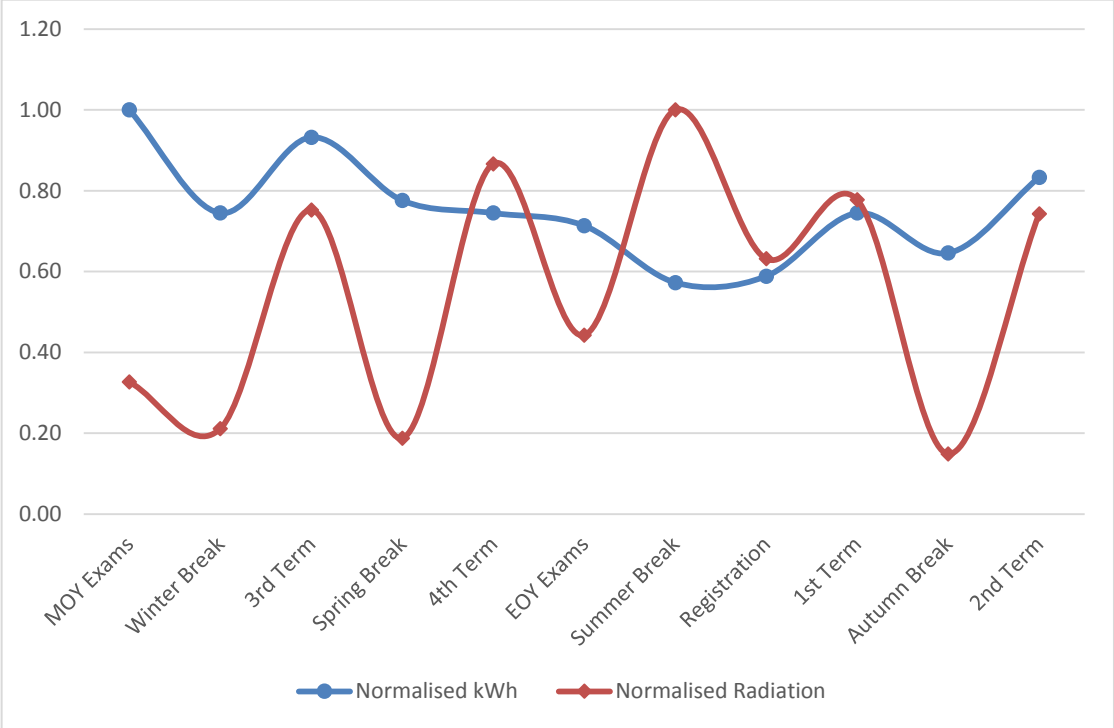



Figure B. 2: Normalised data

# C ECONOMICS

Though a solar array will reduce the target location's environmental impact, capital is still required to purchase and install the system. To determine whether a suitable sized solar array will yield a return on the investment made, the payback of the system is calculated and is the period it takes to recuperate the initial capital investment for the system. The Net Present Value, (NPV), method is used because it gives an accurate description of the future value of money in today's context and is governed by Equation B11. ***n*** in Equation C1 represents the number of years, since a solar panel is usually guaranteed for 25 years [61] this is chosen as ***n*** for the purpose of this research.

$$\sum_{i=1}^{n} \frac{(Future\ Value)_i}{(1+WACC)^i} \quad \text{[C1]}$$

***WACC*** is the weighted average cost of capital. The equation to calculate WACC is quite complex and since most of the variables are not known for the target location an average of 7.7 % is used and is in line with KPMG's average rate found in their 2013 Cost of Capital Study [72].

A simple payback calculation only takes the invested capital and savings into account. This is not a true reflection of the real picture, maintenance and degradation of the panels that form the solar array need to be added. Other items to consider are carbon taxes and offsets as well as tax incentives. These are briefly discussed in the subsequent sections.

## C.1 CAPITAL

The capital required for the solar array is calculated by taking the average cost per kW as calculated from taking the average pricing from seven different vendors from a recently tendered project at One Zero Consulting (Pty) Ltd. The price included inverters, labour, fixing and sundries. The names of the seven vendors were removed, their final price and system size as well as the cost per kW is given in Table C.1 below [65].

