Residential PV System Design

Design and Implementation of a PV System with a BESS for an RDP House in South Africa

Prepared by:

Tareeq Saley

SLYTAR001

Department of Electrical Engineering
University of Cape Town

Prepared for:

Prof. Paul Barendse

Department of Electrical Engineering
University of Cape Town

November 2020

Submitted to the Department of Electrical Engineering at the University of Cape Town in partial fulfilment of the academic requirements for a Bachelor of Science degree in Mechatronics

Key Words: PV, Power Electronics, MPPT, RDP, Simulink

Declaration

1. I know that plagiarism is wrong. Plagiarism is to use another's work and pretend that it is one's own.
2. I have used the IEEE convention for citation and referencing. Each contribution to, and quotation in, this final year project report from the work(s) of other people, has been attributed and has been cited and referenced.
3. This final year project report is my own work.
4. I have not allowed, and will not allow, anyone to copy my work with the intention of passing it off as their own work or part thereof

Name: **Tareeq Saley**

Signature:

Date: 11 November 2020

Terms of Reference

With the penetration of the sustainable energy, the installation of the renewable energy generators such as the wind turbine and photovoltaic (PV) array has increased drastically during the past decade. One of characteristics of the renewable energy is its intermittence. By adding energy storage units such as batteries or ultra-capacitors to the renewable energy generation system, they have the potential to solve the aforementioned problems. With the increasing penetration of the solar energy and growth in demand for a highly reliable energy supply, the battery energy storage system (BESS) is expected to be used together with the PV inverter to achieve both power generation and self-consumption.

The aim of this project is to develop a power management system for a residential PV inverter with battery energy storage system.

Acknowledgements

I would like to thank my parents for being the backbone and support structure I needed to allow me to see through my undergraduate degree over the last 5 years. They were ever ready to do what was necessary just to make my studies easier. My accomplishments to this date is down to their tireless effort and sacrifice and I am truly blessed to have been raised by them.

Secondly, I would like to thank my mentor and ex-boss, Frederick Trout, for always being willing to assist and advise me throughout my research. As a director of a renewable energy distributor with over 20 years of experience in the solar energy field, he offered critical advice to me when I needed it.

Thirdly, I owe it to my bursar, Toyota South Africa Motors, for lifting the financial burden off my shoulders throughout this year and honouring me with the privilege of being one of their sponsored students. I would also like to thank StudyTrust for managing my entire bursary and offering me added help and mentorship where necessary to alleviate the stresses that came with studying this year, especially given the COVID-19 pandemic.

Fourthly, I would like to thank my supervisor, Prof. Barendse, who was always willing to offer his time to me when I needed assistance. He would go to the extreme to ensure that I fully understood topics that were fuzzy prior to consulting him and left no stone unturned in that respect.

Lastly, I'd like to thank Allah for giving me the strength to pursue this degree regardless of the hardships, barriers and hiccups that came my way. I owe every success, before this and beyond this to Him.

Abstract

This project entails the design, analysis, and implementation of a residential PV system for RDP homes across South Africa. The energy poverty crisis in South Africa has led to many informal settlements relying on cheaper and unsafe energy alternatives to meet their household's power consumption demands. This is because, regardless of the vast amount of coal that South Africa has at its disposal, coal-generated electricity is too expensive for them to consider. Also, the crumbling and outdated power stations have led to South Africa's state-owned power provider, Eskom, needing to lessen the burden on their grid and fast.

This research first goes on to describe the theoretical elements to this project, both in terms of the technology that applies and the socio-economic challenges that warrants its need. Thereafter, the PV system is designed based on estimated energy consumption characteristics of low-income households. The respective components necessary to design this system is then sized according to the household's energy needs. The process behind the designs engineering implementation relative to the electrical circuitry in the household is then discussed. This is followed by a detailed cost-analysis which weighs up the feasibility of the designs implementation, given tariff rate increases and low-income household electricity expenditure. The designed system is then validated through modelling it from first principles and simulating it in Matlab Simulink.

The results of this research suggest that, at least in simulation, the designed system can meet the household load demands whilst achieving good control across its components. The system's components also compliment each other and are sized well enough to cater for the system's needs.

As achievable as this project seemed through simulation and as feasible as its implementation seemed through the cost-analysis, the likelihood of it being realized is slim. This is because of South Africa's hesitancy to invest in solar power and because of the deep-rooted economic crisis that the country faces.

Table of Contents

1. Introduction

1.1 Background to the study

South Africa is a country that is deeply affected by an electricity supply crisis. The country's over reliance on non-renewable energy as a means of power generation has resulted in a lack of production of resources therein and an inability to guarantee uninterrupted power supply to the country. The demand is far greater than the supply and the corruption and mismanagement that has plagued the state-owned electricity firm, Eskom, are to blame for this. Neglecting its infrastructure has led to the outdated power plants running at the upper limits of their capacity and a problem with any of them causes a blackout. The consequences of these power cuts have led to the population suffering from these power cuts; closed shops are not good for an economy that's already grappling with recession, congestion is worse because the traffic lights don't work, and the crime rates are in the rise because alarm and security systems shut down [1]. Given the power conundrum our country is facing, choosing to use the Earths renewable sources as a means of generating power will potentially aid in compensating for the power shortfall that leads to these blackouts.

This research therefore explores the development of PV systems for residential properties and assesses the feasibility of its realization on a large scale in South Africa.

1.2 Objectives of this study

1.2.1 Problems to be investigated

Greater reliance on an alternative source as a means of generating power needs to be considered to lessen the load on the Eskom grid. There is also a severe poverty and unemployment challenge that the government needs to try to overcome. Illegal power connections in respect of those challenges has been costing Eskom millions of rands. The government needs to find a solution that will allow for incentivized offerings to people who are willing to consider individual means of electricity generation over grid-produced electricity, whilst ensuring that they're also able to cut all unwarranted expenses that Eskom might incur. Eskom requires both a lesser load and the necessary financial resources in order for them to be afforded the chance to upgrade, maintain and develop their old power plants whilst still ensuring that the country receives uninterrupted power supply in the interim.

The question worth asking is whether the implementation of renewable energy as a means of power generation across South Africa, and particularly for low-income households, will benefit Eskom in this regard.

1.2.2 Purpose of the study

83% of South Africa's primary electricity needs are provided by coal [2]. The rest of the world, in comparison, has coal accounting for 36% of their electricity production [3]. The problem with this, however, is not South Africa's lack of coal reserves and the risk of coal running out anytime soon; rather it is South Africa's over-reliance on coal as a means of energy production. The residential sector's energy demands amount to 8% of the total energy demands of the country. Since coal is responsible for 76% of these energy demands, this means that 6% of South Africa's coal-related energy demands are from residential properties. The need for South African households to make the switch to solar or other forms of renewable energy powered electricity generation is now greater than ever before.

30.1% of South Africans are unemployed according to BusinessTech [4]. According to another BusinessTech publication, 55.5% of the population lives below the upper-bound poverty line, which is currently at R1,227 per person per month. The typical energy expenses of a low-income household amounts to about R600 monthly [5]. Some of these people have been fortunate enough to be offered Reconstruction and Development Programme households by the government. By offering PV system solutions to these RDP households, not only will the burden on the grid be lessened, albeit slightly, but it will allow for those household's inhabitants to be afforded the chance to sell any surplus electricity produced back to the grid. This will allow for these inhabitants, who are obviously poor, to earn a passive income in the process thereby bridging the inequality gap in this country even further. The idea of having electricity fed back onto the grid is no longer as far-fetched as it previously seemed. The Western Cape Government has already developed a Small-Scale Embedded Generation programme which allows for solar PV systems to be grid-tied and feed in any excess electricity generated. Many municipalities already have the rules and tariffs in place for this and the remaining municipalities are being supported by the Western Cape Government and GreenCape [6].

The purpose of this research is therefore to design a photovoltaic system for a Reconstruction and Development Programme household. An attempt will also be made to analyse the feasibility of its implementation in respect of compensating for the power supply shortage that our country faces together with lowering the country's poverty rate.

1.3 Scope and Limitations

This research is purely simulation based and no actual attempt at physically implementing the design was made. The data gathered in respect of the load profiles of RDP houses is based on an estimation rather than fact because of a lack of resources in that regard. Due to the covid-19 pandemic, no attempt was made at reaching out to inhabitants of these households to source their load profiles and energy expenditure budget.

1.4 Plan of development

Chapter 1: Introduction
Chapter 2: Literature Review
Chapter 3: PV System Design
Chapter 4: Design Process
Chapter 5: Cost Analysis
Chapter 6: Modelling and Simulations
Chapter 7: Results & Discussion
Chapter 8: Conclusions
Chapter 9: Recommendations
Chapter 10: List of References
Chapter 11: Appendices
Chapter 12: Table of Figures
Chapter 13: EBE Forms

2. Literature Review

2.1 Sustainable energy as a means of power generation

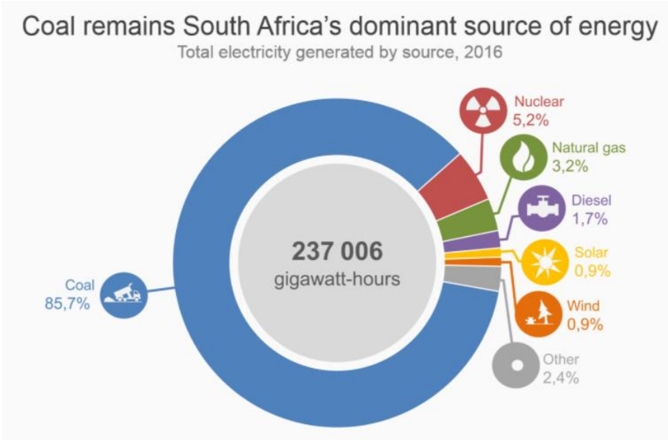


Figure 1: Energy source breakdown in South Africa

In the above diagram [7], Stats SA offers a breakdown of the sources of energy that dominate South Africa. Expectedly, because of the vast reserves in coal and the amount of coal-driven power stations in the country, coal is overwhelmingly the largest contributor to the energy sector. The need for a strong alternative or secondary source of energy has been elaborated in the introduction. However, there is very little emphasis on sustainable energy as a means of electricity generation at present according to figure 1, but in his budget vote speech of 11 July 2019, Minister of Mineral Resources and Energy Gwede Mantashe put nuclear energy firmly back on the table [8].

This can be taken with a pinch of salt, however. In 2007, under President Thabo Mbeki, Eskom announced plans to double its generating capacity to 80-gigawatt electrical (GWe) by 2025, including 20GWe of new nuclear capacity. This would raise nuclear energy's contribution to electricity generation from 5% to more than 25%, while slashing that of coal from 87% to below 70% [8]. Yet, it's 2020 and the country's nuclear energy generation hasn't increased beyond the 5% mark [9]. This is not a surprise as the consistent corruption in the state-owned enterprise has caused for the project to be numerously halted due to a lack of funds [8]. As of October 2019, the government's intention to focus on nuclear energy has still been strong and it has outlined plans to build 1 GW of new nuclear capacity by 2030, and to extend the operating lifetime of its existing plant by 20 years [9]. However, that does not take away from the fact that South Africa's energy sector is in crisis and will remain in that position for the foreseeable future.

That leaves us with having to evaluate the other sources of sustainable energy in the interim, specifically, sources that will not necessarily have consumers reliant on Eskom as a provider for this means of energy. Wind energy in South Africa has a fair potential; however, it will only thrive in areas that have strong and steady winds. This means that it will be a good alternative only along the coastal areas of Western and Eastern Cape. Since RDP houses are spread across the continent, and since the unpredictability in wind power generation will most likely impact some or most of those places, it is not as good an alternative worth considering. Also, the lack of flexibility of wind power plants means that there is no guarantee that wind energy can be supplied to all areas in South Africa that consist of RDP houses.

Solar energy does not have as much of the drawbacks related to wind energy in terms of flexibility and unpredictability. It also does not have moving parts which would add to maintenance costs and has a relatively cheaper installation price generally. This makes it a better choice overall for small scale power generation [10].

In terms of solar power accessibility within South Africa most areas in South Africa average more than 2 500 hours of sunshine per year, and average solar-radiation levels range between 4.5 and 6.5kWh/m2 in one day. The southern African region, and in fact the whole of Africa, has sunshine all year round. The annual 24-hour global solar radiation average is about 220 W/m2 for South Africa, compared with about 150 W/m2 for parts of the USA, and about 100 W/m2 for Europe and the United Kingdom. This makes South Africa's local resource one of the highest in the world. The use of solar energy is the most readily accessible resource in South Africa. It lends itself to several potential uses and the country's solar-equipment industry is developing. Annual photovoltaic (PV) panel-assembly capacity totals 5MW, and a number of companies in South Africa manufacture solar water-heaters [11].

2.2 Environmental Benefits of Solar Energy

2.2.1 Reduction in Water Usage

Given that PV systems are most efficient in some of the driest places across the country, having power generated through them as opposed to fossil fuels is crucial.

To put this into perspective, the Koeberg nuclear power station, located near Cape Town, used about 1,3 Ml of fresh water per day in 2018 [12]. This was especially concerning given that just two years ago Cape Town had been experiencing its worst drought since 1904. Water is used in the power station for cooling generators, processing and refining fuel and transporting fuel through pipes [13].

By shifting towards solar energy as a means of power generation, no water is used whatsoever in generating power through solar panels. The operation of solar photovoltaic cells does not require water at all to generate electricity, reducing the strain on this precious resource [13]. The only water necessary for its maintenance is the rainwater necessary for cleaning the panels when they get dirty.

2.2.2 Reduction in Air Pollution

The quality of the air that we breathe plays a huge impact on our health. Harmful carbon dioxide and methane gases are released into the atmosphere through the generation of electricity using fossil fuels.

Amongst some of the sicknesses that are associated with air pollution are asthma and allergies, bronchitis, pneumonia, headaches, anxiety, heart attacks and even some cancers. By using the sun to generate electricity, there are far less harmful emissions released into the air compared to burning fossil fuels [13].

2.2.3 Helps to Slow Climate Change

Air pollution is not the only consequence of greenhouse gases released into the atmosphere; these gases also play a detrimental role on climate change by enhancing greenhouse effects. The greenhouse effect is a natural process which allows the Earth temperature to rise to a liveable temperature, however, burning fossil fuels has enhanced this effect to the point where temperatures are increasing faster than ever before.

Catastrophic weather events such as flooding, cyclones, storms, extreme heat, and drought have all been linked to this. In contrast, none of these effects are caused by the generation of electricity through solar panels because solar panels produce no greenhouse gases whatsoever [13]. If implemented on a large scale, this will have a huge impact on South Africa's fight against climate change especially considering that it is the 13th largest emitter of carbon dioxide emissions globally [14].

2.2.4 Less Reliance on Fossil Fuels

Solar energy supplies are massive; if all the sunlight shining on the earth could be harnessed for just one hour, the entire world could be powered for a whole year using that energy. There is no cost related to the sunshine needed to provide power, and there's abundant power in that respect. On the other hand, the possibility of fossil fuels running out increases yearly. Lesser reliance on those finite resources and switching to renewable energy instead could lead to cheaper electricity, reduced greenhouse gas emissions and a stronger, more stable energy future [13]. This is especially considering that the price of solar PV (photovoltaic) panels dropping by more than 10% per year, and Eskom seeking double digit increases for the foreseeable future [15].

2.3 Reconstruction and Development Programme Houses

2.3.1 Energy Poverty in South Africa

"Meeting South Africa's household energy needs is not just about having access to the grid, or a suite of renewable technologies on hand. It requires tackling the roots of poverty in one of the most unequal societies in the world", writes Leonie Joubert, a science writer and journalist for Energy Transition [16].

Massive progress has been made by the government to electrify households across South Africa. To put this into numbers, only 37% of households had access to electricity in 1994 and that has increased to 87% 20 years later in the year 2014 [17]. However, energy poverty is a lot more complicated than that. According to Sustainable Energy Africa, a household is considered as energy poor when a household spends 10% or more of its income on energy, this was confirmed by the approach used by the South African Department of Energy to determine household energy-poverty [18].

The Department of Energy, using this approach in 2012, found that on average, South Africans spend 14% of their total monthly household income on domestic energy needs. Thus, 47% of South Africans households were found to be energy poor as they spend more than 10% of their income on domestic energy needs [19].

Furthermore, by considering another Sustainable Energy Africa report based on a Mthenthe Survey, it states that the energy burden per household in the low-income category (assuming highest monthly household income – R3 200 – and average consumption of R364/month) would be around 15%. Of course, many low-income households would have an income lower than this upper end of the low-income bracket, rendering that burden greater [20].

2.3.2 Typical 2-Bedroomed RDP House

To fairly analyse the energy consumption usage of RDP houses, a standard RDP house that can cater for a family of four is considered. A set of existing RDP houses such as this is shown below [21].

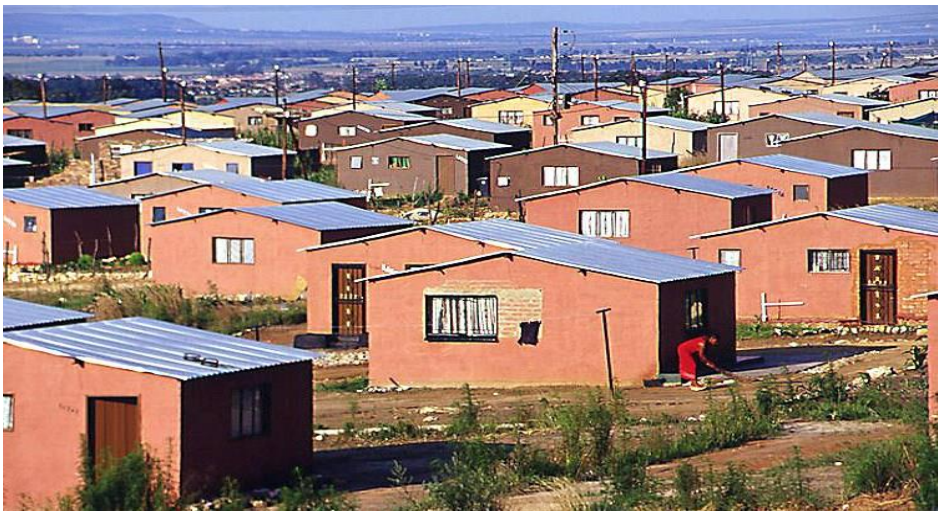


Figure 2: Typical RDP houses in South Africa

To understand how PV systems can be implemented in these households, the roof sizing and general structure of the household needs to be considered. An engineering drawing for RDP households is illustrated in figure 3 below [22].

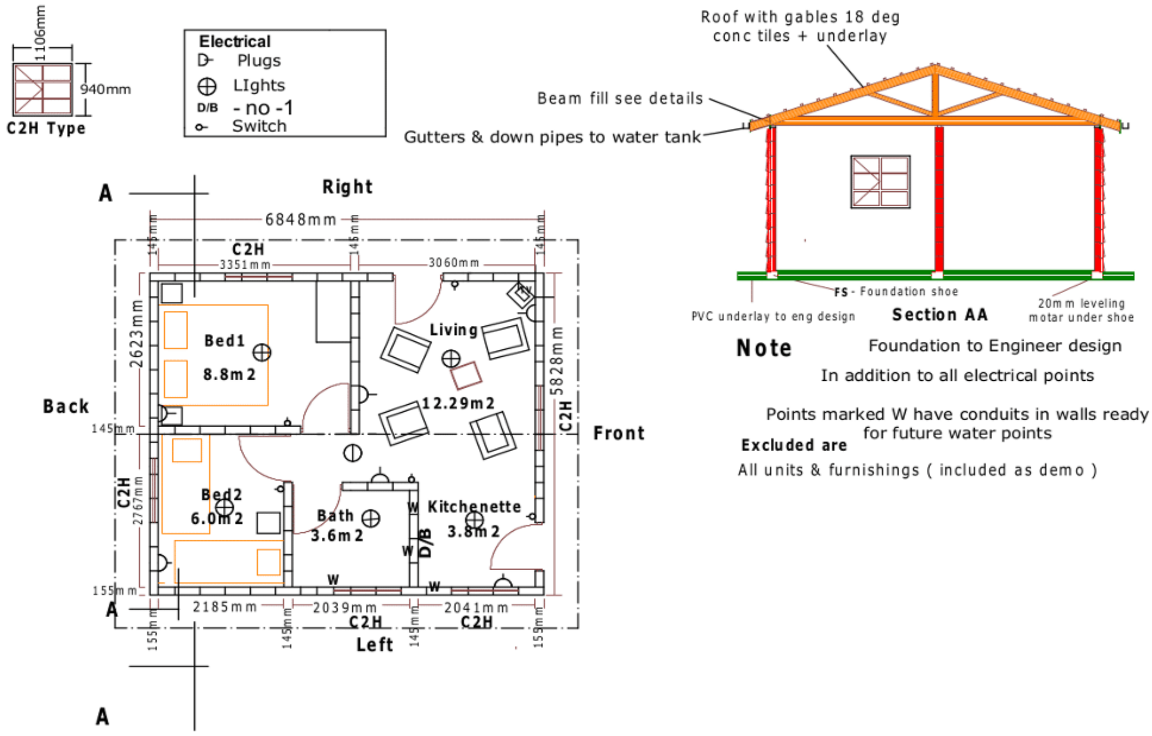


Figure 3: Electrical drawing for a proposed RDP household

Based on the ideal roof structure shown in figure 3, a roof-mounted design will be suited for this intended purpose.

2.3.3 Sources of Energy for RDP Houses

The complex poverty dynamics in South Africa has led to low-income households resorting to cheaper forms of energy because they cannot afford to buy enough electricity. Most of the forms of energy and fuels that they turn to are unsafe. Common fuels include coal, wood, paraffin, and candles. The term used to describe the pattern of fuel usage for low-income households is 'Multiple Fuel Use'. Figure 2 below, originally sourced from the Department of Energy in 2013, illustrates the prevalence of MFU in low-income households in South Africa, even when electricity is present [23].

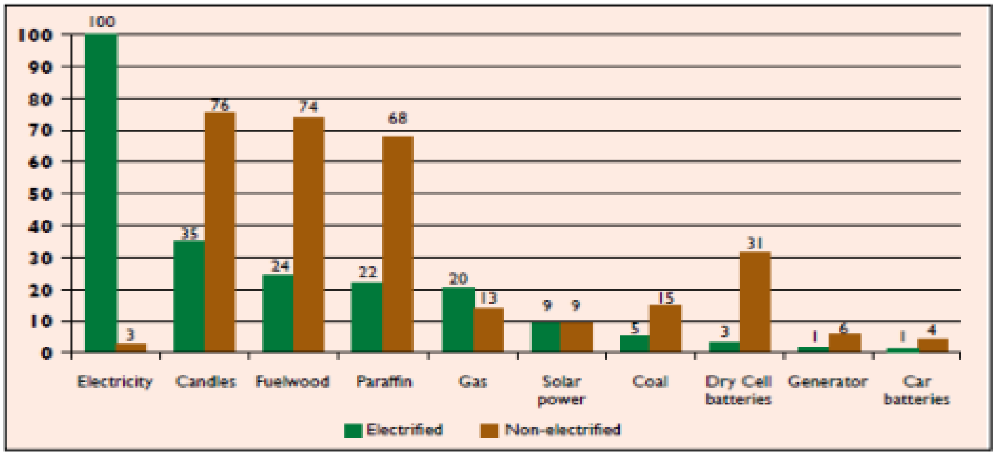
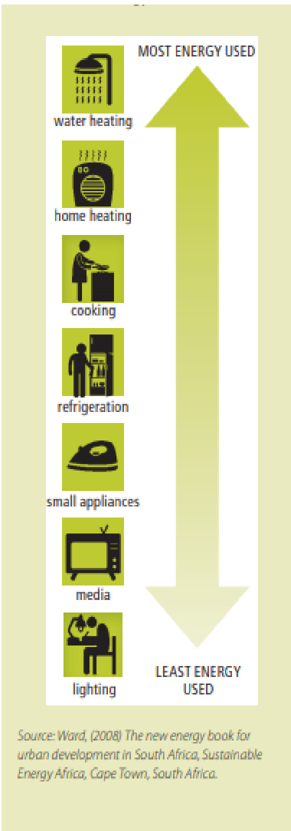


Figure 4: Graph displaying the multiple fuels used by electrifying and non-electrifying low-income households in South Africa

The energy patterns related to the applications of these fuels within the household is given in figure 5 below [24].



	High – mid income households with electricity	Low income households with electricity (formal & informal)	Low income households without electricity
Lighting	Use electric lightbulbs e.g. incandescent, LED	Use electric lightbulbs – low penetration of energy efficient lightbulbs, paraffin lamp or candles	Use candles, paraffin lamps
Cooking	Mostly use electrical appliances; hot plates, microwaves, ovens. A small percentage use gas cook stoves.	Combine electric appliances with paraffin, gas, wood and coal appliances	Mostly use paraffin and wood appliances with coal, gas sometimes used when available
Water heating	Mostly either use electric or solar water geysers	With installation of SWH these are used or they use electric stoves or kettles	Generally use cooking stoves for heating water
Space heating	Most households have ceilings but also use either electrical or gas heaters	Generally use electrical appliances or they use paraffin heaters or coal/wood mbawula	Generally they do not use anything any fuels otherwise they use paraffin stoves/ heaters, wood/ coal mbawula

Figure 5: Energy usage relative to household purpose in low-income households

As can be seen above, these households use the most amount of energy on water heating. This water is either heated up by SWH systems for households that have those installed, but by electric appliances otherwise. This carries the greatest burden on their electricity expenditure. These households can find fuel alternatives for lighting, cooking and space heating, with the latter two purposes also contributing significantly towards their electricity expenditure.

2.3.4 Energy Usage and in RDP Houses

This subsection will further elaborate on the household appliances that are commonly found in low-income households. It will then assess the respective shares that each energy source contributes towards fulfilling the households purposes. This is reflected in the two tables below [20].

Appliance Ownership	
Appliance	*%*
Cell-Phone	99%
Television	96%
Radio	65%
Dishwasher	58%
Microwave	58%
Electric Stove	46%
Fan	32%
Washing Machine	26%
Oven	1%

Table 1: Table of appliance ownership % amongst low income households

Energy Contributions	
Purpose	*Fuel Contributions*
Lighting	72% tungsten bulbs, 28% CFL; only one hh used paraffin for lighting
Cooking	97% electric, 2% paraffin,1% gas
Space Heating	Electric heaters (35%), blankets, warm clothing (42%), paraffin (19%); firewood 2%, gas (1%)
Water Heating	42% elec geyser, 42% kettle, 13% pot on hotplate, 3% paraffin

Table 2: Energy contributions by fuel sources towards household purposes

From amongst the appliances given in table 1, some of those that most heavily affect the electricity bills of these households can be deduced from table 2. These appliances are the microwave/electric stove/hotplate, which is electricity operated in 97% of households for cooking and in 13% of them for water heating, the electric kettle which 42% of households use for water heating, and finally the electric heater which 35% of households use for space heating. The percentage of low-income households that own electric heaters has, however, not been accounted for in Table 1.

2.4 Fundamentals of PV Technology

2.4.1 PV Cell

A photovoltaic (PV) cell is a technology used for energy harvesting. Through a process called the photovoltaic effect it can convert solar energy into useful electricity. There are several different types of PV cells which all use semiconductors to interact with incoming photons from the Sun in order to generate an electric current [25].

Layers of a PV Cell

There are several layers that make up a PV cell, each with a purpose. The specially treated semiconductor layer, that compromises of two distinct sublayers (n-type and p-type) is responsible for the photovoltaic effect mentioned above. The electricity produced by this semiconductor is then collected by conducting material on either side of it. The rear side or shaded side of the cell can operate whilst being completely covered in the conductor, however, the front or illuminated side must use the conductors sparingly to avoid blocking too much of the Sun's radiation from reaching the semiconductor. Finally, an anti-reflection coating layer is applied to the illuminated side. This layer is used to reduce the losses associated with radiation reflecting off the surface of the cell since all semiconductors are reflective in nature. Figure 7 highlights the basic operation of a PV cell [25].

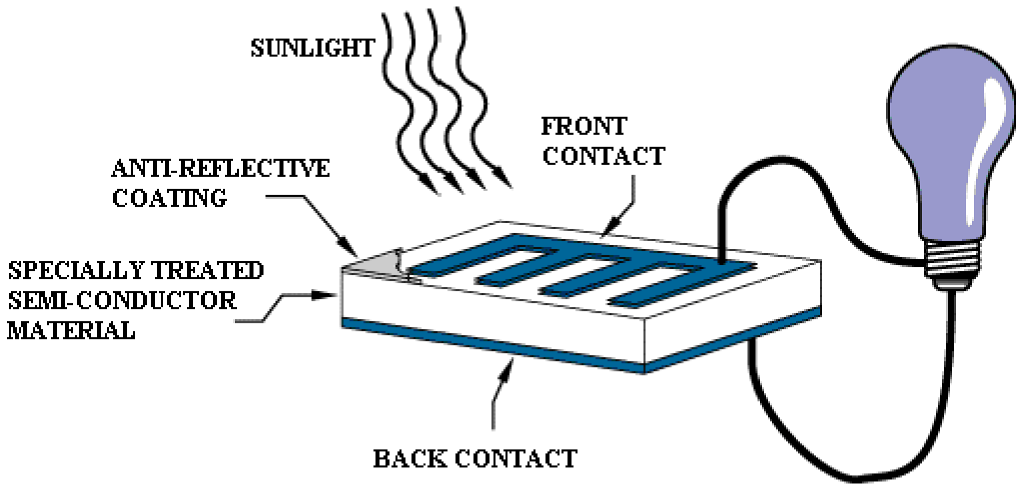


Figure 7: Basic operation of a PV cell

Types of PV Cells

There are a variety of materials that can be used for the manufacturing of photovoltaic cells. The most common commercially used material for construction is Silicone (Si). Other materials include Gallium Arsenide (GaAs), Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS) [25].

These cells can be produced from both brittle crystalline structures such as Si and GaAs as well as flexible thin films such as Si, CdTe and CIGS. Crystalline solar cells can be further classified into two categories—monocrystalline and polycrystalline. Monocrystalline PV cells are comprised of a uniform or single crystal lattice, whereas polycrystalline cells contain different or varied crystal structures [25].

Even though most commercial solar cells only have a single 'p-n junction' layer, multi-layer p-n junction cells have been developed and offer greater efficiency at a higher cost.

PV Cell Efficiency

There are many factors that affect PV cell efficiency, making it a huge design concern. The most important concern is that a quarter of the solar energy that the Earth receives cannot be converted into electricity by a semiconductor [25].

The band-gap energy is defined as the minimum photon energy required to knock an electron of a crystal structure. If a photons energy is less than the band-gap, it is absorbed as thermal energy. The energy in the photons of the sun covers a wide array of values, therefore some of the incoming energy does not have sufficient energy to remove an electron from a silicon PV cell. If the photons energy is higher than that of the band-gap, it is converted to heat energy and isn't useful for electricity production [25].

Even when some of the electrons are made available through the photovoltaic effect process, not all of them will make it to the metal contact to generate electricity. This is because some of them will not be accelerated sufficiently by the voltage inside the semiconductor [25].

The above reasons have led to the theoretical efficiency of silicon PV cells to be about 33% [25].

The efficiency of PV cells can, however, be increased through using a more efficient semiconducting material such as Gallium Arsenide, adding additional layers or p-n junctions to the cell, increasing the purity of the semiconductor, or by concentrating the sun's energy using concentrated photovoltaics. On the other hand, PV cells will also degrade due to a variety of factors including UV exposure and weather cycles causing them to output less energy over time [25].

2.4.2 PV Module

The output provided by a single solar cell, which is around 0.1 watts to 2 watts, is not enough to be considered as useful. Therefore, the power output levels of PV systems can be increased by connecting a few cells in series to provide the required power and voltage outputs. This combination of solar cells is referred to as a PV module or solar module. Solar modules are the basic building blocks of a solar electric power generation system [26].

The solar cells of a solar module are connected in the same fashion as the battery cell units in a battery bank system. This means that the positive terminal of one cell is connected to the negative terminal of the next. The total voltage of the module is then the sum of the voltages of the connected cells [26].

Ratings of PV Modules

The output provided by PV modules is dependent on two factors: intensity of incidence light and ambient temperature. The rating of a PV module must then be specified under such set conditions. It is common practice to express the rating of the PV or solar module at a temperature of 25°C and 1000 w/m^2 light radiation. The outputs that are measured are the open circuit voltage (Voc), short circuit current (Isc) and peak power (Wp) [26].

These conditions, however, merely test the modules to determine their operational abilities and output capacities. Conditions at the respective sites of installation differ from these since solar radiations and temperature vary with location and time [26].

IV Characteristics of PV Modules

By taking the x-axis as voltage and the y-axis as current, the following graph can represent the V-I characteristics of a solar module. The knee of the curve indicates the operating condition in which the current and voltage result in maximum power point (MPP). The voltage and current values at MPP are referred to as "Vmpp" and "Impp," respectively. This graph is given below [27].

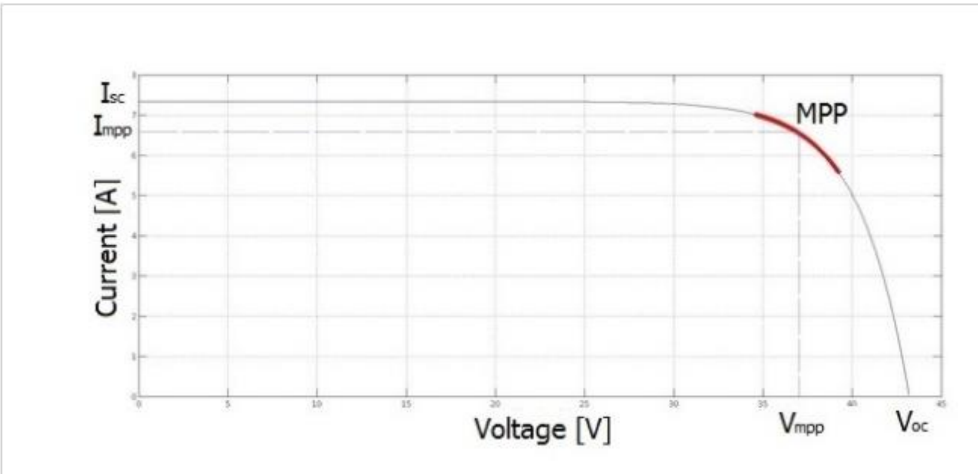


Figure 8: IV Characteristics of a PV Module

2.4.3 PV Array

To further increase the power delivered to the PV system, PV modules are connected in series or parallel resulting it what is called a PV array. In series connections, the voltage of the system with each connected module increases whilst the current equals to that of a single module. In a parallel configuration, the current increases with each connected module and the voltage remains constant. In both cases, the power delivered to the system equals to the product of the power of each module and the number of modules in the system. The array configuration (i.e. the number of modules connected in series or parallel) is dictated by the required system voltage. The peak reverse voltage that a module can withstand also governs the number of series connected modules in an array [28].

The parameters of an array are the same as that of a single cell or single module. The only difference is in their magnitudes.

The input to configuring an array is the final required system voltage. For example, if the load is a 24V DC pump, only two modules are to be connected in series to produce 24V nominal outputs. Strings of two modules connected in series can further be connected in parallel to obtain the required power levels. The figure below is the suggestive array configuration for a 24V DC system [28].

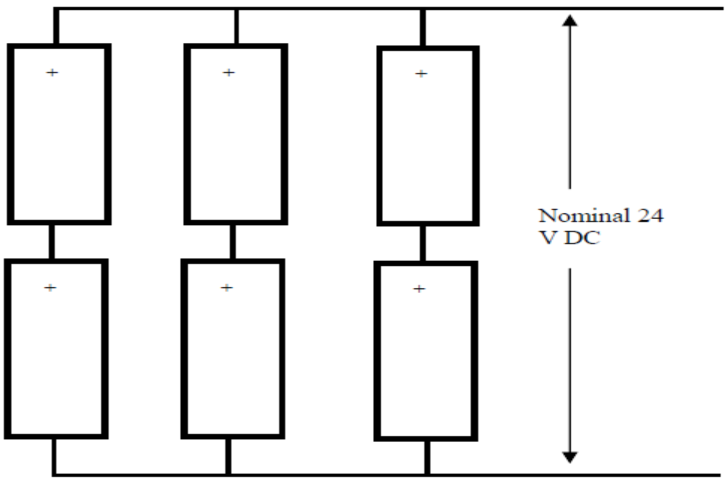


Figure 9: Example of an array configured for 24V DC applications

There are two ways that arrays can be configured for the voltage of the system to match that of the battery bank. The first is a parallel-series configuration which has the modules connected in parallel to produce a string and then the strings connected in series to produce the nominal output voltage. In the second case, the series-parallel case, four modules are first connected in series to make a string and finally four of these strings are further connected in parallel to obtain required power level [28].

The first method has the drawback of needing to reconfigure the entire system if one string is removed for any reason, leading to no power being supplied to the load. This makes the second method the preferred approach. This is illustrated in figure 10 below [28].

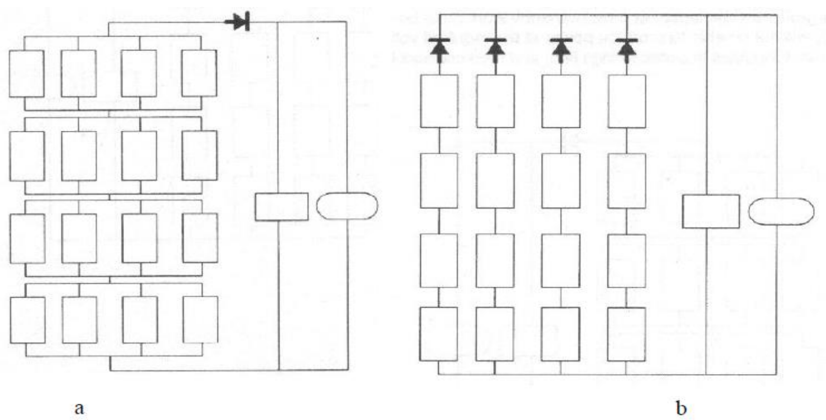


Figure 10: Methods of configuring an array (a) parallel-series (b) series-parallel

If one of the strings, in the case of figure 9(b), had to experience severe shading or one of the modules are short circuited through damage, an isolation diode connected in each string will prevent the system from losing current backwards down the shaded or damaged string [28].

2.5 Components of PV Systems

2.5.1 Battery

Types of Batteries

In the case of home energy storage, there are 3 chemical compositions that contribute towards the construction of a battery: lead acid, lithium-ion, and saltwater. Lithium-ion batteries are generally the best option to choose, but the other battery types are more affordable.

Lead Acid Batteries

Lead acid batteries have always been the preferred choice of batteries for off-grid PV systems. The downside to these batteries is that they have a relatively short life and a lower DoD than other battery types. However, they are the most cost-effective option for home energy storage and are ideal for homeowners looking to become independent of the grid and who require a substantial amount of storage as a consequence [29].

Lithium-ion Batteries

Newer energy storage technologies mainly consist of batteries that involve some sort of lithium-ion chemical composition. These batteries, when compared to their lead acid counterparts, are much lighter and more compact. They also have a longer lifespan and higher DoD. This is, however, at the expense of them being much more costly [29].

Saltwater Batteries

The saltwater battery is a relative newcomer in the home energy industry. Saltwater batteries rely on electrolytes instead of heavy metals such as those used in other home energy storage options. The batteries that use heavy metals need to be disposed of through special processes whereas a saltwater battery can be easily recycled. As a new technology, however, saltwater batteries remain untested. Their rise to prominence is also questionable since the company that produces them for home use filed for bankruptcy in 2017 [29].

Choosing Between Battery Options

There are various specifications to commercial batteries that need to be considered during the PV design process. Some of the most important ones are the battery's capacity & power ratings, depth of discharge (DoD), round-trip efficiency and warranty [29].

Capacity relates to the amount of electricity the battery can store. Most batteries are stackable meaning that multiple batteries can be used for extra capacity as per the design requirements. The power rating of the battery is an indicator of how much of that stored electricity can be provided by the battery at any given moment [29].

To maintain the solar batteries life span, they always need to retain some of their charge because of their chemical composition. The depth of discharge (DoD) of a battery refers to the amount of a battery's capacity that has been used. A higher DoD will therefore mean that more of the batteries capacity can be utilized [29].

The round-trip efficiency of a battery refers to the amount of battery energy that can be used relative to the amount that was stored. A higher round-trip efficiency percentage implies that more economic value can be achieved from the battery [29].

Most batteries will cycle daily leading to their ability to hold a charge decreasing with each charge. Solar batteries usually carry a warranty that stipulates a certain number of cycles or years of useful life. Manufacturers will also guarantee a certain amount of capacity that the battery will be able to carry over the course of the warranty [29].

2.5.2 Charge Controller

A solar charge controller receives power generated by the panels and manages the voltage going into the battery storage. Its primary purpose is to serve as a regulator by ensuring that the deep cycle batteries do not overcharge during the day when solar power generation is at its peak. It also protects the batteries from any electrical overload in the case where the panels produce more voltage than the battery can handle. This is especially important to prevent the battery from degrading too quickly, overheating and possibly becoming a fire hazard. An illustration of the way it operates its given in figure 11 below [30].

Figure 11: Operation of a solar charge controller

There are two main types of solar charge controllers: MPPT controllers and PWM controllers.

PWM Charge Controller
A PWM controller holds the battery voltage to a safe maximum until the battery is fully charged. Once the battery is fully charged, the controller will drop the voltage and trickle the charge such that the battery will remain topped up. It is the more affordable option but is less flexible in terms of expandability and limited for growth [30]. PWM controllers are best suited for smaller systems with low voltage panels and a small battery.

MPPT Charge Controller
These controllers can measure the voltage at maximum power of the battery and step it down to the battery voltage, making them more sophisticated. Larger systems that require matching panel and battery voltages are better equipped with these controllers as opposed to PWM controllers. Apart from this, MPPT controllers also offer reduced power loss, meaning that the voltage running through the cables is higher which leads to a higher number of Amps [30].

These charge controllers have an excellent efficiency ranging between 93% and 97%. This leads to a power gain of 20%-45% in winter and around 10%-15% in winter depending on factors such as temperature, weather, and battery state. They are, however, more expensive and greater in physical size than PWM controllers [30].

2.5.3 DC-AC Inverter

An inverter essentially acts like the brain of the system in that it is responsible for converting the DC voltage produced by the panels into AC voltage at a certain desired magnitude and frequency. Its usage in solar systems specifically relates to powering up household appliances/devices that require an AC source.

The basic idea behind DC-AC conversion is to turn ON and OFF the DC supply voltage (e.g. 12 V) at a regular interval (as governed by the frequency of the required AC signal; e.g. 50 Hz) and boost the magnitude of switched voltage to a required level (e.g. 220V). The graphical representations shown in figure 12 below illustrate the basic principle of the conversion.