Table C. 1: Vendor prices

| Vendor | Total Cost | System Size (kW) | Cost per kW |
|---|---|---|---|
| 1 | R 3 512 861.27 | 200 | R 17 564.31 |
| 2 | R 4 047 818.91 | 240 | R 16 865.91 |
| 3 | R 4 684 327.08 | 240 | R 19 518.03 |
| 4 | R 4 988 256.00 | 286 | R 17 441.45 |
| 5 | R 4 734 647.54 | 240 | R 19 727.70 |
| 6 | R 4 957 991.00 | 247.2 | R 20 056.60 |
| 7 | R 3 955 187.02 | 226.61 | R 17 453.72 |

## C.2 INFLATION

The average South African Inflation rate for 2014 is 6.1 % as calculated from Statistics South Africa's November 2014 Consumer Price Index Report [73] and is used in the calculations.

## C.3 SOLAR PANEL DEGRADATION AND MAINTENANCE

All solar panels slowly degrade over time. This is usually calculated at 1 % per annum. The chosen Trina solar panel has a more linear degradation and guarantees 80 % output at 25 years, [61]. This results in a degradation of 0.8 % per annum. The equation to calculate a month's solar output after panel degradation is given in Equation C2

$$(Month\ a)_b = Month\ a\ \times (1 - \%degradation)^b \quad \text{.....[C2]}$$

Where

**a = 1 – 12 (January to December)**
**b = 0 – 25 (year 0 to year 25)**
**Month = kWh consumed for month in question**

As discussed, solar panels need to be cleaned, so R 1000 is budgeted per month for this purpose and will form part of the duties of existing cleaning staff. This amount is considered sufficient and based on de Groot et al's research at Villiera wine farm [8]. The farm is equipped with a 131.74 kWp system. It costs R 854,34 to clean the panels three times a year, this amounts to R 6.48 per kWp

## C.4 CARBON TAX AND OFFSETS

The South African National treasury released "The Carbon Tax Policy Paper" in May 2013 for public comment. In the Policy, a tax of R 120 per ton of emitted carbon dioxide effective from January 2015 with a 10 % annual increase is proposed [27]. To ease economic burdens, the treasury has proposed that a 60 % tax free threshold be implemented. This means that the maximum total carbon tax payable will be R 48 per ton. This estimate is used for the payback calculations.

Carbon tax payers can also further reduce the amount of tax payable by increasing their efficiency – this can increase their tax free threshold to 65 %. Carbon emitters whose carbon emissions are unavoidable can also be offered some leniency. In total, carbon users can end up having a maximum combined relief of 90 % of their total usage [31]. Lastly – carbon emitters can also purchase carbon offsets, (or carbon credits), to reduce the amount of tax payable. The

price per carbon offset is not known at this stage, it is unlikely that it will be more than the proposed taxation estimate and is taken to be R 80 per ton, as used by Promethium carbon in their calculations [28].

The amount of carbon dioxide emissions per fuel was discussed in Section 2.3 and amounts to 1.13 kg per kWh. Solar photovoltaics also emit carbon only while they are manufactured, not when they are used to produce electricity. For this reason, and because the data for the carbon emissions from manufacturing machinery required to process non-renewable resources is unavailable, it is believed that it should be left out of the calculation.

The tax payable by the generation of electricity using is coal is calculated using Equations C3 and C4

$$kg_{CO_2} = kWh_{produced} \times 1.13 \frac{kg}{kWh} \quad \text{[C3]}$$

$$Tax_{CO_2} = \left(kg_{CO_2} \times tax\ rate\right) \times (1 + annual\ increase)^b \times (1 + inflation)^b \quad \text{[C4]}$$

Carbon offsets are calculated using Equation C5

$$Offsets_{CO_2} = \left(kg_{produced} \times offset\ rate\right) \times (1 + inflation)^b \quad \text{[C5]}$$

Where

**b = 0 – 25 (year 0 to year 25)**

## C.5 TAX INCENTIVES

In 2009, South Africa began the process of legislating a tax incentive for energy efficiency. In November 2013 – the 12L regulation for the allowance of energy efficiency savings was implemented [68] unfortunately the regulation excludes savings yielded from using renewable energy resources. However, in the regulation, the South African National Energy Development Institute, (SANEDI), has been tasked to appoint suitably qualified people/companies to measure and verify claims. Upon verification – SANEDI will approve the claim and ensure that it complies with the regulations. Claims can be submitted for up to 12 consecutive months and the tax incentive amounts to R 0.45 per approved kWh [30]. This project is still in its infancy so the time taken to submit and approve claims is uncertain. Never the less, $R\ 0.45/_{kWh}$ is used as shown in Equation C6. Though no rebates can be claimed from utilising solar energy as yet, this option is explored to determine its potential impact on the payback period.

$$Tax\ Rebate = \left(kWh_{produced} \times rebate\ rate\right) \times (1 + inflation)^b \quad \text{[C6]}$$