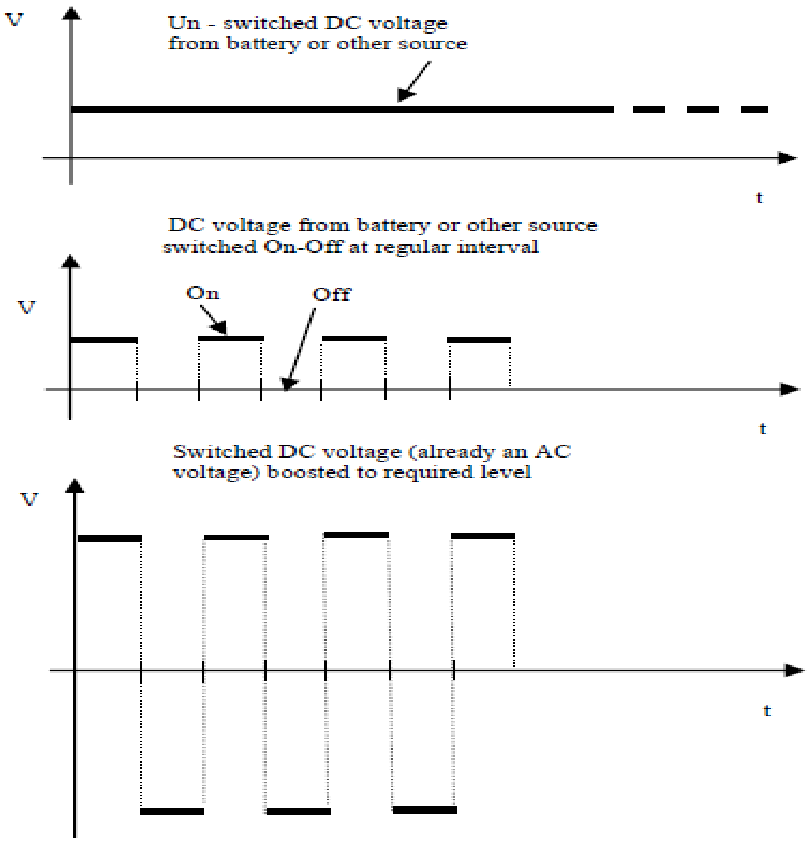


Figure 12: Basic principles of DC-AC conversion

Inverter Topologies

There are 3 main branches of PV system topologies in relation to the inverters used for them based on the systems architecture. These are described as the central inverter topology, string inverter topology and microinverter topology. A diagram illustrating these topologies is given below [31]:

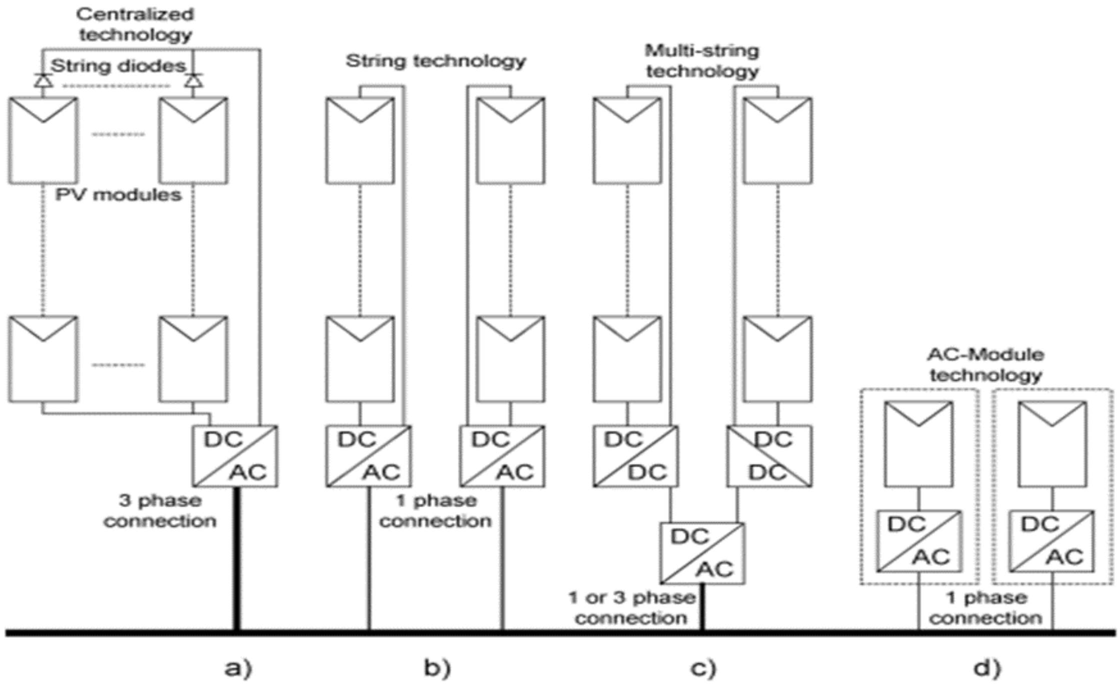


Figure 13: Diagram representing different inverter topologies

Central Inverter Topology

Central inverter systems consist of several panels connected in series to form strings. By using string diode, these strings are then connected in parallel thereby forming a larger system. Robustness, ease of structure and convenience in operation make this topology a preferred choice for larger systems. Its downfalls, however, include a low power factor, lack of flexibility, and the absence of MPPT for each module. This means that partial shading/clouding to some modules would affect the overall system, reducing efficiency drastically [32].

String Inverter Topology

The string inverter topology manages to partially overcome the limitation of the centralized inverter topology. Several panels are connected in series to form a string. AC power is fed to this string by attaching an inverter to it. Since each inverter is connected to a single string of panels, the power rating of these inverters is much lower than that of a centralized inverter. Each string also has its own MPPT attached to it allowing for more accurate power point tracking than the centralized inverter system, therefore reducing the effects of partial shading/clouding [32].

Micro-inverter Topology

The drawbacks of the centralized and string inverter topologies are overcome by the development of the micro-inverter topology. This topology makes use of module integrated inverters allowing for each module to have its own inverter and MPPT system. These inverters can supply power directly back to the grid. This topology does well in reducing the shading/clouding effects on the system. This is because only the module/modules that experience the partial shading/clouding have their performance(s) affected by it with the rest of the modules not being affected at all [32].

The following table analyses the inverter topologies and compares them in terms of effect of shading, cost, losses, efficiency, reliability, total energy harvesting and some other aspects [32].

Parameters	Central inverter	String / multi string inverter	Microinverter
Phases	3 phase	1 phase /3 phase	1 phase
Energy harvesting	Less	More than central	Greater than both
Shading effect	Shading on one module affect overall performance	Shading on one module affect performance of modules connected to that string	Shading on one module affect performance of only that module
Rating	High (>2kW)	Medium(upto 2 kW)	Low (upto 400 W)
Scale	Large scale	Medium /large scale	Small scale
Installation cost	Low	More than central	Higher than both
Maintenance cost	High	Less than central	Very low
Efficiency	Average	More than central	Greater than both
Inverter arrangement	Single inverter for all modules (plant oriented)	Inverter attached to each string	Inverter attached to each module

Table 2: Table of comparison of inverter topologies

Residential properties would not need to make use of the centralized inverter topology, as this is suited for three phase systems whereas a residential property would require a single-phase system. The requirements for this design relate to producing relatively inexpensive packages to a significant number of residential properties in RDP houses. This means that cost is much more of a contributory factor behind choosing the topology than efficiency. The Solar Advice website makes mention of the modern string inverter has been improving over the years making it the most cost effective [33].

2.5.4 DC-DC Converter

Typical output voltages of PV panels are around 30V, which is far too low to be converted to AC and be fed back to the grid. Therefore, before the DC current is fed to the inverter, DC-DC conversion is necessary. DC converters can transform voltages to different levels by adjusting the respective currents of connected components. This assumes the ideal case where input power equates to output power, but conversion losses lead to efficiencies ranging between 90% to 95% [34].

DC/DC conversion allows keeping the voltage on the PV and voltage on the load separately controlled. There two main types of DC/DC converters depending on the direction of voltage change: (1) boost converters transform smaller voltage to higher voltage and (2) buck converters transform higher voltage to lower voltage [34].

MPP Tracking

DC-DC converters are specifically used in MPPT charge controllers. Their purpose is to regulate the input voltage at the PV module's MPP and provide load matching for the maximum power transfer [35]. This allows the solar power system to constantly operate at maximum power.

If the assumption is made such that at a certain ambient irradiance, an array or single solar cell operate at the maximum power, then if there is a change in solar irradiation , the performance characteristic (I-V curve) of the cell or array changes as seen in figure 14. Thus, the output current drops significantly if the output voltage is kept constant. The MPP tracker is able to maintain the maximum power output by adjusting the voltage to the new Vmpp value [34].

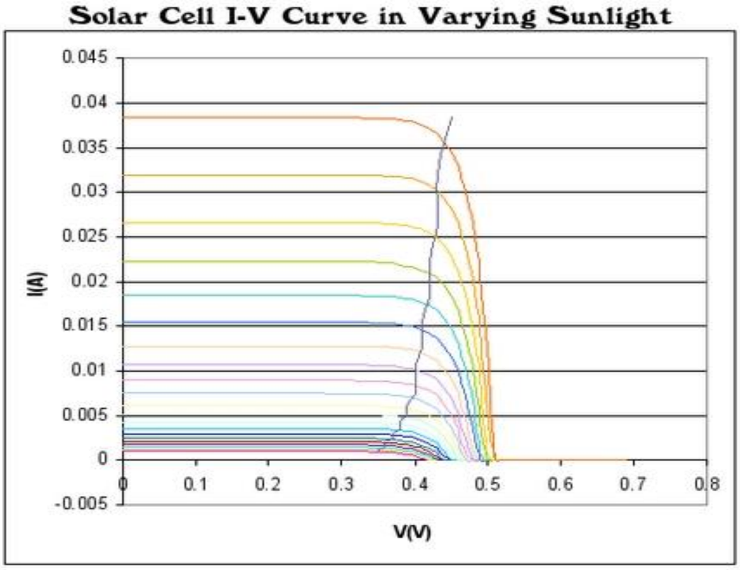


Figure 14: I-V performance curves of a solar cell in varying sunlight. The upper curves demonstrate the cell performance at higher irradiance conditions. The vertical path crossing the performance curves indicates the shift of the maximum power point

2.6 Overview of PV Systems

2.6.1 Types of PV Systems

There are three main types of PV systems: grid-tied, off-gird and hybrid. Each has advantages and disadvantages, and their usefulness depends on the customer's energy supply and what they want to get out of the system. These are further detailed below.

i. Grid-Tied

A grid-tied system is a basic solar installation that uses a standard grid-tied inverter and does not have any battery storage. This is perfect for customers who are already on the grid and want to add solar to their house [36]. These systems can qualify for government incentives which ultimately help to cover the costs related to the system. They also use relatively fewer components than the other systems and are relatively cost-effective and simple to design. The underlying reason why this system would be installed is to benefit from the incentives and lower a property's utility bill.

Grid-tied systems automatically disconnect when not linked to the grid. This means that when there's a power outage the PV system loses power as well in order to protect the safety of the linemen who are working on the power lines in the event of power being fed back to the grid. The disadvantage of these systems is therefore that one cannot store energy in case of an emergency or as a back-up power supply. Also, it is not possible to control when the power can be used from the system, such as during peak demand times.

An AC-coupled system with the original inverter coupled with a back-up battery inverter can still be a solution worth considering if the owner intends to add storage at a later point in time [36].

ii. *Off-Grid*

Off-Grid solutions are convenient for customers who, because of their geographical location or the high cost of drawing in the power supply, want their power supply to be generated independently and completely off the grid.

The advantages to this system involve being self-sufficient by being able to power remote places that are distant from the grid and having fixed energy costs associated to the power supply. The modularity of the system also allows for the capacity of the system to increase as power demands grow.

In the event of weather conditions causing partial module coverage, the power output of the PV system is significantly affected. Therefore, it makes sense to combine this system with a back-up generator to fulfil the power demands of the system during these conditions. Another disadvantage would be losing out on some of the government incentives related to PV systems. Finally, this system is relatively pricier because they require relatively more components than a standard grid-tied system. An illustration of this system is provided below [36].

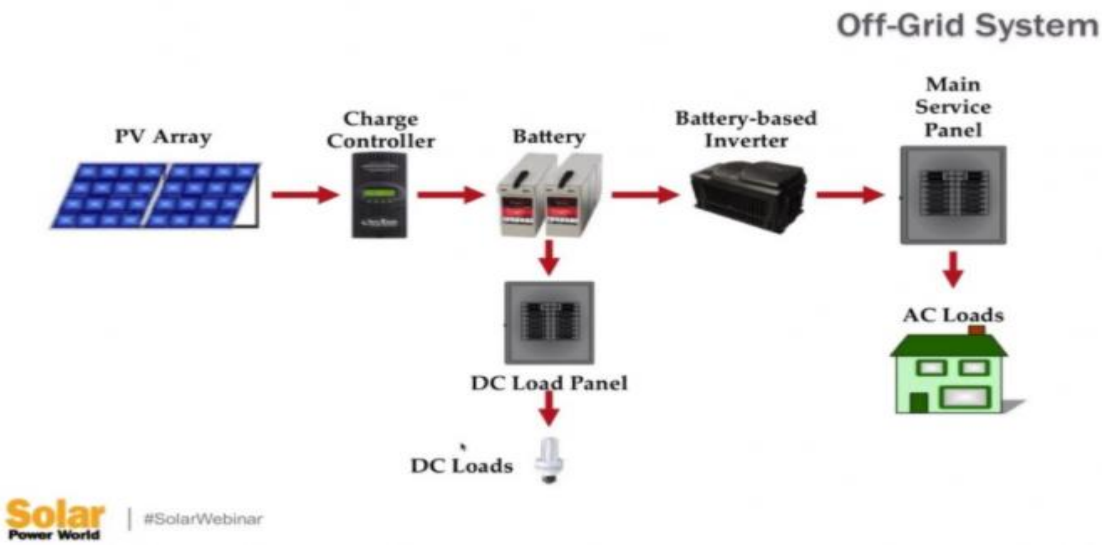


Figure 15: An off-grid PV system illustration

iii. *Hybrid System*

The hybrid PV system is a system which has the benefits of both grid-tied systems and off-grid systems. This is a grid-tied system with a battery back-up. This is a useful system to implement in areas that are prone to power outages.

By having the best of both worlds, this system allows for users to still benefit from government incentives whilst lowering their utility bill. At the same time, there is guaranteed back up power supply in case of an outage or emergency through the energy stored in the battery. The energy stored in the battery can also be stored for later use so that it can be used during peak demand times.

A disadvantage to this system is that they cost relatively more than standard grid-tied systems and are less efficient. A charge controller is needed as an additional component to protect the batteries. A sub panel is also required that contain the loads that are necessary for backing up. Hence, more components are required. This system is illustrated by figure 16 below.

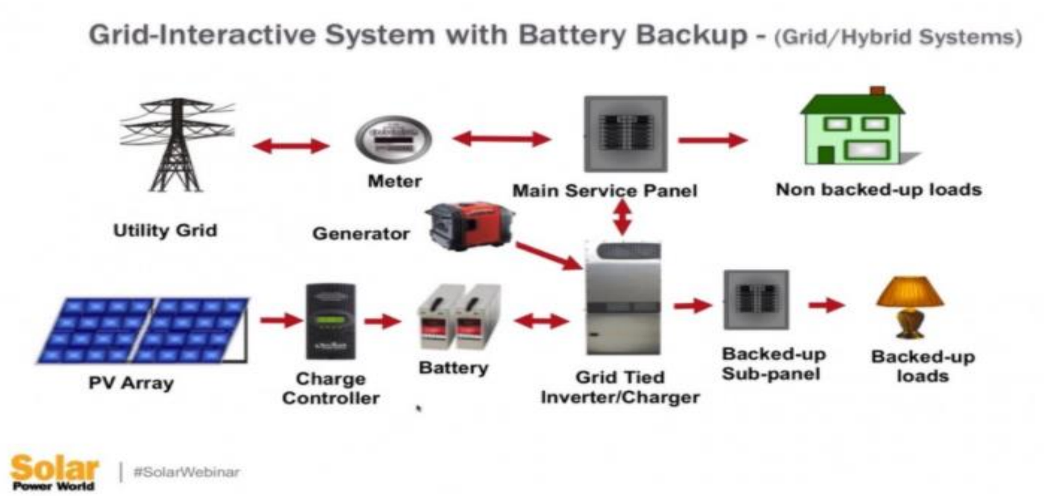


Figure 16: Illustration of a hybrid PV system

2.6.2 Intermittency

All the benefits of solar energy, and renewable energy in general, do not come without limitations. Undoubtedly, the most concerning problem of solar energy is intermittency because solar power can only be generated in sunny conditions. Without some level of predictability in power generation, this can lead to blackouts. At the opposite end of the spectrum, when solar energy is at its peak, there are times where too much power can be generated [37].

For the National Grid to work properly, a 50kHz frequency needs to be maintained. This is fine for energy generation that can be controlled but is difficult to achieve for renewable energy sources. When the demand increases, the amount of supplied energy needs to be high and when the demand is low the amount of energy going into the grid needs to be reduced [37].

The CEO of Thupela Energy, Philip Calcott, has said that should solar photovoltaic (PV) become South Africa's cheapest form of electricity, intermittency could limit the technology's penetration of the energy market. However, Calcott pointed out that for solar to extensively penetrate the market, backup power would be required [38].

"The backup sources will have to have a low capital cost, be flexible and have a relatively low fuel cost, if it is fuel driven," he said.

3. PV System Design

3.1 Energy Consumption Analysis

To develop a load profile for a standard two-bedroomed RDP house, the power ratings of typical household electrical appliances and their respective usage periods needed to be considered. The following table, with power consumption information taken from DaftLogic [39], illustrates an assumption of the average energy consumption of an RDP house daily during winter and summer periods. These are appliances that the average RDP house consists of and is based on Table 1: Table of appliance ownership % amongst Table 2: Energy contributions by fuel sources towards above. The power ratings of these appliances were also compared to similar low-cost appliances that are commercially available.

Appliance	Typical Number of Devices	Power(kW)	Hours Operational in Winter	Hours Operational in Summer	Energy Consumed Per Day(kWh)
Tungsten Bulb	5	0.0600	8.0	5.0	1.500 – 2.400
Fan	1	0.0700	0.0	6.0	0 - 0.420
Electric Heater	1	2.0000	3.0	0.0	6.000
Kettle	1	1.2000	1.5	1.5	1.800
2-Plate Stove	1	2.0000	1.0	1.0	2.000
17" LED TV	1	0.0185	6.0	6.0	0.110
Cell-phone	4	0.0060	3.0	3.0	0.072
Microwave	1	0.7700	0.5	0.5	0.385
Dishwasher	1	1.8000	3.0	3.0	4.800
Radio	1	0.0020	3.0	3.0	0.006
Refrigeration (33% Duty Cycle)	1	0.150	8	8	1.200

Table 3: Typical low-income electrical household appliances with power consumptions

Table 3 suggests that during summer, when consumption is probably at its lowest, the average daily energy consumption is 12.293kWh. This increases in winter to 18.773kWh in winter. The electric heater is not a necessity though as this can be replaced with extra blankets, thermal insulation for the household and even a gas heater. The dishwasher, as well, can be replaced with handwashing instead. This would allow for the electricity energy consumption figures to be reduced to 7.493kWh in summer and 7.973kWh in winter.

3.2 System Sizing

The following calculations for this subsection are based on the guidelines given by Leonics [40].

There is not a significant difference between the 7.973kWh energy consumption in winter and the 7.493kWh energy consumption in summer. Hence, the average of these two numbers, 7.733kWh will be used for further calculations.

3.2.1 PV Power Demands

The appliances total daily consumption given above is multiplied by a factor of 1.3 to get the total Watt-hours per day which must be provided by the panels [40].

3.2.2 PV Module Sizing

The climate of the site location coupled with the size of the PV module give the peak Watt (Wp) produced. Different sizes of PV modules will lead to different amounts of power being generated. Different site locations lead to different panel generation factors. In South Africa, our average sunshine can be worked on 4.8 hours of sunshine; the panel generation factor[41]. The total Watt-peak rating needed for PV modules is calculated by dividing the total Watt-hours per day needed from the PV modules by 4.8.

It should be noted that if more PV modules are installed, the system will perform better, and battery life will be improved. If fewer PV modules are used, the system may not work at all during cloudy periods and battery life will be shortened [40].

3.2.3 Inverter Sizing

Since the load requires that AC power output be fed into it, an inverter is necessary. The input rating of the inverter should always be higher than the total wattage of the appliances and it must have the same nominal voltage as the battery. Ideally, the inverter size should be 25%-30% larger than the total wattage of the appliances. Finally, and for grid tied systems specifically, in order to allow for safe and efficient operation, the PV array rating and the input rating of the inverter should be equal [40]. The total appliance wattage will therefore be multiplied by a factor of 1.25 to find the appropriate inverter size. It will be assumed that all appliances will run simultaneously at some points in time.

3.2.4 Battery Bank Sizing

Deep cycle batteries are preferred for solar PV systems. This is because deep cycle batteries are designed to be discharged to low energy levels and can be charged and discharged rapidly and consistently day by day for years. The battery should be designed such that it is large enough to store sufficient energy to operate the appliances at night and on cloudy days[40]. The following procedure is used to calculate the size of the battery bank:

a) Calculate total Watt-hours per day used by the appliance.
b) Divide the total Watt-hours per day used by 0.85 for battery loss.
c) Divide the answer obtained in item ‘b’ by 0.6 for depth of discharge.
d) Divide the answer obtained in item ‘c’ by the nominal battery voltage.
e) Multiply the answer obtained in item ‘d’ with days of autonomy (the number of days that you need the system to operate when there is no power produced by PV panels) to get the required Ampere-hour capacity of the deep-cycle battery.

The nominal battery bank voltage is selected such that the continuous current through the system is below 100A based on the system’s power demands.

3.2.5 Charge Controller Sizing

The solar charge controller is typically rated against Amperage and Voltage capacities. The solar charge controller will be selected to match the voltage of PV array and batteries and then identify which type of solar charge controller is right for the RDP application. It will be ensured that the solar charge controller has enough capacity to handle the current from the PV array[40].

For the series charge controller type, the sizing of controller depends on the total PV input current which is delivered to the controller and also depends on PV panel configuration (series or parallel configuration)[40].

Charge controllers are, however, not needed for grid-tied systems. This is because once the battery is full, the excess energy will be directed to the grid instead of the PV battery bank helping to avoid overloading of the batteries [42].

To calculate the size, the number of panels multiplied by their watts should be taken to get the total watts of the solar array. That figure is then divided by the voltage of the battery bank to get Amps. This figure is then multiplied by 1.25 to compensate for cold temperatures [43].

4. Design Choices

4.1 Design Cases

Three design choices were considered to make an informed decision regarding which PV system will be both beneficial to the inhabitants of the RDP houses in terms of lowering their electricity expenses, whilst ensuring that its mass roll-out and implementation is feasible enough for the government to consider.

The three cases and their respective power needs and the appliances that they cater for are illustrated in table 4 below:

Case	Appliances Powered	Daily Power Needs
A	*Full power coverage for all appliance needs:* - Lights - Fan - Cooking - Kettle - TV - Cellphone Charging - Microwave - Radio - Fridge	7.733kWh
B	*Partial power coverage catering for most necessary appliances, considers that a gas stove and solar geyser is also fitted in each house for cooking and water heating:* - Lights - Fan - TV - Cell phone Charging - Microwave - Radio - Fridge	3.933kWh
C	*Basic power coverage to cater for some necessities whilst being the most economical solution. Considers that a gas stove and solar geyser is also fitted in each house for cooking and water heating. Also considers that LED bulbs are used as opposed to tungsten bulbs:* - LED Lights (7W each) - TV - Cell phone Charging - Fan - Fridge	1.820kWh

Table 4: Breakdown of design cases for various applications depending on need and feasibility

4.2 Component Selection

To establish which components would best suit each respective case, the methodology explained in the System Sizing section will be used. This will allow for the size of the modules, the size of inverter, the size of the charge controller and the size of battery bank to be calculated for each case. These calculations can be found in Appendix A.1 - Component Selection Calculations and are summarized in the table below.

	Case A	Case B	Case C
PV Power Demands (kWh)	10.05	5.11	2.37
PV Module Sizing (Wp)	2094.35	1065.19	492.92
Inverter Sizing (W)	5670	1670	370
Autonomy Period (hrs)	12	8	48
Battery Bank Sizing (Ah)	205.33	139	387
System Voltage (V)	48	24	24
No. of Batteries	4	2	4
Charge Controller Sizing (A)	N/A	N/A	N/A

Table 5: Sizing of various components of each design case

4.3 Cost Comparisons for Each Case

Three sets of commercial offerings will be analysed for each case as a means of briefly gauging how much each case would cost. The three companies who were considered were Sustainable, Solar Shop and Solar Panel Energy. Various offerings were considered but the 3 offerings that best matched the component sizes for each case were ultimately chosen. These prices include the essential components required for the system but all cabling, batteries, connectors and fuses necessary for system installation are excluded. The costs of the solar heater and gas stove are also excluded for cases B and C respectively and will be dealt with in the Cost Analysis section.

What is important to realize is that the true cost of the system components might not be truly reflected in the following tables, since the quoted prices are all retail prices instead of wholesale prices. However, as a means of drawing comparisons between the relative feasibility of each option, these retail prices are considered. All prices were captured on 22/09/2020 and the tables related to each commercial offering for each case can be found in A.2. The most affordable offering for each case is presented in the table below.

Case	Price
A	R50850
B	R21200
C	R31902

Table 6: Cost comparison of designed cases

4.4 Final Design Choice

The final design choice hinges on many different factors, most of which are related to feasibility. A grid tied system has the practicality of electrifying all the appliances as listed in table 2. However, given that the average cost to construct an RDP home, across all 9 South African provinces and as listed in Appendix A, is approximately R131450 (R117 777 for construction, R7673 for water and sanitation and R6000 for raw land), spending about R50 000 for a Case A solution is probably unfeasible [44].

Having a completely off grid system that is independent of the Eskom grid, as Case C suggests, is not a wise idea. This is because the storage capabilities of the designed system that features a two-day autonomy period might not be enough to cover the needs of houses that are built in areas that are prone to consecutive overcast days. Even though a conservative, two-day autonomy period has been used, the risk of a house being out of power might exist. Not much research has been made in battery capacity sizing relative to the South African climate; nevertheless, this research assumes that a two-day autonomy period will suffice for this intended purpose.

The natural question to ask is 'Can't the battery capacity be increased to overcome this issue?'. The short answer is, no, because it is not feasible. The main drawback in the implementation of a feasible PV system is the cost of storage. By looking at the various competitor tables for Case C in the previous section, what is easily noticeable is that the storage costs are significantly higher than that of the rest of the components required for the system.

The potentially greater concern of a completely off-grid solution would be that any other appliances that the inhabitants of an RDP home would like to install will not be able to be powered up. This becomes a significant problem as many inhabitants will not be able to have the financial means for upgrading their respective systems.

Case B offers a really feasible solution that will be able to power essential appliances. With the exception of catering for an electric geyser or an electric stove, all other appliances will be powered. The problem with relying on the grid, however, is that the frustrations of load shedding and power outages would still affect systems connected to the grid. A completely grid tied solution is also not suited for this specific task more so because the grid would not necessarily suit homes developed in rural areas that have limited and no access to Eskom's grid.

Also, Case B considers a microwave, a radio and tungsten light bulbs in its consumption analysis. There are alternatives to each of these appliances in that the microwave's usages are also offered by the gas stove, modern TVs and cell phones can be used as radios, and energy efficient LED bulbs can replace tungsten bulbs.

In the case of not including an electric stove, stipulated by Case B and Case C; the reason why this exclusion makes sense is because gas stoves in general come in as a most cost-effective solution because it uses significantly less energy and because gas is cheaper than electricity. Gas stoves also last longer, offer a faster cooking time offer better heat control and are exempt from load shedding blues [45]. In the case of not including electric geysers, it is an exclusion that is a lot more complicated.

The Department of Energy (DoE) launched a solar water heater programme in 2008 to equip 1-million homes with solar water heaters (SWHs). By the end of the 2015 year, 400000 units were installed [46]. However, since then, the government has installed just 200 of the 87 000 heaters it purchased for hundreds of millions of rands under its rebooted solar water heater programme since 2018, a Mail & Guardian investigation has revealed [47]. Case B and C optimistically assumes that the SWHs momentum will be restored but this is unrealistic.

A feasible solution that caters for as many appliances as possible whilst being able to mitigate the downfalls of both grid-tied systems and off-grid systems is necessary. Fortunately, there is an alternative that caters specifically for this, that is, converting only part of the home to (off-grid) solar. This will allow for appliances that inhabitants would like to have in their homes not be compromised, meaning their lifestyles will not have to be adapted around minimal power generation. It also means that by having the necessities powered by solar, essential appliances will not be affected by power outages. This is done by simply separating the breakers on the DB board. Further discussions related to this can be found in the Design Process section. Furthermore, RDP homes developed in rural areas will benefit most from this especially if grid access is not yet available in those respective areas as, at the very least, they would have essential appliances powered up by the PV system. Finally, this also would be a bigger step towards lessening the burden on Eskom's constrained grid.

With this in mind, a new, final and optimal case can be proposed. The proposed solution is to have the appliances suggested by Case C in Table 2 powered through the off-grid solar system, and to have all other appliances (including an electric geyser or kettle for water heating if needs be) powered by the grid. This will ensure that, until the government is able to roll out SWHs, the convenience and lifestyles of RDP inhabitants are not affected by a lack of warm water. If we consider that the inhabitants stick to using the kettle to heat water as suggested in Table 1, over a 30-day period this would cost them 45kWh of electricity. The Department of Energy offers low income households 50kWh of free basic electricity per month. This essentially means that the inhabitants would not have to fork out any money from their own pocket to power basic home appliances. The water heating expense will be subsidized by the free basic electricity subsidiary and the rest of their appliances will be powered by solar. The only cost to them would be the operating expenses related to their gas cooker.

The proposed solution is therefore to implement Case C as a full off grid system which will cater for the necessary appliances of the household whilst having the grid catering for the rest of the appliances. This will be accomplished by splitting the DB board accordingly. The PV components required for the proposed solution is:

- 1 x 500kVA 400W 24V inverter
- 2 x 280W PV Modules
- 2 x 200Ah Deep Cycle Batteries
- 1 x 30A MPPT Charge Controller

5. Design Process

5.1 System Layout

5.1.1 Separating the Circuits

The first consideration in relation to the layout of the system is the need to separate the circuits. In order for only part of the home to be converted to solar or battery power, the wiring circuits in the home need to be separated so that some are powered by Eskom and some are powered by the solar or battery power.

The following diagram represents a simplified form of this. What can be seen is that the Eskom powered appliances are wired completely separately from those powered by the sun. Each appliance can only have one source of power. The wires connected to certain appliances that are powered by one source need to be completely different from those connected to another source of power [48].

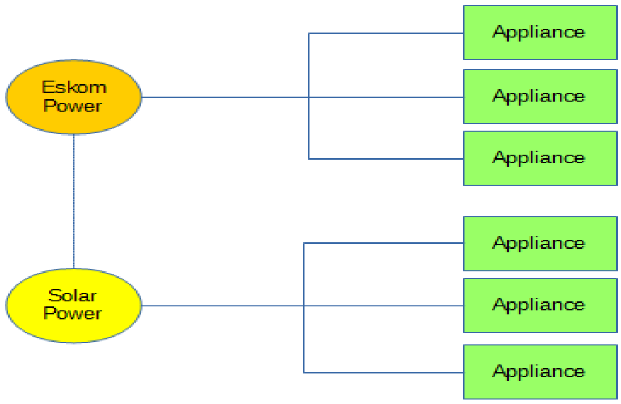


Figure 17: Separation of Eskom and solar circuits

From figure 17, the two power sources (Eskom and Solar) can also be connected, this is represented by the line that connects the two power sources. This is optional and its main purpose is for Eskom power to be used to charge up the batteries on overcast days, as well is to allow the solar generated power to be fed back to the grid for grid-interactive systems. The system to be designed will not cater for the latter in order to reduce costs. This setup can be very difficult to achieve in existing homes within which wires have been convoluted over time, or where alterations have been done to the wiring configuration that are not in compliance with the wiring code. For existing systems this would demand considerable effort and cost from the electrician's side. However, for newly designed RDP homes this is not an issue.

The above diagram is merely a simplified representation of the overview when converting part of a home to solar. The safety issues and regulation requirements have not been explained and will be detailed in the System Configuration subsection that follows.

5.1.2 Separating the Breaker

An easy way of separating the circuits involves separating the breaker on the DB board during the electrical design implementation. An illustration of a standard DB board is given below [48].

Figure 18: An image of a standard DB board

The breakers towards the left-hand side represent the main switch and the earth leakage switch. Beside them is a row of other current limiting breakers that power associated appliances in a home. An easy approach is to focus on one breaker at a time and connect all its associated appliances to solar or battery power. For existing homes, apart from having to rewire the breaker and its associated Neutral and Earth wires, no other wiring needs to be redone thereby decreasing complexity and hence cost if the breaker was originally installed correctly.

The following diagram is a simplified representation the above detail [48].

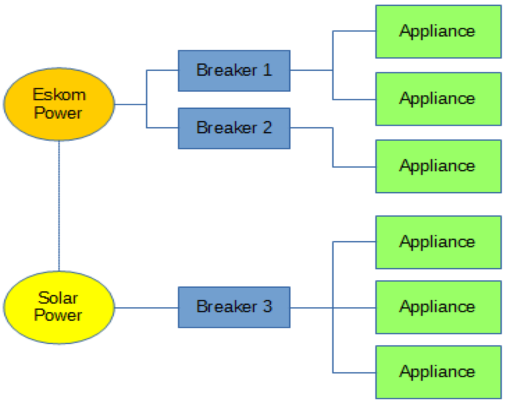


Figure 19: Diagram representing breaker separation

Figure 19 shows how Breaker 3 has been disconnected from the grid and connected to solar power. All the associated appliances of Breaker 3 are completely separated from the other appliances in the household. The collection of wires that are separated specifically are the Neutral, Earth and Live wires for that respective breaker.

Since our task involves restricting the power hungry appliances from being supplied by solar power because of the costs related to increasing the size of the system to cater for them, appliances such as an electric geyser and an electric stove will be connected to the grid. As suggested before, all the appliances stipulated by Case C in Table 2 will be powered by solar; these are the LED lights, the TV, the cell phone charging ports, the fridge and the fan or any other low consumption appliances that make up 1.82kWh of drawn energy.

5.1.3 Layout and Wiring

A typical layout of an off-grid PV system is shown below in figure 10 [49].

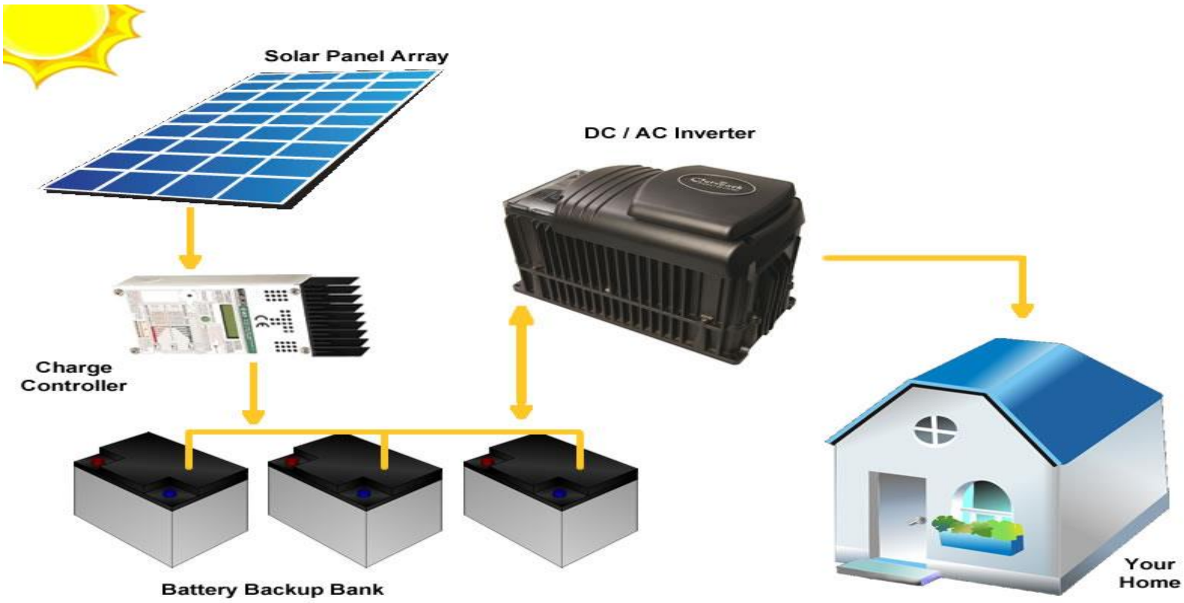


Figure 20: Diagram of the layout of a typical off grid PV system

From figure 20, the PV array feeds solar generated power to the charge controller. The solar charge controller receives the power from the solar panels and manages the voltage going into the storage. It ensures that the deep cycle batteries do not overcharge during the day and blocks any reverse current going into the solar panels. The charge controller feeds the power into the batteries which store energy to use on demand. The batteries then interact with the DC/AC inverter to invert the DC solar generated power into AC for it to be used by the household appliances.

A second illustration below suggests the component layout of this system relative to an RDP home [50].

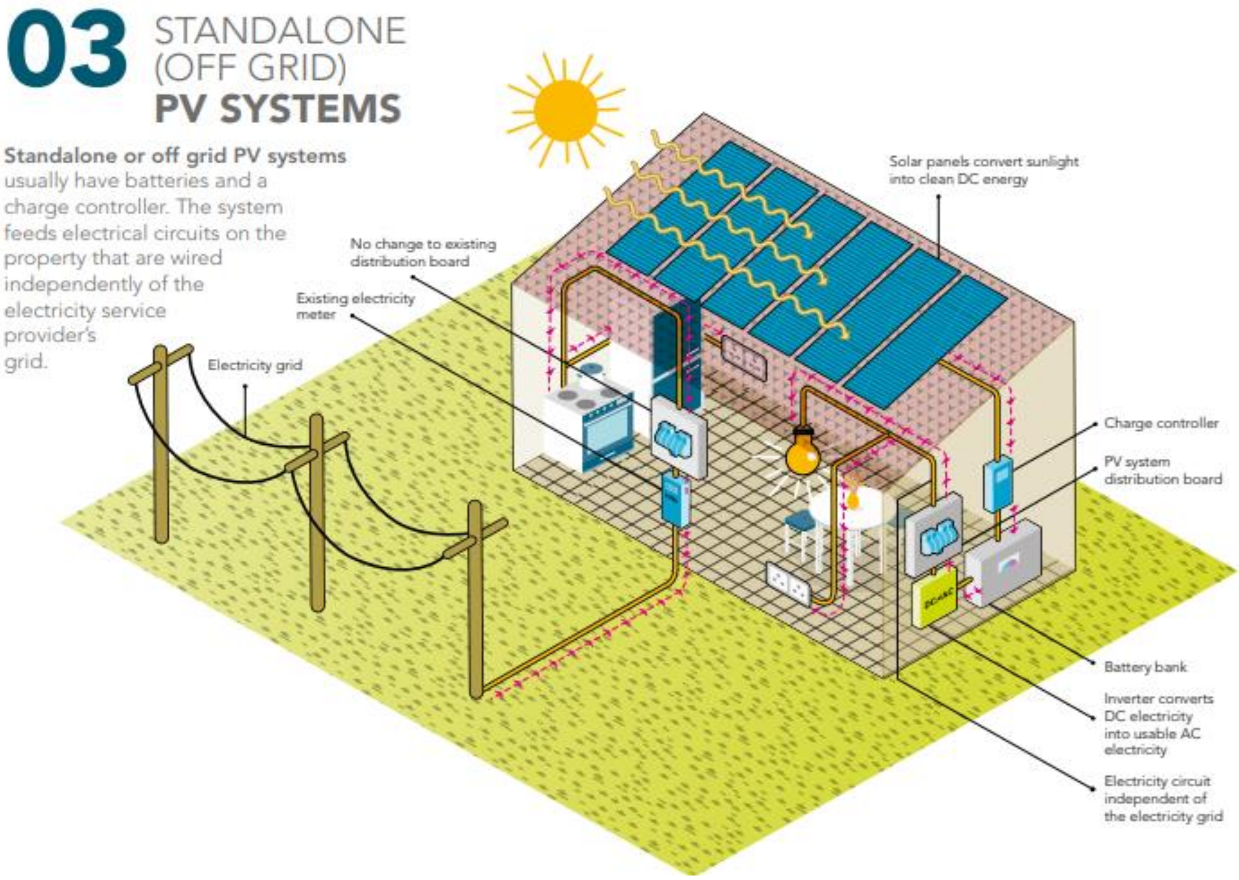


Figure 21: Component layout and placement for an RDP house

In figure 21 above, the splitting up of the circuits for solar and Eskom generated power is performed by having two separate DB boards altogether. This is another alternative to designing the system. The figure depicts the suggested positioning of the various PV components and depicts how various appliances are connected to their respective power suppliers. The only difference is that in the actual design that this report suggests, the fridge will also be powered by solar power.

5.2 System Configuration

5.2.1 Protection of Off-Grid PV Systems

This subsection speaks to various methods which can improve the safety of PV system installations. It discusses some of the common problems that might occur and how to mitigate the harmful effects or risks that an arise because of them.

i. Earthing for Off-Grid PV Systems

A key safety mechanism in the event of a fault in an electrical system is the inclusion of an earth wire. This is done by the earth wire providing an alternative path for the electricity.

An Eskom powered home has the household earth wire connected to a neutral point of the transformer in the council substation. At the substation it is also connected to the ground by means of a stake driven into the ground. This is illustrated in the diagram below [51].

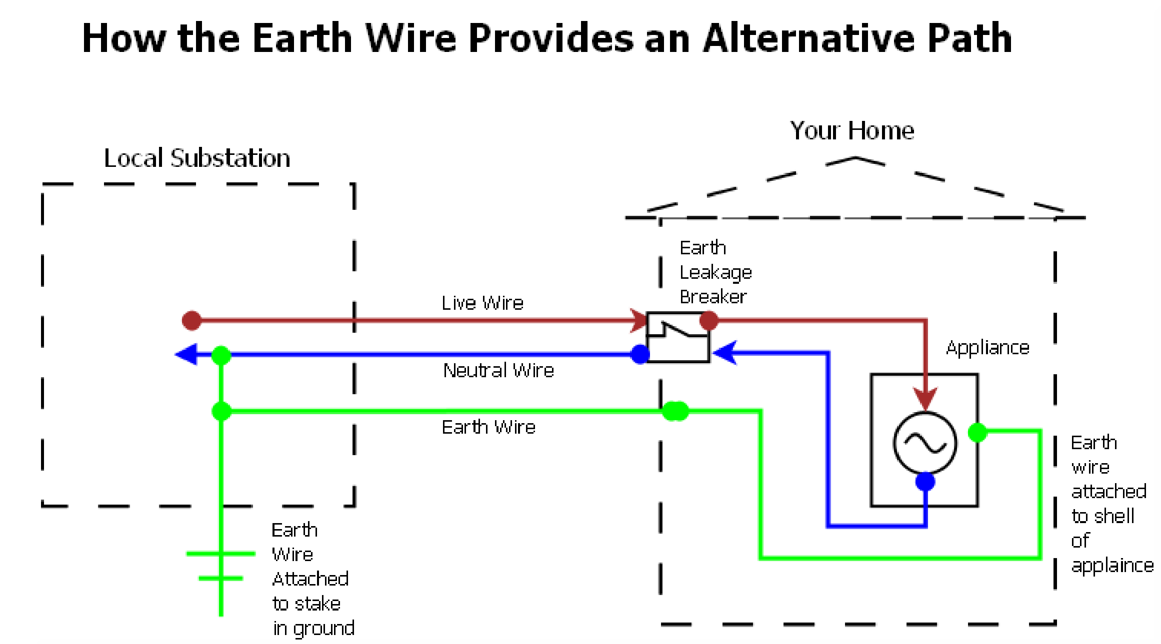


Figure 22: An illustration of how the earth wire is connected to ground

An alternative path is therefore created for the electricity to flow back into the substation in the event where the wire touches the shell of the appliance. If the earth leakage breaker detects that the net flow of electricity between the live wire and the neutral wire is not 0, it trips, and the flow of electricity is stopped.