Where

**b = 0 – 25 (year 0 to year 25)**

## C.6 ELECTRICITY PRICE INCREASES

As mentioned, the price of electricity has been drastically increasing since 2008. The National Energy Regulator of South Africa, (NERSA), is responsible for approving Eskom's requests for electricity price increases. These increases are governed by several factors but fixed into a multi-year pricing determination, (MYPD), revenue cycles. Eskom has recently submitted the third MYPD, which will determine electricity price increase for April 2013 – March 2018, to NERSA for approval. The indicative year on year tariff increase average for all categories is summarised in Table C.2 [74] along with NERSA's approved tariffs [75] and the known actual implemented tariffs [69]. The known implemented tariffs are only available up to the current period – 2015/2016.

Table C. 2: Indicative year on year electricity tariff increases

| Year | 2013/2014 | 2014/2015 | 2015/2016 | 2016/2017 | 2017/2018 | Average |
|---|---|---|---|---|---|---|
| Proposed Average Tariff Increase | 16.07 % | 15.95 % | 16.18 % | 15.89 % | 16.04 % | 16.03 % |
| NERSA Approved Tariff | 8 % | 8 % | 8 % | 8 % | 8 % | 8 % |

The reason for the variation in the actual tariff proposed for the 2015/2016 year was released in a statement by NERSA in October 2014 [76] and will be a single deviation from the approved tariffs so that Eskom can recuperate costs for their regulatory clearing account. An average electricity price increase rate of 12.54 % is used to calculate future savings on electricity and is based on Eskom's actual price increases since 2000 shown in Table C.3 [69].

Table C. 3: Actual electricity tariff increases

| Period | Actual increase (%) |
|---|---|
| **2000** | 6.35 |
| **2001** | 4.06 |
| **2002** | 9.00 |
| **2003** | 6.99 |
| **2005** | -0.05 |
| **2006** | 6.26 |
| **2007** | 5.93 |
| **2008** | 8.53 |
| **2009** | 27.39 |
| **2010** | 28.16 |
| **2011** | 26.00 |
| **2012** | 19.96 |
| **2013** | 14.77 |
| **2014** | 12.10 |
| **2015** | 8.78 |
| **Average Price Increase (%)** | 12.54 |

Equations C7 and C8 takes this into account along with the following average tariffs, (from Section 3.5.3).

- $kWh_{AVG} = R\ 0.83$
- $kVA_{AVG} = R\ 159.70$

$$Energy\ Savings_{kWh} = \left(kWh_{produced} \times kWh_{AVG}\right) \times (1 + inflation)^{b} \text{.....[C7]}$$

$$Energy\ Savings_{kVA} = \left(kVA_{saved} \times kVA_{AVG}\right) \times (1 + inflation)^{b} \text{.....[C8]}$$

Since peak demand is billed according to the maximum recorded value each month, only the amount saved is considered. This is equivalent to the maximum recorded value without the solar installation minus the maximum recorded peak demand value with the solar installation.

Note: the amount of power produced from the solar panels per annum degrades but it is assumed that the consumed power will not increase for calculation purposes.

## C.6 FEED-IN TARIFFS

In 2009, NERSA developed the renewable energy feed-in tariff policy, (REFIT), and again revised it in 2011. A summary of the tariff structure for PV for 2009 and 2011 is [66]:

- 2009 – R3.94 / kWh
- 2011 – R 2.31 / kWh

NERSA officially terminated the REFIT policy in favour of the REIPPPP [66]. The effect of these tariffs are explored to investigate the impact on the payback period and Equation C9 is used to calculate the associated savings.

$$ZAR_{feed-in} = (kWh_{saved} \times feed-in\ tariff) \times (1 + inflation)^{b} \quad \text{.....[C6]}$$

Where

**b = 0 – 25 (year 0 to year 25)**

## C.7 FINAL NPV EQUATION

The NPV equation presented by Equation C1 is expanded upon to yield the final equation used in the payback calculation – as shown by Equation C9.

$$\sum_{i}^{n} \frac{(savings\ from\ solar\ output + tax\ benefits + feed-in + carbon\ offsets - maintenance\ costs)_i}{(1+WACC)^i} \quad \text{....[C9]}$$