In a completely off-grid system, there is no connection to the local substation and the council will not supply a connection for the AC earth wire. This infrastructure needs to be self-established within the system design. This can be achieved by connecting an earth wire to the 230V AC neutral wire that is connected to the inverter. This becomes the main earth wire and all other earth wires can then lead back to that single point. This point is also connected to a stake driven into the ground. The diagram of this is given below [51].

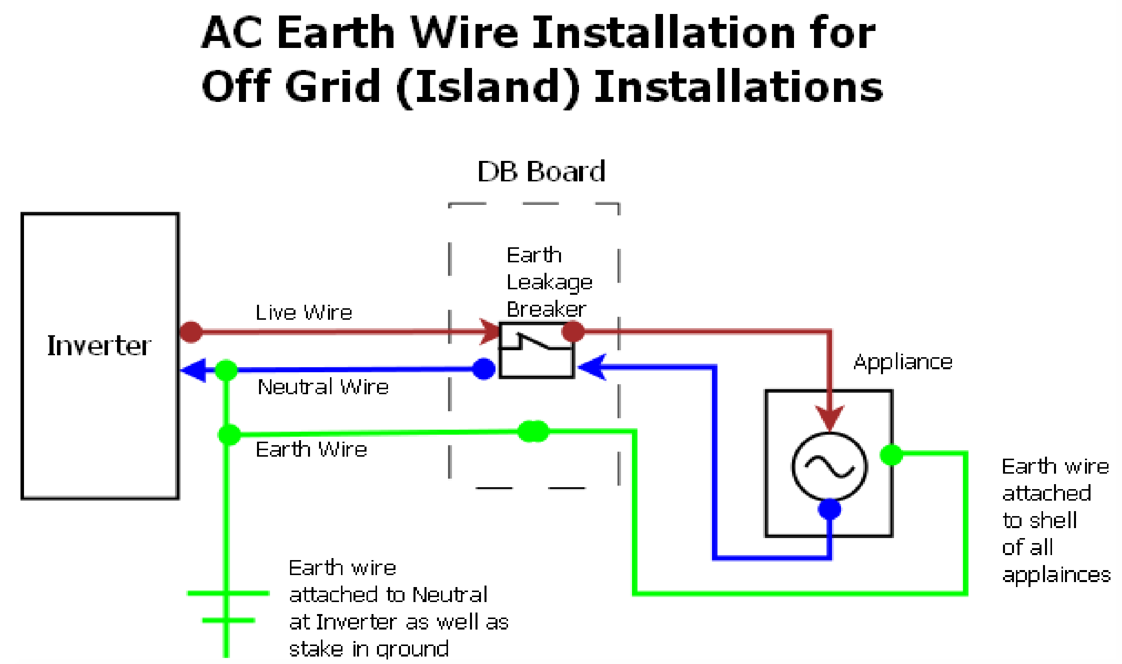


Figure 23: Earth wire connection for an off-grid system

ii. *Ground PV Arrays to Reduce Lighting Damage*

By having the PV array mounted on the roof, there is a possibility that the PV panels might be struck by lightning or have lightning strike relatively close to it. This could damage not just the PV array, but all associated components that it is linked to it such as the MPPT and inverter. It is therefore prudent to add lightning protection to the system.

The main objective of the protection is to minimize the amount of damage caused by the lightning on the solar array and its associated components by providing a straight, short, preferential path for the lightning to follow. This can be achieved by having an earth wire that is thick enough and that runs straight down from the PV array to a spike in the ground. This is because lightning will always take the shortest path.

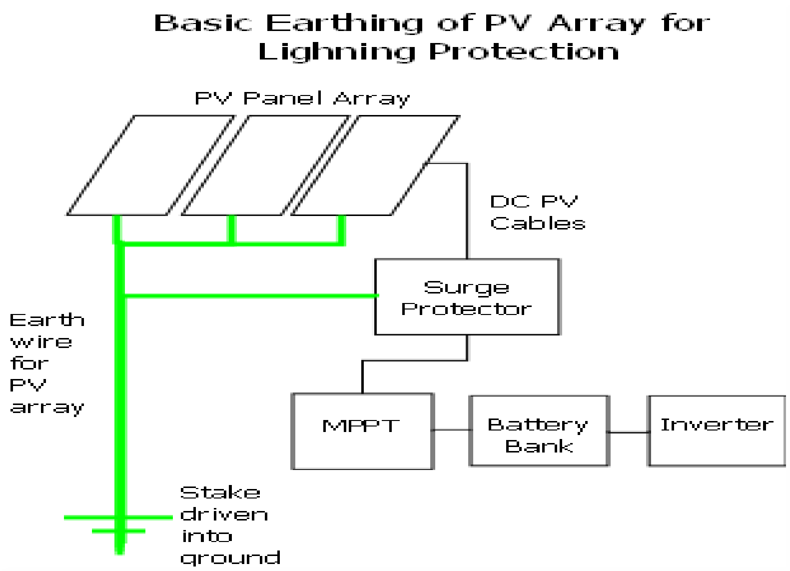


Figure 24: Lightning protection of a PV system

Additionally, to further prevent the lightning from flowing down the PV cables and into the MPPT or solar inverter, a DC surge protector in a combiner box can be used. When the surge protector detects a spike in the voltage, it offers a route from the PV cables directly to earth for the lightning to pass through. This is illustrated in figure 24 above [51].

iii. Protection of DC Circuits

Photovoltaic panels that come as part of a PV system are responsible for producing direct current (DC) which differs from the alternating current (AC) used to power household appliances. There are certain dangers inherent in DC circuits that need to be considered during design. The DC system can be dangerous because of two reasons [51]:

- The sun will continuously energize the PV system in the event of a fault since it cannot be switched off. The same applies for battery power in that the battery will keep supplying stored energy to the circuit in the event of a fault until the batteries run flat.
- An arc is drawn by the DC current when a contact opens. What this means is that if a gap between the terminals slowly becomes wider, a high temperature arc will be formed between the two terminals which can melt the terminals or any nearby plastic and becomes a fire hazard. This further implies that in the event that a joint loosens, there is a possibility of it arcing and hence starting a fire.

The following precautions can be taken to help prevent the risks associated with the DC current [51]:

- Specialized PV fuses should be installed on the PV cables
- At least one suitable fuse per string of parallel batteries should be installed for the battery bank
- It should be ascertained that the correct cables and connectors are used for installation, and that all connectors are tightly fastened to prevent any loose joints
- All cables should be properly routed and secured to avoid the cables from getting snagged and the connections from coming loose
- The voltage ratings of the various system components should not be exceeded

6. Cost Analysis

The success of this research project hinges on whether the system that was designed is feasible enough for the government to want to consider implementing on a large scale. This warrants an in-depth analysis to be performed in relation to what the overall cost of the system will be, how the government will be able to afford having it rolled out on a large scale and how it will benefit both the government and the inhabitants of RDP households in the long run.

6.1 System Procurement

The procurement procedure related to the PV components will rely on sourcing various components or packages from solar companies who offer them at the most competitive price. These components or packages will either match or exceed their respective specifications in relation to sizing, whilst ensuring not to oversize the system to minimize cost.

The procurement will focus specifically on companies that offer solar systems on a retail basis and will not cater for any trade discounts offered for bulk purchases. Many companies were considered, and their prices weighed up against each other, however, only the cheapest offerings will be displayed throughout this section.

Two methods of procurement will be explored, the first being sourcing the cheapest individual solar components from different suppliers and tallying up the total cost related to sourcing components in that way. The second method is to find the cheapest complete DIY solar kit that is commercially available from a single supplier. In both cases, the selected components or kits should meet or exceed design specifications. These two solutions will then be weighed up against each other to determine whether it would make sense to source all components from one single supplier or to source individual components from separate suppliers. The two factors that will determine this decision are cost and convenience.

The selection related to all the electrical components – namely wires, cables, breakers, switches, and isolators have been assumed as accurately as possible. The selection of these components was based on the commercial offerings of similar sized systems and were tailored around the specific system to be designed. Calculating the sizing of these individual components is beyond the scope of this research task.

The companies that were considered for system/component procurement are all based in South Africa. They are:

- Solar Panel Energy (https://www.solarpanelenergy.co.za/)
- GC Solar (https://onlineshop.gcsolar.co.za/)
- Sustainable (https://www.sustainable.co.za/)
- Solar Shop (https://www.solar-shop.co.za/)
- Sinetech (https://sinetechstore.co.za/)
- Solar Advice (https://solaradvice.co.za/)
- FreshTec Energy (https://freshtec.co.za/)
- ARTsolar (https://artsolar.net/)
- JAP Solar (https://japsolar.com/)
- The Sun Pays (https://shop.thesunpays.co.za/)

6.2 Cost Breakdown

This cost breakdown will cover the costs related to acquiring all the necessary components for installing the PV system. It also includes the average installation cost, which according to Solar Advice is R7 000 per day. This means that for half a day of labour, the estimated time within which the system should be installed, the cost would be R3 500 for labour. Solar Advice also averages the cost of consumables to be R1 500 [52]. The delivery costs have been excluded; also, most companies offer free nationwide delivery when purchasing solar system kits from them. Auxiliary components such as solar panel mounting kits have also been excluded.

It should be noted that, in the case of RDP homes, the electrical installation costs for a standard $40m^2$ RDP home was given as R10 496.16 by the Minister of Human Settlements in 2018 [44]. There is a possibility that for newly developed RDP homes, electricians can be hired to install both the electrical and solar installations on the same callout. This would further decrease the costs of installation.

The cost breakdown will only display the cheapest solutions for each respective method. All prices quoted below were spotted on 28/09/2020.

6.2.1 *Method 1: Sourcing Components Individually from Different Suppliers*

Component	Quantity	Supplier	Price
280W PV Modules	2	The Sun Pays	R2 990,00
800W 24V Inverter	1	Sustainable	R3 774,00
200Ah Batteries	4	GC Solar	R15 200,00
30A MPPT Charge Controller	1	GC Solar	R1 628,00
Battery Cable Pack and Lugs	1	Sustainable	R611,78
MC4 Connector Kit	2	Sustainable	R202,00
Battery Disconnector w 160A fuse	1	JAP Solar	R620,00
10m Solar Panel Cables (R & B)	1	Sustainable	R380, 00
Installation	N/A	N/A	R3 500,00
Consumables	N/A	N/A	R1 500,00
			R30 406,78

Table 7: Table of costs for components sourced individually from different suppliers

From the above table, it can be noted that the cost of the system to be designed without installation and consumable fees included is **R25 406,78**. This figure will be important in comparing this method with method 2 below.

6.2.2 *Method 2: Sourcing Entire Solar Package from A Single Supplier*

PV System	PV Modules Size	Inverter Size	Battery Size	Charge Controller Size	Supplier	Price (excl installation & consumables)
2kW	2 x 250Wp	700W	4 x102Ah	20A	Sustainable	R25 406,00
2.4kW	3 x 330Wp	2.4kW	4 x 100Ah	In-built	Solar Panel Energy	R25 858,82
2.4kW	2 x 305Wp	2.4kW	2 x 100Ah	In-built	Solar Shop	R18 781,50
1kW	2 x 250Wp	1kW	2 x 120Ah	In-built	SineTech	R23 714,20
3kW	3 x 390W	3kW	2 x 100Ah	In-built	Freshtec	R24 942,40

Table 8: Table of costs for solar system kits and packages that are offered by different suppliers

Table 8 lists all the commercial solar system kits offered by various suppliers. Some suppliers did not have kits small enough to cater for this specific design and were excluded from the table. The five listed offerings represent those that best matched the specifications of the design. Most importantly, all the listed offerings have DIY kits that do not meet the battery bank size specifications for a two-day autonomy period.

The 2.4kW kit from Solar Shop is the most cost-effective solution. The kit costs **R18 781,50.**

6.2.3 Feasibility Assessment

There is a R8574,72 difference between the two methods. This is seemingly a large difference and it would make sense to then source the components from one supplier rather than a host of suppliers to save on logistics costs as well. However, the two solutions that are proposed are not the same as the main drawback of the DIY kits is the lack of storage. Adding on extra storage in a series-parallel connection to make up for the shortfall for a 24V system would cost at least R9000 more (a 200Ah battery connected in series and another 100Ah battery connected in parallel) in the Solar Shop offering, for example. This would make procurement more expensive relative to method 1. The next cheapest alternative in Method 2 that can partially meet the system's demands is that offered by Sustainable Energy. This kit costs R25 406,00 which is almost the same figure as the R25 406,78 (excluding installation and consumables) that method 1 would cost but still does not meet storage requirements.

Method 1 will be selected as the preferred procurement method. The only disadvantage to method 1 is the logistical issues related to procuring individual components from different suppliers. However, since the products will be bought in bulk, a lot of these issues and costs related to delivery, for example, can be catered for by the respective suppliers.

The next thing worth considering is whether this is indeed feasible to implement. Given that the average cost of an RDP home as discussed in the Design Choices section is R131 450, the R30 406,78 cost of designing a PV system for an RDP home represents an additional 23,13% to be added to that figure. This means that the average RDP home cost would increase to R161 856,78. Again, this excludes any trade or installation discounts that will be offered by suppliers or installers.

The government, however, is unlikely to increase their budget for the national housing programme. This comes from an AllAfrica report which states that just this year, the budget for the programme had been cut by R12 billion following mounting evidence of its deteriorating performance [53]. It is worth noting that the cost of the policy adjustment currently incorporated into the IRP to build two new coal-fired power stations has been calculated at a present value of R23-billion. For that money, South Africa could provide 756 411 low-income households with the system outlined above for free [54]!

There is also another argument, by Dr Bischof-Niemz who worked at Eskom on the Integrated Resource Plan, that considers low-income households and how to make them beneficiaries of the energy transition and of SSEGs.

"Making SSEGs attractive for low-income households would require that they are allowed to feed electricity back into the grid and that they are paid a tariff for that energy that is higher than would be the case for wealthy homeowners or commercial enterprises."

He goes on to say that,

"to incentivise uptake, the feed-in tariff should be set at a level that is sufficient to pay off the PV system and earn the host an income. In addition, it should be set at a level where it makes sense for the qualifying household to sell all the electricity produced back into the grid, while continuing to consume both the free lifeline and normal-priced electricity supplied from the municipal distributor."

And, in his opinion [54],

"Encouraging low-income households to become electricity vendors could lead, for instance, to a mass legalisation of illegal electricity connections. Secondly, it could result in a substantial increase in the payment of nonpaid electricity bills, which is currently a serious problem for many municipalities and Eskom, because, naturally, no consumer of electricity would be paid for electricity produced until the consumption bill is settled. Further, the opportunity to become a micro-electricity vendor, turning the owner's roof into a power plant, would create an income-generating opportunity anywhere in the country where there is a connection to the electricity grid."

This makes complete sense and in an ideal country where corruption didn't eat into government subsidiaries and budgets, where the state-owned power enterprise that runs these operations wasn't already in turmoil and where the country hadn't been moved to 'junk status', this would have been the ideal solution. It also would do a great deal of good in further incentivizing the implementation of the PV system to RDP household inhabitants and make this a more attractive prospect for them to consider.

However, his idea ignores the fact that these systems will still be vulnerable to load shedding. It also looks past the fact that less and less money, as discussed earlier, is being budgeted for RDP developments and even Solar Water Heating Systems in RDP houses. An additional outlay of R50 000 per RDP house seems beyond the realms of possibility, even if the long term social and economic benefits could potentially be greater than having off-grid systems implemented in them. The government, being in the economic predicament that they're in, would rather want to dedicate a portion of that money to actually providing more RDP houses for deserving South Africans if the trade-off between creating more houses and creating houses that are more energy efficient exists.

Unfortunately, the prospects of the design stipulated in this research could potentially be beyond the governments financial reach when it comes to its implementation. The purpose of this task is not to provide an in-depth financial analysis to assess the true extent to which the design can be achieved, so no further research was made in that respect. However, under the assumption that it is indeed achievable, the next subsection will provide a basic assessment of how the government will be able to reclaim some of the costs of the PV system implementation from inhabitants. This subsequently assumes that the government would want the inhabitants to pay them back for the PV system implementation in their respective households. The reason for designing this system as a repayable solution is so that the government is not financially constrained any further and so that all that would be required by them is capital to fund its implementation.

6.3 Repayment Structure

For the government to recoup the capital it lays out without necessarily making RDP household inhabitants struggle with the repayment, a financial package needs to be developed that works around how much those inhabitants can afford to pay. A 2015 report by Sustainable Energy Africa related to the household energy use in selected areas in and around Cape Town states that low-income households spent R364.58 per month on electricity [20]. This subsection will calculate the period within which government can expect RDP inhabitants can fully pay off their PV systems, assuming that the government will demand full repayment of them.

It is assumed that the repayment period for each individual system will be n years. The future value formula can then be used to calculate what the value of the government's investment, per system, will be after n years. This formula is given below:

$$FV = PV(1+\frac{i}{m})^{mn} \tag{1}$$

Where:

- *FV* represents the future cost of the investment after n years to be calculated
- *PV* represents the current cost of the system which is R30 406.78
- *m* is the number of times the interest is compounded annually, which is 1
- *i* is the interest rate at which the system should be repaid
- *n* is the number of years within which the system will be paid back

The next step involves having to use equation 2 below, the future value of a periodic investment equation, which can be used together with equation 1 find both the *FV* value of the investment and the period, n, within which it will be paid off by the inhabitants. Equation 2 will cater for increase in electricity tariffs; hence the average overall inflation rate of electricity tariffs is considered in the paragraphs that follow it. Equation 2 is given below.

$$FV = \frac{CC(1+\frac{k}{m})^{mn}}{\frac{m}{n}} \tag{2}$$

Where:

- *FV* is the cost of the investment after *n* years that needs to be paid back
- *CC* is the current cost of electricity to low-income households per annum
- *m* is the number of times the interest is compounded annually, which is 1
- *n* is the period within which the system will be paid back
- *k* is the average rate of increase of electricity tariffs across South Africa

From the above two equations, the only known variables thus far are *CC* and *m*. The interest rate, *i*, can be estimated based on historical South African lending rates. The cost of electricity is known for the year 2015 but the present *CC* value needs to be estimated based on historical tariff increases over the past 5 years. Historical tariff data can also be used to find that the average rate of tariff increases over the past few years so that the value, *k,* can be estimated for the next *n* years. That will lead to the *FV* and *n* being the only two remaining unknowns, these will be solved for by substituting equations 1 and 2 into each other.

6.3.1 Calculation of Interest Rate

By assuming that the government expects a repayment figure that includes interest, this interest rate can be calculated based on the historical lending rate in South Africa.

A table of the changes in the prescribed rate since 1993 is given below [55]:

Date range	Rate of interest
1 October 1993 – 31 July 2014	15.5% pa
1 August 2014 – 29 February 2016	9% pa
1 March 2016 – 30 April 2016	10.25% pa
1 May 2016 – 31 August 2017	10.50% pa
1 September 2017 – 30 April 2018	10.25% pa
1 May 2018 – 31 December 2018	10% pa
1 January 2019 – 31 August 2019	10.25% pa
1 September 2019 – 29 February 2020	10% pa
1 March 2020 – 30 April 2020	9.75% pa
1 May 2020 – 31 May 2020	8.75% pa
1 June 2020 –	7.75% pa

Table 9: Table of interest rate changes since 1993

From 2014, its clear that the interest rate decreased from 15.5% to around 10% up until this year. It did, however, drop even further this year due to the COVID-19 pandemic. However, this is likely to be a temporary decrease up until the pandemic ends. To calculate the interest rate, the figures ranging from August 2014 until the end of February 2020 will be used. Tallying these rates up (70.25%) and dividing them by the respective period with which they apply (7 terms), the average interest rate is calculated as 10.04%.

6.3.2 Calculation of the Current Cost of Electricity for Low-Income Households

The cost of electricity in an average low-income household in Cape Town, as discussed earlier, was R364.58 per month in the year 2015. There is limited information related to the overall average electricity expense across low-income households across the whole of South Africa. The figure of R364.58 will therefore be used in further calculations to represent this.

The average cost of electricity in 2015 was 85c/kWh. The average cost of electricity in 2020 is 105c/kWh [56]. An estimation of the present cost of electricity for low-income households can be made by simply multiplying R364.58 by the factor 105/85. This method estimates the present-day cost to be R450.36 monthly and R5 404.32 per annum.

6.3.3 Calculation the Tariff Increase Rate

In 2019, Power Optimal released statistics related to the increase in electricity tariffs since 1988. The graph below shows the Eskom tariffs from 1988 to 2019, plotted against CPI (Consumer Price Index) or inflation over the same period. It also shows projections up to 2022, based on currently projected increases as approved by NERSA (8.1% in 2020 and 5.2% in 2021), as well as Stats SA and the Bureau for Economic Research's inflation projections [57].

Figure 25 below illustrates just how intense Eskom's electricity crisis is. Prior to the 2008 electricity crisis, electricity tariff increases did not keep tread with inflation. This was partly due to government policy to keep electricity tariffs as low as possible for poor communities, but also due to Eskom having an oversupply of electricity (in the 1990's) and not investing in new capacity (in the 2000's). This adversely affected the tariff rates thereafter and led to the tariff rates increasing by 446% from 2007 to 2019. In comparison, the inflation rate from 1988 to 2007 was 223% and the rate of inflation from 2007 to 2019 was 98% [57].

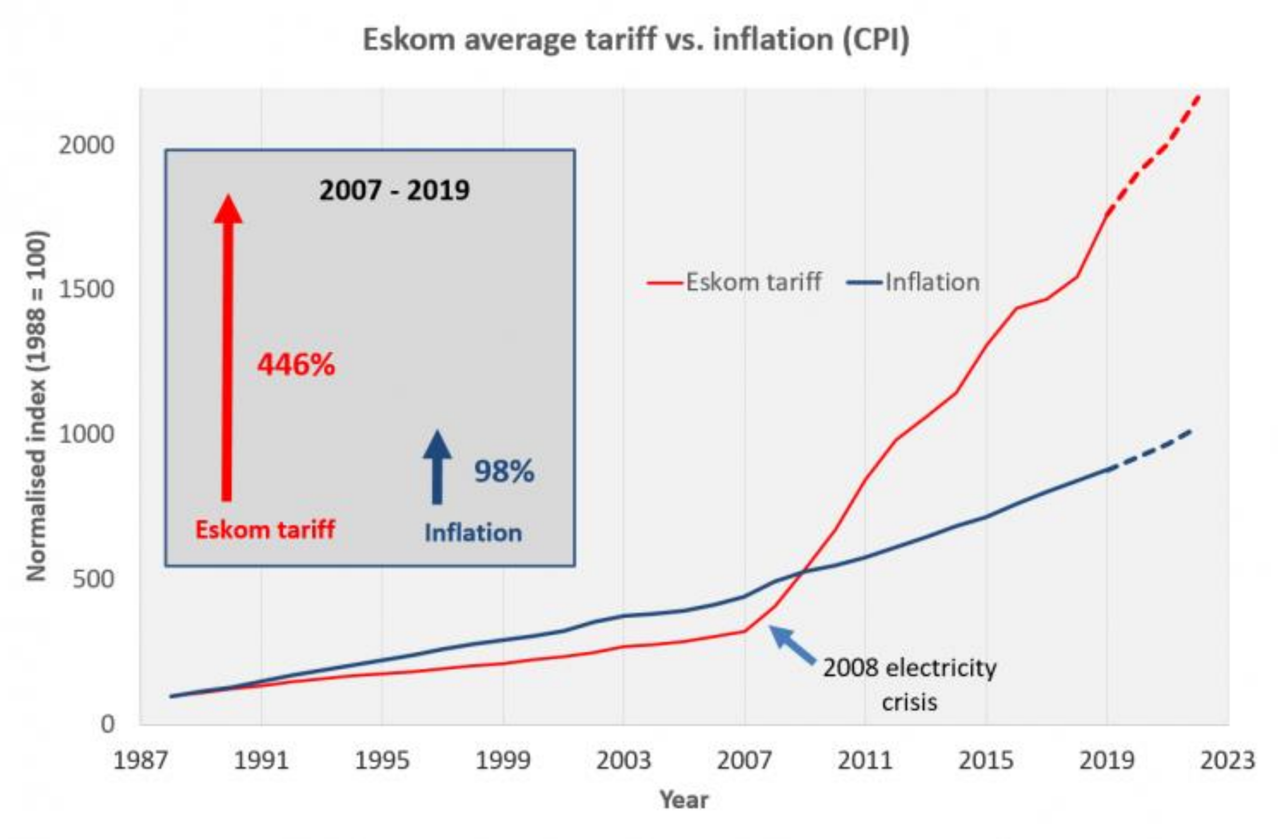


Figure 25: Graph of average tariff rates vs Inflation

Equation 1 can also be used here to calculate the interest rate, given the 446% increase in tariff rates over a 13-year period. This formula will be rewritten under newly labelled variables so as to not confuse them with the aforementioned Equation 1 variables.

$$fv = pv(1 + \frac{k}{x})^{xy} \tag{3}$$

With *pv = 1*, *fv = 4.46, x=1* and *y = 13* this gives the average tariff rate, *k*, as 12.21%.

6.3.4 Calculation of the Repayment Period

With the values of *k*, *i,* and *PV* now known, the two unknowns that remain are *FV* and *n.* By substituting all known values into their respective equations, the two equations can then be solved simultaneously to find the values of both *FV* and *n.*

Therefore, by substituting *PV = R30 406.78, i = 10.03%, m= 1, CC = R450.36,* and *k = 12.21%* into equations 1 and 2 respectively and thereafter solving them simultaneously, the value of *n* is 5.09 and the *FV* value is R49 460.90.

This means that by paying the exact same rate for electricity as they do at present, inhabitants of RDP households will be able to fully pay-off their PV systems over a period of 5 years and 1 month.

This is a relatively short pay-back period, and the government might want to consider extending the repayment period to further lessen the financial burden on these inhabitants depending on their financial means and standing.

6.4 Long Term Gains

6.4.1 Benefits for the RDP household Inhabitants

RDP household inhabitants will have full ownership of their PV systems after just 5 years and 1 months. This means that, if the PV system continues to produce 2.366kWh per day beyond this period, they will be saving on electricity expenses that equates to 70.98kWh of energy per month. Together with the 50kWh of free basic electricity offered by the government, this would lead to household having a free energy supply of 120.98kWh per month. This is a brilliant investment for them, and it will lead to the value of their homes being increased.

The flexibility of the system will also allow for them to expand it if they choose to do so. There is also a possibility for them to expand these systems and change the inverters to grid-interactive inverters, thereby allowing them to earn a passive income by exporting unused electricity to the grid.

6.4.2 Benefits for Government

For the government, this method will be allowed for them to recoup the capital expenditure laid out on this project within a relatively short period. The state-owned enterprise, Eskom, will significantly benefit from the decreased pressure on its grid.

According to the BBC, The South African government had said that 3.2 million homes were built from 1994 to 2018. Assuming that no new RDP houses were built since then and that the solar energy produced by each household is 70.98kWh, this would mean that Eskom would be saving on 2.73GW of coal-generated power every year just by RDP houses being powered by solar energy.

By developing this project further and finding the financial resources to offer grid-interactive systems to the inhabitants, Eskom will benefit by having power sold to them at a low price, allowing the burden on the grid to be lessened even further.

Perhaps the implementation of this project will also lead to less illegal electricity connections and cable theft, allowing for the government to save millions of rands in that respect too.

Finally, this will also allow South Africa to take a step towards decreasing their reliance on coal as the dominant source of energy. This will lead to a decrease in greenhouse gas emissions and benefit the country in its fight against climate change.

7. Modelling & Simulations

According to the design process given in Design Choices and based on the specifications provided by the various suppliers, the designed system should work in implementation. To further verify the systems application and to determine its suitability in implementation, the entire system was modelled, designed, and simulated using Simulink. This section will include the modelling and simulation of each respective photovoltaic and power electronics component. The datasheets of the fundamental selected PV components, as stipulated in Table 7: Table of costs for components sourced individually from different suppliers, can be found in Appendix C – Datasheets. The link to the Github repository containing the simulation files is https://github.com/tareeqsaley/FYP-EEE4022S

Two important considerations are evaluated in this section, the suitability of each chosen component with respect to each other and the optimality of the design in terms of costs.

7.1 PV Module

7.1.1 Modelling

The first step in the modelling process involves modelling the PV array. An extract of the datasheet with respect to the module chosen for the design as per the Cost Breakdown section of this document is given below. To reiterate this is a 280W Poly PERC 5BB Solar Panel.

Type	Value
Rated Maximum Power(Pmax) [W]	280
Open Circuit Voltage(Voc) [V]	39.12
Maximum Power Voltage(Vmp) [V]	31.38
Short Circuit Current(Isc) [A]	9.45
Maximum Power Current(Imp) [A]	8.93
Module Efficiency [%]	17.2

Table 10: Datasheet of the 280W solar panel chosen for system

The above datasheet stipulates the characteristics of the module without necessarily going into detail of the current and voltage parameters of the solar cells stringed together in the module. To establish a model of the cell from first principles, these parameters need to be calculated.

Two distinct models have been used in studies for mathematical modelling of PV cells: the single-diode model and the double-diode model. The latter is mathematically intensive albeit more accurate, the former being simpler with an acceptable level of accuracy [58]. This research uses the single-diode model; its equivalent circuit and respective governing equation is given below [59].

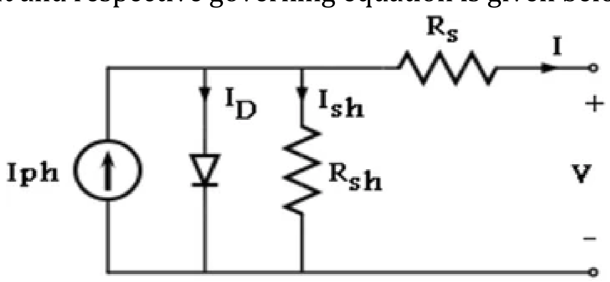


Figure 26: Equivalent circuit of PV cell (single-diode model)

$$I = I_{ph} - I_o\left[e^{\frac{q}{aKT}(V+R_sI)} - 1\right] - \frac{V + R_sI}{R_{sh}} \qquad (4)$$

With,

- I = array output current
- V = array output voltage
- I_o = saturation currents of the diode
- T= array temperature in K
- I_{ph} = light-generated current
- K = Boltzmann constant
- R_s = series resistor of PV model
- R_{sh} = shunt resistor of PV model
- I_D = currents of the diode
- a = The ideality factor

An expansion of figure 27 which represents strings of cells connected in series and parallel to form a solar array is given below.

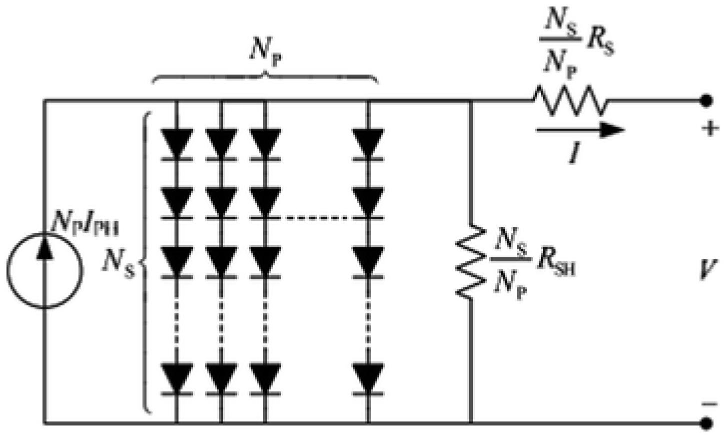


Figure 27: Equivalent circuit of PV array

There are five currents which control the photovoltaic characteristics of the PV module. They are the photo-current (I_{ph}), saturation current (I_o), reverse saturation current (I_{rs}), shunt resistor current (I_{sh}), and the output current (I). The equations for these respective formulae are given below [59].

$$I_{ph} = [I_{sc} + K_i(T - 298)] \times \frac{I_r}{1000} \tag{5}$$

Where K_i is the short-circuit current of cell at 25°C and 1000W/m2; T is the operating temperature represented in Kelvin; and I_r is the solar irradiation in W/m2.

$$I_{rs} = \frac{I_{sc}}{e^{\frac{qV_{oc}}{N_s akT}} - 1} \tag{6}$$

Here, q is the electron charge constant; N_s is the number of cells connected in series; a is the ideality factor of the diode; and k is Boltzmann's constant.

$$I_o = I_{rs} \left[\frac{T}{T_r}\right]^3 e^{[\frac{qE_{g0}}{ak}(\frac{1}{T} - \frac{1}{T_r})]} \tag{7}$$

Here, T_r represents the nominal temperature; and E_{g0} is the band gap energy of the semiconductor.

$$I_{sh} = \frac{V\frac{N_p}{N_s} + IR_s}{R_{sh}} \tag{8}$$

Here, N_p is the number of PV cells connected in parallel; R_s is the series resistance (Ω) and R_{sh} is the shunt resistance (Ω).

$$I = N_p \times I_{ph} - N_p \times I_o \left(e^{\frac{V/N_s + IR_s/N_p}{aV_t}} - 1 \right) - I_{sh} \tag{9}$$

Finally, the output current is stated above with the diode thermal voltage, V_T given below.

$$V_t = \frac{kT}{q} \tag{10}$$

It should be noted that usually the value of R_{sh} is very large and that of R_s is very small, hence they may be neglected to simplify the analysis. Taking this into consideration, the input parameters for equations 5 to 10 are given as :

- $T_r = 298.15K$
- $a = 1.7$
- $k = 1.3805 \times 10^{-23} J/K$
- $q = 1.6 \times 10^{-19}$
- $I_{sc} = 9.45A$ at STC
- $V_{oc} = 39.12V$ at STC
- $E_{g0} = 1.1eV$
- $R_s = 0.0001\Omega$
- $R_{sh} = 1000\Omega$

These five current equations were then used to simulate a single PV module based on the above parameters and the datasheet parameters in Table 10: Datasheet of the 280W solar panel chosen for system.

7.1.2 Simulation

Using Simulink, the respective current formulae given by eq.5 to eq.9 were all recreated in Simulink so that the I-V characteristics of the modelled PV array could be simulated. The respective Simulink subsystems which represent each equation are expanded in B.1 - PV Module Simulations .

Subsystem blocks for each respective current were created and an interface for these blocks to interact with each other was then designed in order to model a PV module. The two inputs into the model are the solar irradiation and temperature, with the outputs being the current and voltage. Figure 68: Simulink block diagram modelling a PV module68 in B.1 - PV Module Simulations illustrated this model.

Finally, Figure 69: Simulink model of PV module to determine characteristic curves9 in B.1 - PV Module Simulations represents the Simulink model used to determine I-V and P-V characteristics of the modelled module at STC. The results for this are shown and discussed in section 7.1.

7.2 PV Array

7.2.1 Modelling

The configuration of the solar array needs to be structured such that the selected inverter is not overpowered by the panels. The rated input voltage range of the inverter, as per its datasheet in Appendix C – Datasheets, is 21.6VDC to 32VDC. Since the maximum power voltage of each module is 31.38VDC, it is intuitive to connect the two modules in parallel to satisfy the inverter's input range. This is because in a parallel connection, the voltage of the system will remain constant while the current doubles.

Apart from knowing the configuration of the array, the values of the load resistances of the array need to be known. These need to be set such that the array can meet its maximum power voltage. Through the trial and error process and knowing that the output of the PV array should be 560W (280W for each panel multiplied by two panels), this resistance was estimated based on Ohm's Law.

7.2.2 Simulation

To ensure that the signal produced by the PV module is dependent exclusively on the system voltage, which is generated by the PV array, the ramp function in Figure 68: Simulink block diagram modelling a PV module was removed. Instead, a controlled current source block was added to Figure 69: Simulink model of PV module to determine characteristic curves so that the current signal at the output is converted into an equivalent current source. A load resistor was then connected to the circuit so that the system could maintain its respective MPP current and voltage values. Knowing what those values were, the size of the resistor was altered through a trial and error process until they were achieved. The updated PV system with a single module and the PV module subsystem are given in Figure 71: PV system with a single module in Simulink in Appendix B.2.

From Figure 71: PV system with a single module in Simulink, it can be seen that the PV system is able to almost perfectly generate the expected 280W of power from the theoretical MPP voltage (31.38V) and current values (8.93A) using a load resistor of 3.5Ω.

The next step involved connecting two modules in parallel to establish the desired 560W of power. The system should also ensure that the voltage remains constant as part of parallel configuration requirements. By Ohm's law ($V = I \times R$), for a constant voltage, and a doubling of the current as per the parallel configuration, the resistance should be halved. The Simulink block diagram representing the two modules connected in parallel is given in Figure 72: Simulink block diagram representing two 280W modules connected in parallel in Appendix B.2.

7.3 DC-DC Converter

7.3.1 Modelling

A boost converter was selected for this design. As mentioned in the literature review, its purpose is to boost the DC voltage of the solar array to a sufficient value so that it can be converted into AC power required for the load. The circuit diagram for this converter is provided below [60].

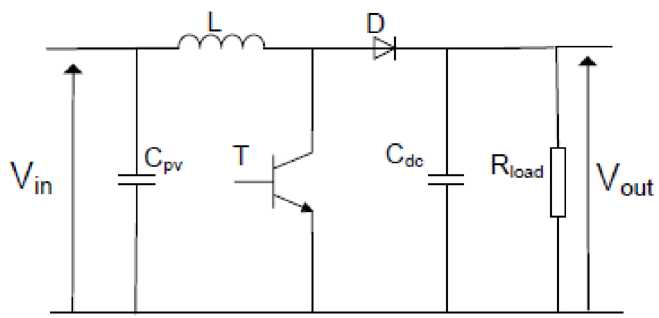


Figure 28: Circuit diagram of a boost converter

The DC input voltage is in series with an inductor L that acts as a current source. A switch T is in parallel with the current source that turns on and off periodically, providing energy from the inductor and the source to increase the average output voltage.

i. ***On-State***

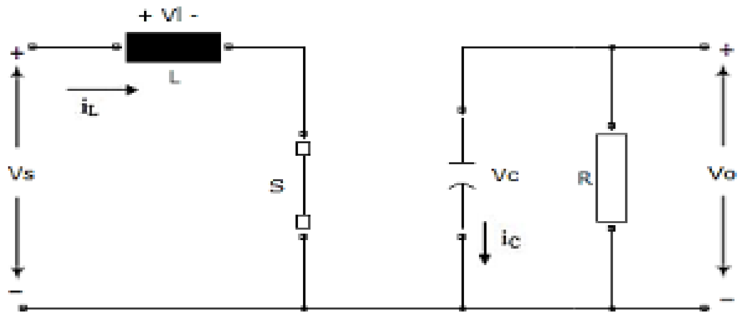


Figure 29: Transmission state of semiconductor switch

In the figure above, for a constant voltage the rate of rise of the inductor current is also constant to prevent saturation [61]. Using Kirchhoff's voltage law,

$$\frac{\Delta i_L}{\Delta t} = \frac{V_s}{L} \tag{11}$$

Solving for the inductor current this gives,

$$\Delta i_L = \frac{V_s}{L}\Delta t \tag{12}$$

ii. ***Off-State***

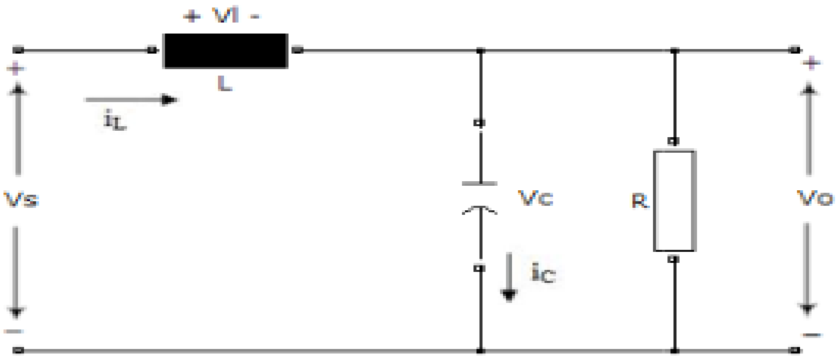


Figure 30: Cut-off state of semiconductor switch

Figure 30 shows that, if the source voltage is constant, the inductor voltage can be given by [61]:

$$L\frac{\Delta i_L}{\Delta t} = V_L = V_s - V_o \tag{12}$$

$(1 - D)T$ is the interval value when the switch is cut off. The inductor current is then:

$$\Delta i_L = \frac{V_s - V_o}{L}(1 - D)T \tag{13}$$

And since the net change in the current is 0 over a single period, further simplification gives:

$$V_o = \frac{V_s}{(1-D)} \tag{14}$$

The 'D' value ranges between 0 and 1, thereby causing the output voltage to be higher than the input voltage.

7.3.2 *Component Selection*

The design of the boost converter requires the value of load resistance, inductor, and capacitor specifications. There are six parameters that are used to calculate these values, these are listed in table 11 below with more detail related to their choices thereafter.

Parameter	Value
Nominal input voltage V_{in}	31.38V
Nominal output voltage V_{out}	47.07V
Maximum output current $I_{out(\max)}$	11.90A
PV maximum power P_{max}	560W
Switching frequency F_s	10kHz
Estimated inductor current ripple ΔI_L	5.35A

Table 11: Input parameters for DC-DC converter component selection

- $\boldsymbol{V_{in}}$: This is the DC voltage provided by the solar array that is fed as an input to the converter.
- $\boldsymbol{V_{out}}$: Selected to be 1.5 times larger than Vin(nom) since the converter has a wide input voltage range that depends on the solar irradiation [62].
- $\boldsymbol{I_{out(\max)}}$: This is the maximum output current based on the selected output voltage and maximum power values.
- $\boldsymbol{P_{max}}$: The total power provided by the PV array.
- $\Delta \boldsymbol{I_L}$: Estimated to be 0.3 times the size of the maximum output current multiplied by $\frac{\boldsymbol{V_{out}}}{\boldsymbol{V_{in}}}$ [63].

With these parameters having been calculated, the various component sizes can be calculated. These calculations are given in A.3 - Boost Converter Component Sizing Calculations.

7.3.3 *Simulation*

The Simulink block diagram for the simulated boost converter was designed based on the abovementioned calculations and is given in B.3 - Boost Converter Simulations.

7.4 Charge Controller

Tracking the maximum power point (MPP) of a photovoltaic array is an essential stage of a PV system. Various MPPT methods have been introduced with variants of them developed to overcome their disadvantages. Two of the most common algorithms that are used for MPPT applications are the Perturbation & Observe and Incremental Conductance algorithms [64].