Where

- **i = 0 – 25 (year 0 to year 25)**
- **n = 25**

# D RESULTS




Figure D. 1: Cumulative NPV for Option 1

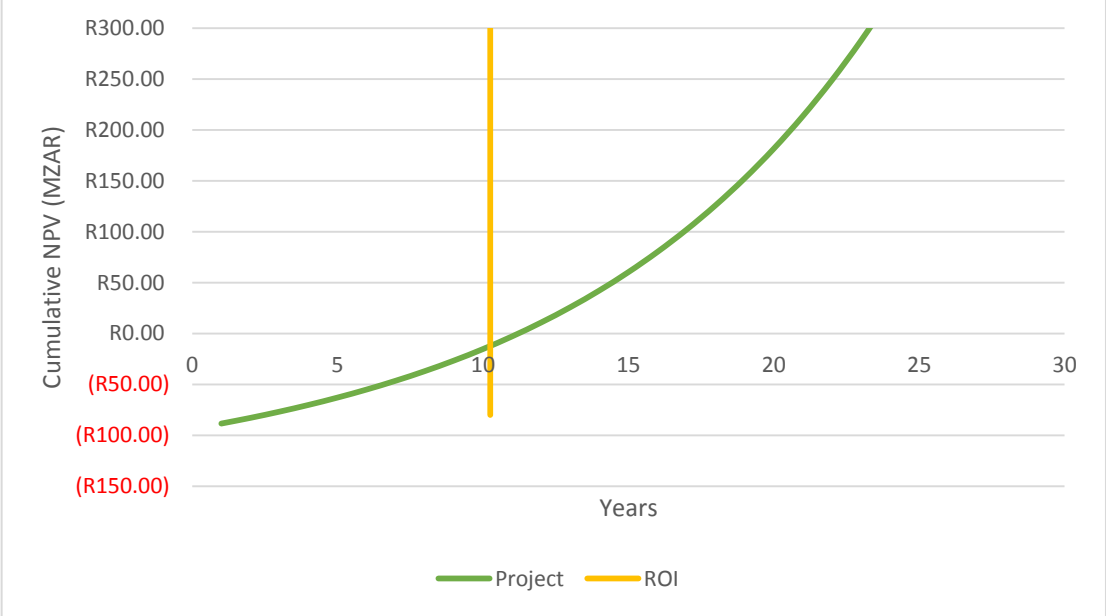



Figure D. 2: Cumulative NPV for Option 2

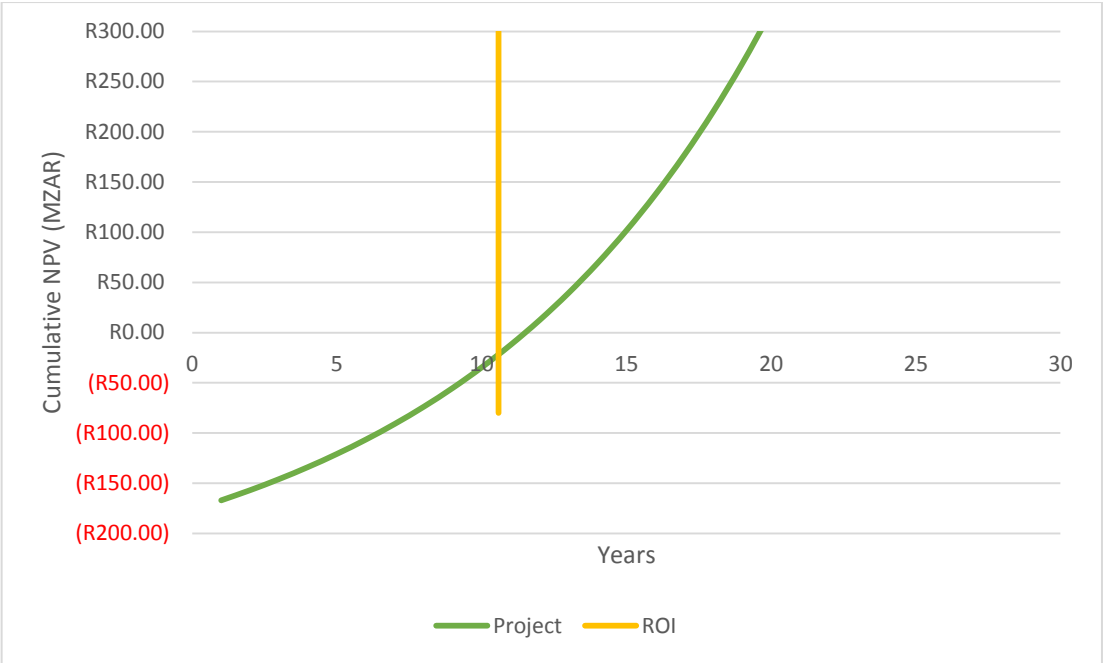


Figure D. 3: Cumulative NPV for Option 3