7.4.1 *Modelling*

i. *Perturbation and Observation Method*

From figure 31 below, this method operates by increasing or decreasing the array terminal voltage, or current, at regular intervals and then comparing the PV output power with that of the previous sample point. If the PV array operating voltage changes and power increases (dP/dV PV > 0), the control system adjusts the PV array operating point in that direction; otherwise the operating point is moved in the opposite direction. The algorithm continues to operate in the same manner at each perturbation point. This method is favoured because of the simplicity of its technique and produces good results provided that there is no drastic change in irradiation. The classic P&O method has the disadvantage of poor efficiency at low irradiation. The flowchart for this method is given below [62].

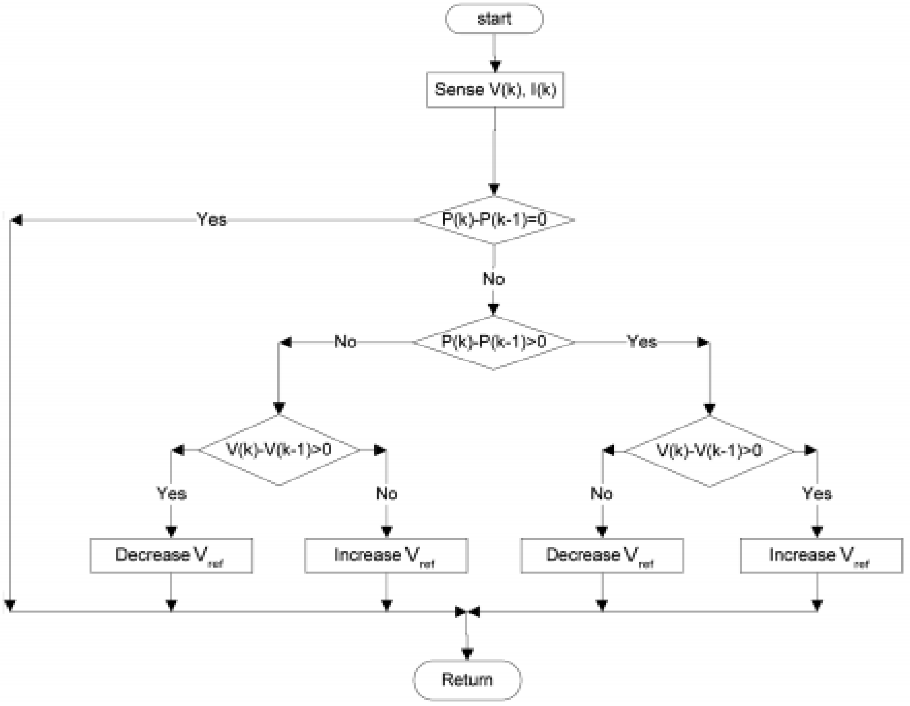


Figure 31: Flowchart of the P&O algorithm

ii. Incremental Conductance Method

The limitations of the perturbation and observation algorithm are overcome by the incremental conductance method because of it using the incremental conductance of the photovoltaic. This algorithm looks for the operating point at which both the conductance and incremental conductance are equal after which it stops perturbing the operating point. The advantage of this algorithm is that it can ascertain the relative "distance" to the maximum power point (MPP), therefore it can determine when the MPP has been reached. It also tracks the MPP more accurately in highly varying weather conditions and exhibits less oscillatory behaviour around the MPP compared to the P&O method, even when the P&O method is optimized. It can, however, be unstable because of it using a derivative operation in its algorithm. It is also prone to measurement noise under low levels of insolation which can lead to unsatisfactory results. Its operation is further illustrated in the flow chart below [64].

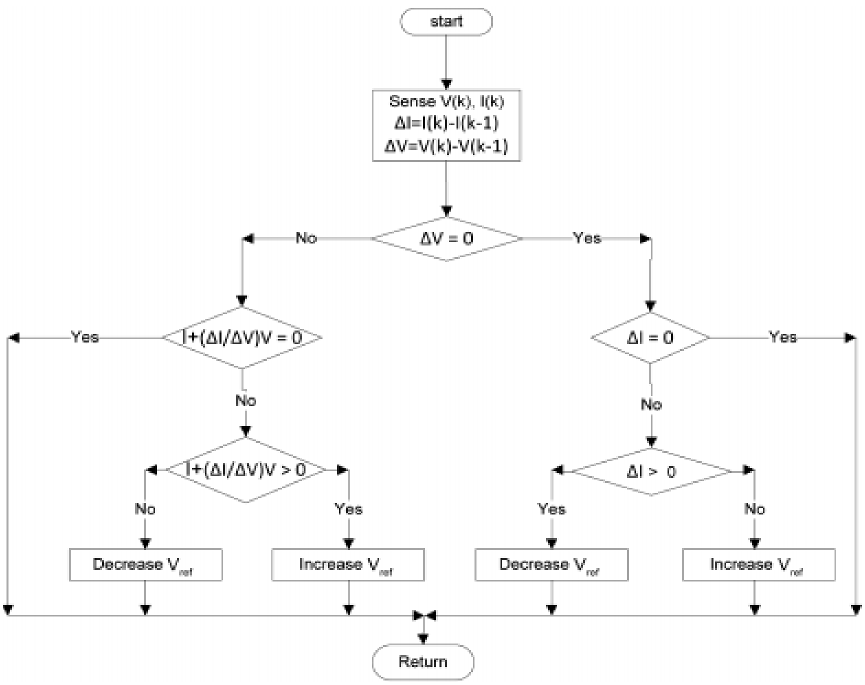


Figure 32: Flowchart of the IC method

7.4.2 Simulation

Research has shown that the enhancement of the P&O algorithm exhibits faster dynamic performance and achieves steady state level better than the incremental conductance method over a broad range of irradiation settings and load profiles. The P&O method will therefore be used for the simulation. The block diagram for a standalone PV system with the charge controller included is given in Figure 33 below.

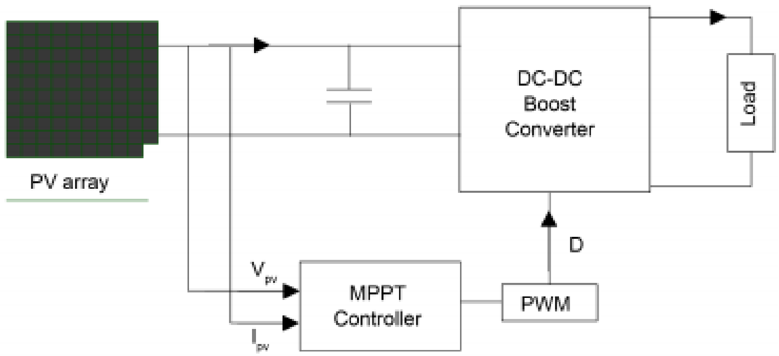


Figure 33: Block diagram of standalone PV system

As can be seen from the figure above, the mathematically modelled PV array and the designed DC-DC boost converter need to interact with both each other and the MPPT controller to be designed. The PV array detects the irradiation and temperature values at a given point in time and uses those values to generate an output voltage and current. These values are then fed into the MPPT controller which then uses the perturb and observe method to compare them to the maximum power point current and voltage. The duty cycle is then decreased or increased until the maximum power point of the photovoltaic is achieved. This duty cycle generates a PWM signal which is fed to the DC-DC boost converter.

The perturb and observe algorithm block was modelled based on its flowchart in figure 31. This can be seen in the diagram in Figure 74: Simulink block diagram of P&O algorithm Appendix B.4.

The integration of the modelled MPPT block together with the existing PV array and DC-DC boost converter that was design is further illustrated in Figure 75: Simulink block diagram of MPPT integrated PV system in Appendix B.4.

An analysis was also done on the efficiency of the system to gauge just how well the MPPT controller performs. The ideal power curve will be used as a benchmark for comparison. This will fundamentally be based on the ideal system producing 560W of power at STC conditions. This block diagram addition used for comparing the system power output to the ideal curve and for calculating the mean efficiency of the system is shown in Figure 76: Simulink block diagram used to compare PV power to ideal and calculate MPPT efficiency in Appendix B.4.

7.5 Batteries

7.5.1 Modelling

Through electrochemical reactions, the stored chemical energy in lead-acid batteries can be converted into electrical and vice versa. This electrochemical reaction is described below.

$$PbO_2 + 2H_2SO_4 + Pb \xrightleftharpoons[charge]{discharge} 2PbO_4 + 2H_2O \tag{15}$$

The battery behaviour, in general, is described by its voltages.

$$V = V_{oc} \pm IR \tag{16}$$

Where Voc is the open circuit voltage and R is the internal resistance. During charge the current, I, is positive and during discharge it is negative. The internal resistance is variable, and depends on other parameters such as capacity, charge/discharge current, and temperature. The equivalent circuit which captures the dynamic performance of lead-acid batteries is shown below.

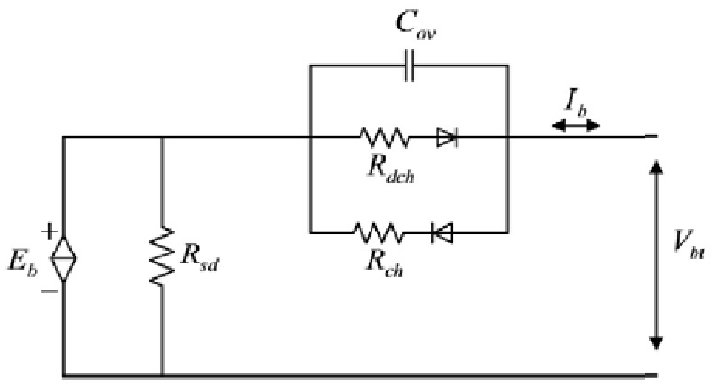


Figure 34: The dynamic model of a lead-acid battery

Figure 34 shows that the electric current, I_b, flows through R_{ch} during charging and through R_{dch} during discharging. R_{sd} models the self-discharge losses in the battery. The terminal voltages of the battery are derived as:

$$V_{bt\_charging} = E_b + I_b R_{ch}(1 - e^{\frac{-t}{R_{ch}C_{ov}}}) \tag{17}$$

$$V_{bt\_discharging} = E_b - I_b R_{dch}(1 - e^{\frac{-t}{R_{dch}C_{ov}}}) \tag{18}$$

7.5.2 Simulation

Simulink's Simscape tool offers a built-in block representing a battery. This block represents the entire characteristics of the physical battery bank and was used in simulation for simplicity. The battery charging and discharging model was designed and integrated into the already designed PV system with MPPT control.

A bi-directional buck-boost DC-DC converter is added to the battery model and was used to step up the lead-acid voltage during discharging and to step it down during charging. Further to this, control blocks were added to the model to ensure that MPPT is maintained efficiently. The complete block diagram with the appended battery model together with a focused view of just the battery model itself can both be found in B.5 - Battery Bank.

7.6 Inverter

7.6.1 Modelling

The solar inverter needed for the conversion of generated DC power from the modules to AC power suitable for the load was then designed. The block diagram representing its integration into the PV system is shown below [65].

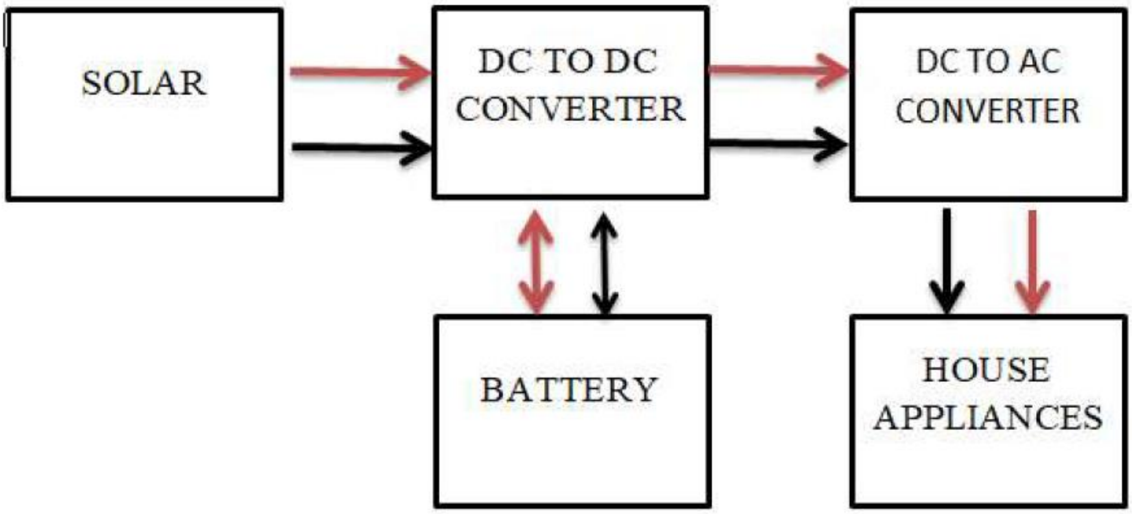


Figure 35: Block diagram representing the inverters integration into the PV system

Based on figure 35 above, the figure 36 below details the circuit diagram required to realize the block diagram [66]. An AC output required a 220V RMS output at a frequency of 50Hz, The full-bridge inverter is connected in parallel to the boost converter with the sinusoidal pulse width modulation method coupled with voltage control used for the switching, R2 represents the AC load and the LC filter parameters are extracted based on the following equation.

$$f = \frac{1}{2\pi\sqrt{L_2 C_2}} \tag{19}$$

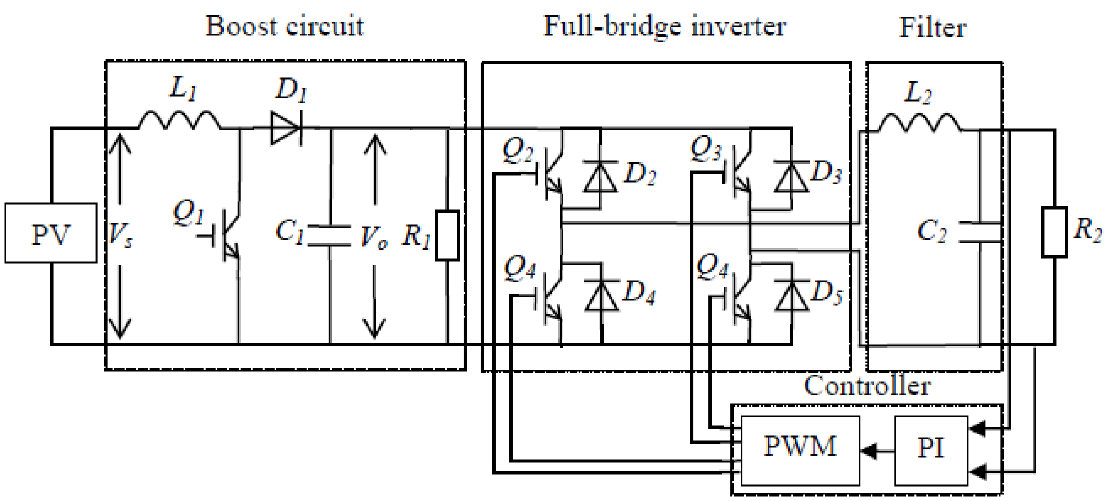


Figure 36: Circuit diagram representing integration of inverter into PV system

There are 3 PWM techniques worth considering for inverter application. Their suitability based on cost, load and application constraints are listed in the table below [67].

Inverter Types (Based on PWM Technique)	Cost	Size	Suitable Type of Load	Applications
Square	Low	Application specific	Resistive	Universal motors in hand tools, Kettles, jugs, radiators, stoves, etc.
Quasi-sine	Moderate	Application specific	Resistive and Inductive	Above mentioned applications plus in refrigerators, freezers, etc.
Sine	High	Application specific	Nearly all types of load	Almost all electrical equipment work efficiently- microwave ovens, motors, etc. digital clocks, etc.

Table 12: Analysis of PWM techniques for solar inverter application

Microcontroller based SPWM inverters provide the best results for applications such as in standalone systems or in grid-connected inverter system with direct supply from PV cells. This method was used for the simulation [67].

7.6.2 Simulation

The inverter used for simulation was designed based on the circuit diagram in figure 36. The full-bridge inverter is controlled in a closed loop by comparing the voltage across the load to the required 230V RMS voltage. A 12V-230V step up transformer is also added to the design to help the inverter meet the required voltage output. From the previously designed boost converter, R1 was excluded from the design as it was not required and C1 was increased to reduce output voltage ripple; all other values were unchanged. The parameters for the simulation are listed below.

Component	Parameter
Inductance L2(H)	797.53e-5
Capacitance C1(uF)	834.39e-5
Capacitance C2(uF)	31.76e-7
AC Load Resistance(W)	370
Ki	0.091
Kp	6.9e-4

Table 13: Component parameter choices for designed inverter

The Simulink diagram used for this simulation is listed in Figure 79: Simulink block diagram of DC-AC inverter in B.6 - Inverter with Figure 80: Inverter voltage control block expanding on the voltage control block used for it.

7.7 Full PV System Implementation

With all the necessary PV components having been designed and simulated based on their respective specifications, the load and irradiance input profiles could then be modelled and implemented in the existing system. The results will ultimately determine whether the designed system will be able to meet load requirements based on historical irradiance levels. Two South African areas were used for analysis, Aggeneys and Cape Town. These areas are specifically selected since Aggeneys experiences some of the highest levels of insolation, whilst Cape Town experiences average levels of insolation, respectively. Also, not much data has been made available regarding the historical average daily insolation that South Africa experiences and these were amongst the relatively few credible data sources to turn towards.

7.7.1 Modelling

i. Load Profile Development

The consumption guidelines in Table 3*: Typical low-income electrical household appliances with power consumptions* together with the estimated appliance usage analysis that follows were used as a basis for determining the load profile.

The appliances that need to be catered for are the LED lights, LED TV, cell phone charging devices, fan, and fridge. It is assumed that the lights will be switched on for a maximum of 8 hours between 18:00 to 00:00 and again from 05:00 to 07:00. The LED TV is assumed to be operational from 16:00 until 20:00 and 22:00 until 00:00. The cell phone charging devices are switched on from 17:00 to 20:00. The fan is switched on from 15:00 to 21:00. Finally, the fridge, based on its duty cycle and in the worst case (while all other appliances are also operational), is assumed to draw power from 14:00 to 22:00. As suggested in 3.2.3, a safety factor of 1.25 will also be multiplied to the total usage curve. The estimated load profile curve over a 24-hour period is given below; the 0 point on the x-axis corresponds to 00:00.

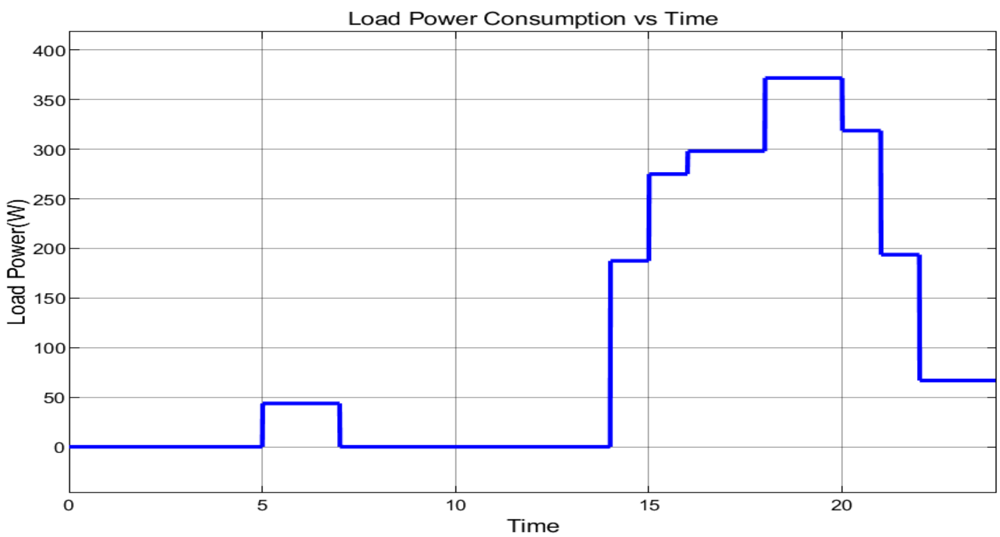


Figure 37: Load profile of RDP household based on estimated appliance usage

ii. Irradiation Profile Development

Aggeneys

In 2009, Eskom captured insolation data across 4 of its substations in the Northern Cape. One of those substations is near a mining town by the name of Aggeneys [68]. The recorded irradiation data for this area spanned over a period of just 3 days, making it impossible to establish the average hourly irradiation data across a full calendar year. Hence, the data used for this profile ranges between 00:00 on 26/03/2009 to 00:00 27/03/2009. The irradiation profile is given below.

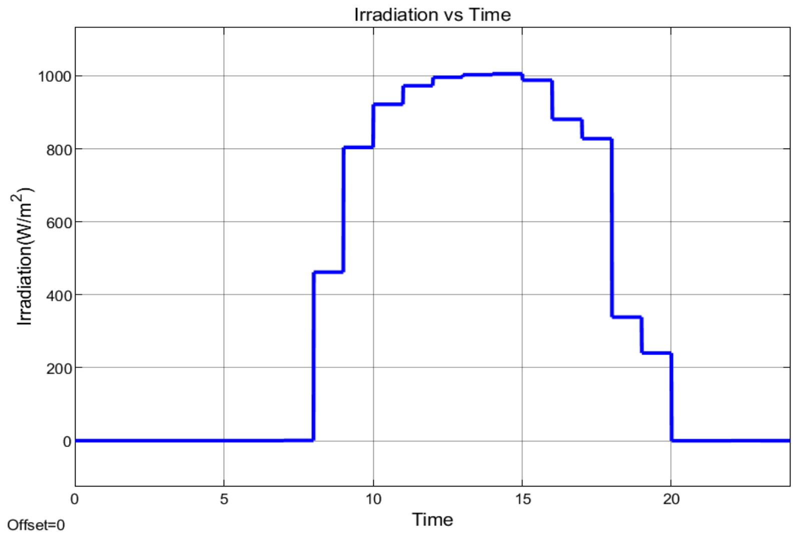


Figure 38: Irradiation profile for Aggeneys

Cape Town

Meteo Cape Town is a website which offers data related to the average hourly temperature and irradiation values since 2015 [69]. This data was used to develop an irradiation profile for simulation purposes. The irradiation profile is given below.

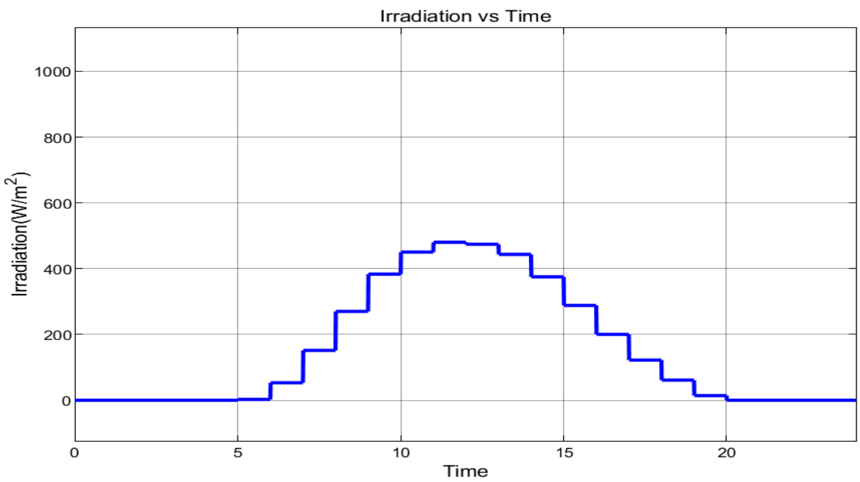


Figure 39: Irradiation profile for Cape Town

7.7.2 Simulation

This research accepts that a simulation based on the insolation data for two areas is not enough to justify the systems application across all South African towns. However, the simulation was used as an indicator to prove that the designed system will indeed be able to meet the load demands whilst being exposed to more 'realistic' irradiance inputs.

Therefore, the irradiation profile given in figure 38 together with its corresponding temperature values were used as inputs to the PV array. The load profile in figure 37, which represents the power across the AC load, was used in the modelled inverter block. The load profile was converted to an equivalent resistance using Ohm's Law ($P = \frac{V^2}{R}$), and fed into a variable resistor such that the PV system is able to dynamically adjust the resistance every hour.

To be able to interpret how the irradiation charges the battery under low/zero load conditions, the initial SoC of the battery will be changed to 75%. The overall PV system with all its integrated modelled blocks is found in Figure 81: Simplified Simulink diagram of entire PV system with integrated component subsystems in B.7 – Full PV System Implementation. The variable resistor block can be found in Figure 82: Variable resistor block used as dynamic load.

8. Results & Discussion

8.1 PV Module

The following two figures below represent the theoretical and simulated I-V curves for the 280W solar module chosen for this design.

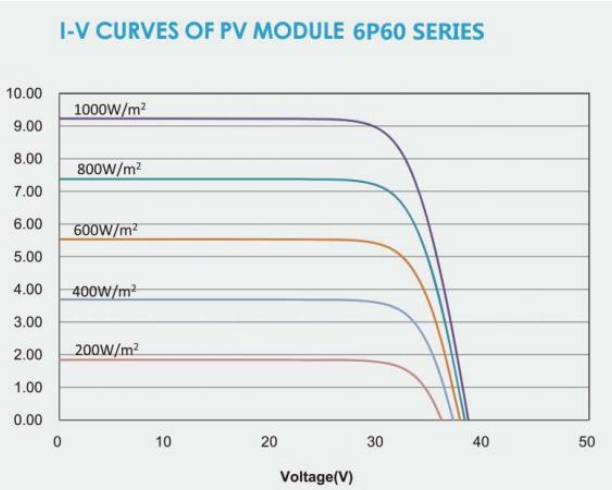


Figure 41: Theoretical I-V curve with varying irradiance

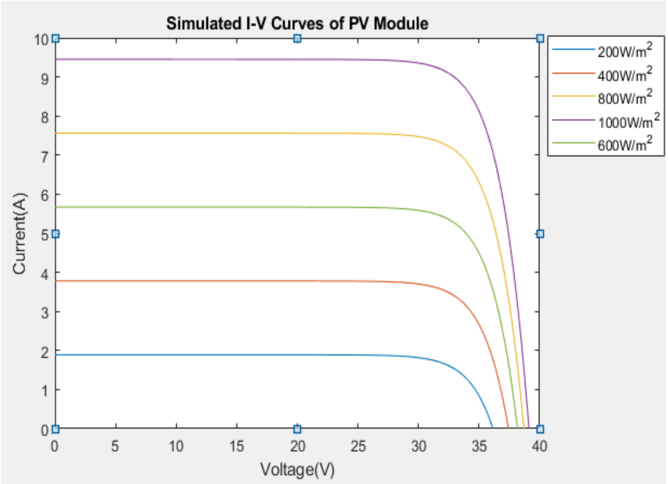


Figure 40: Simulated I-V curve with varying irradiance

The above two figures show that the modelled PV module displays characteristics that almost exactly match those given in the datasheet in Appendix C – Datasheets. It should be noted that the theoretical I-V curves as given in figure 41 give the average approximation for all modules in the 6P60 series, and not just the 280W module. This would explain the slight discrepancy between the theoretical and simulated curves.

It is evident from figure 40 that the voltage and current of the solar array decrease with lower irradiation. This is expected as the effects of overcast weather imply that the solar irradiation will be lower and hence the power provided by the PV system will be lower. This is further substantiated by the P-V curve given below under varying irradiation conditions.

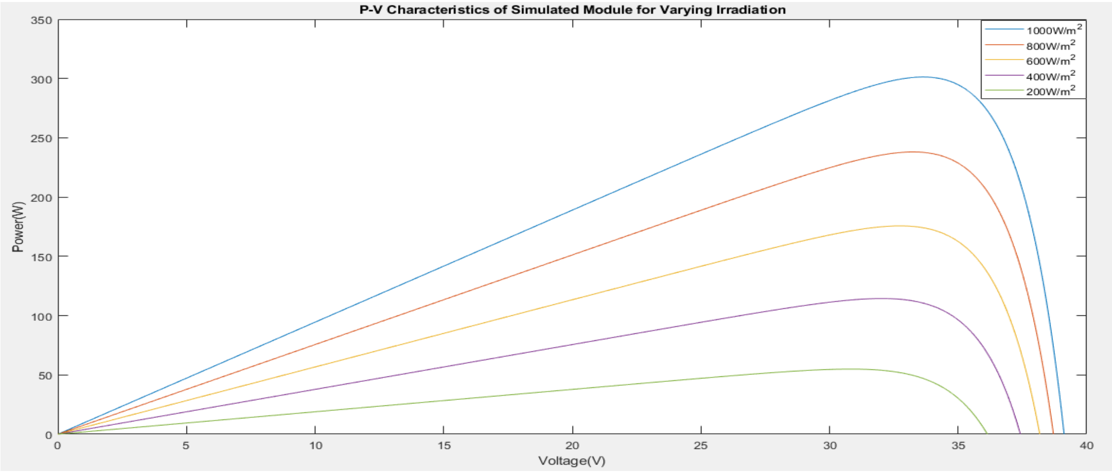


Figure 42: Effects of varying irradiation on solar module output power

The effect of changing temperatures for a fixed irradiation is given in the figure below.

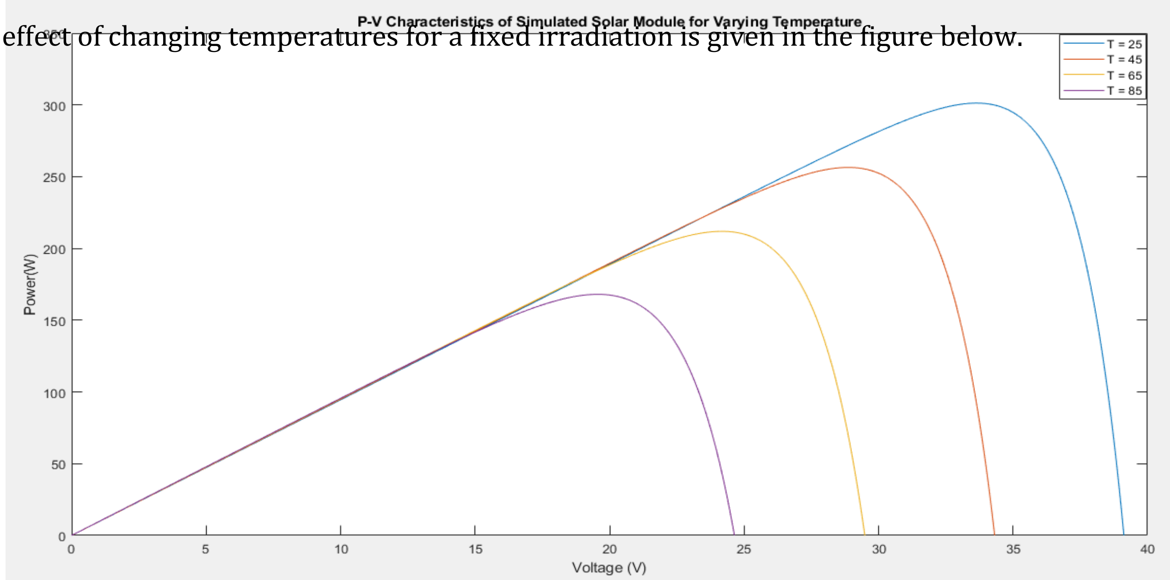


Figure 43: Effects of varying temperature on solar module power output

It is noticed from figure 43 above that, almost counterintuitively, increasing the temperature decreases the efficiency of the solar module hence reducing the power output.

8.2 PV Array

The designed PV array and inverter selections could only be justified if it were confirmed that they would be able to work with each other based on their respective technical specifications.

Figure 72: Simulink block diagram representing two 280W modules connected in parallel in B.2 - PV Array Simulations shows that the expected output voltage of the PV array (31.38V) equates to the MPP voltage value in a parallel configuration. This is within the inverters input voltage range of 21.6VDC to 32VDC and the inverter will therefore not be overpowered by the panels. The chosen inverter, therefore, did not need to be replaced with one of a higher power rating based on specification deficiencies.

8.3 DC-DC Converter

The simulation results of the designed boost converter based on the calculations in B.3 - Boost Converter Simulations is given in the figure below. This figure suggests that the boost converter can successfully boost the input voltage from 31.38V to an output of 47.07V with a 1% output voltage ripple.

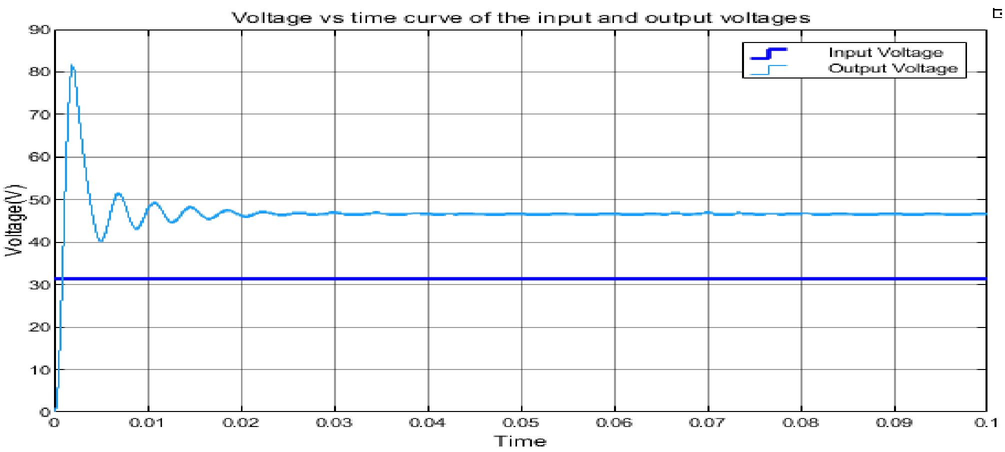


Figure 44: Performance of a simulated boost converter

8.4 Charge Controller

Prior to the addition of the MPPT functionality, the system was unable to track the maximum power point, causing it to be much less efficient. This is noticeable in the two figures below, which represent the performance of the previously designed system without and then with the added MPPT functionality. It is also observed that the power curve is a lot more oscillatory without MPPT functionality. In the figures below, the irradiation value was stepped down to $600W/m^2$ at t

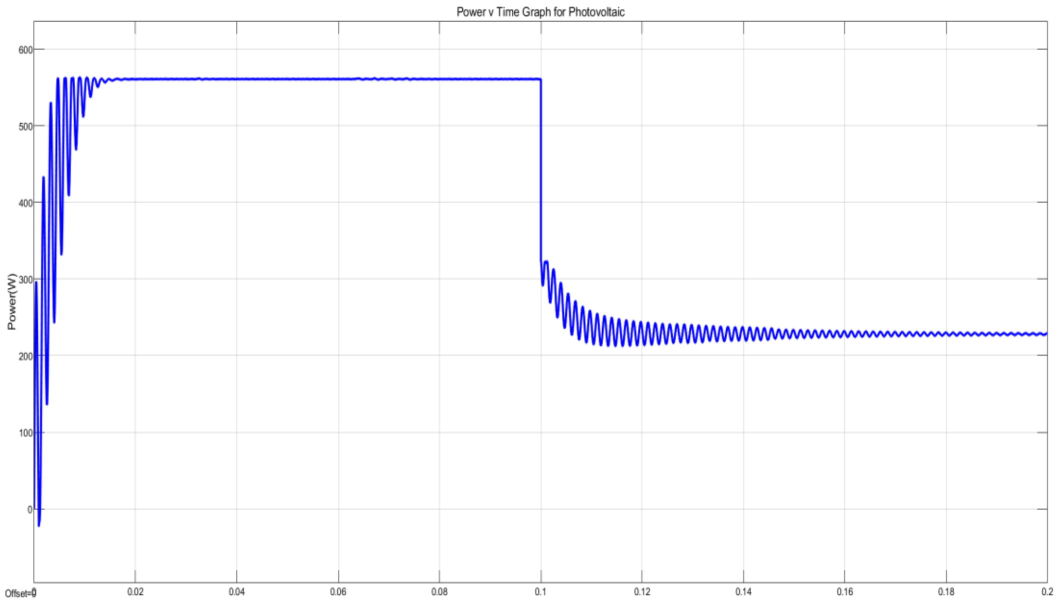


Figure 46: Power output of PV array without the inclusion of MPPT

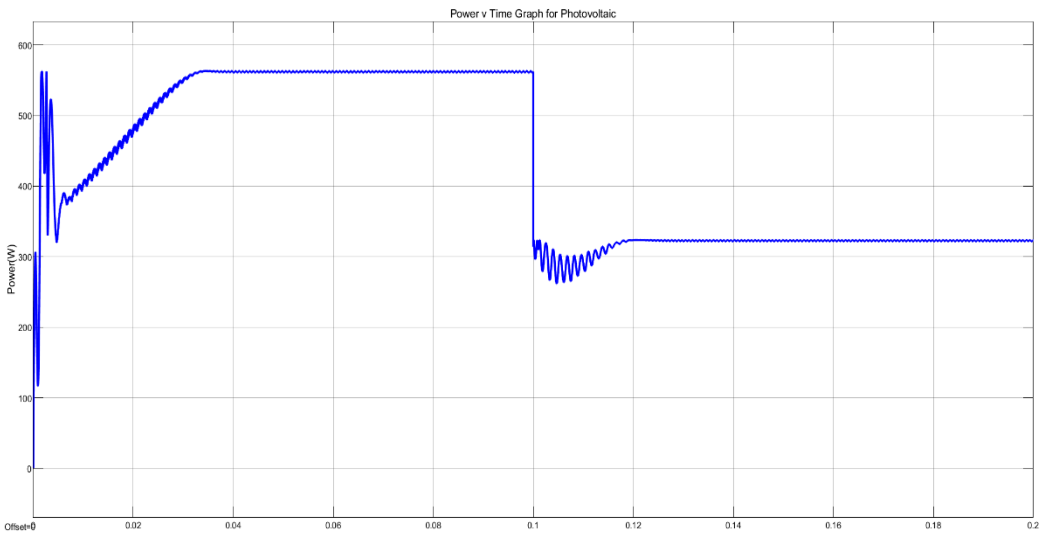


Figure 45: Power output of PV array with MPPT included

8.4.1 MPPT Performance with Varying Irradiation

The irradiation at the input was changed at 0.2s time intervals as follows: $0\frac{W}{m^2}$ at 0s, $600\frac{W}{m^2}$ at 0.2s, $1000\frac{W}{m^2}$ at 0.4s, $400\frac{W}{m^2}$ at 0.6s and $0\frac{W}{m^2}$ again at 0.8s. The voltage, current and power curves representing these changes are presented below

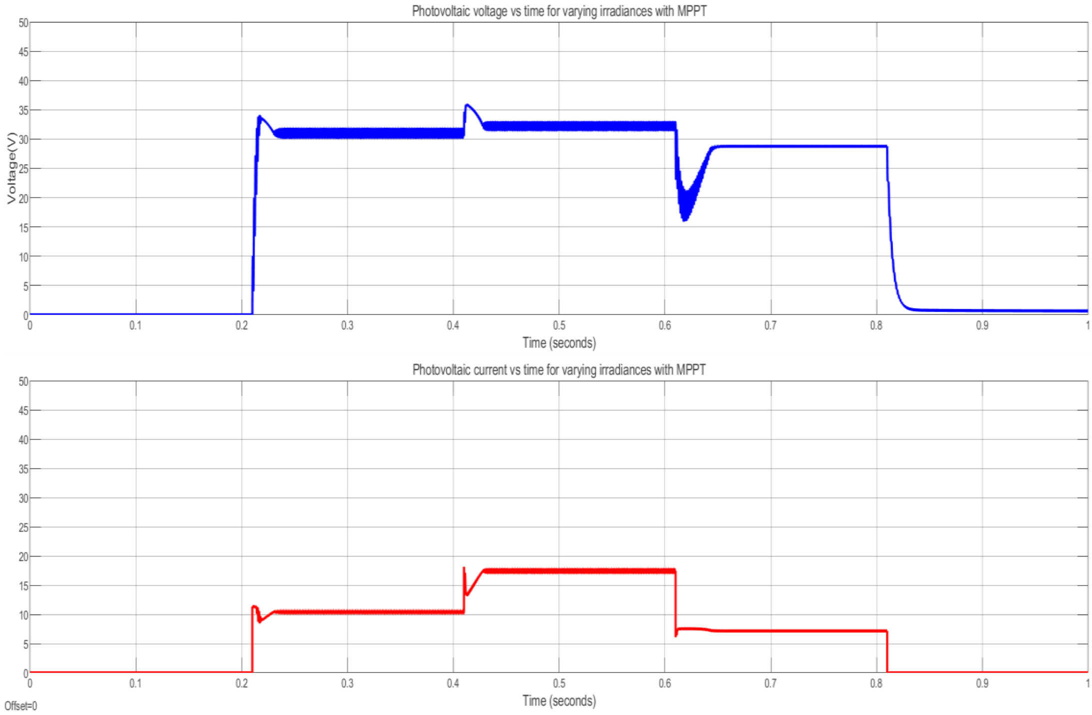


Figure 47: Photovoltaic voltage and current curves for varying irradiation with MPPT

From figure 47, the photovoltaic voltage manages to track the MPP value after each change in the irradiation level. The current is then increased or decreased accordingly so that an optimal power output can be achieved. The photovoltaic power output is given in figure 48.

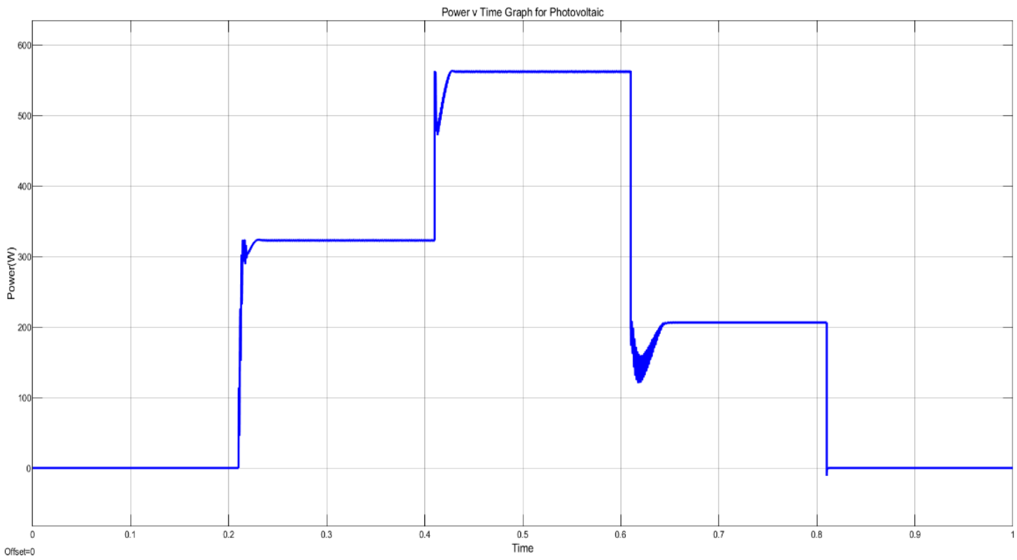


Figure 48: Power output of photovoltaic array with MPPT for varying irradiation

8.4.2 MPPT Performance with Varying Temperature

Figure 49 below shows how the maximum power point is tracked by the current output with the voltage increasing or decreasing accordingly. The temperature at the input was changed at 0.2s time intervals as follows: 298K at 0s, 318K at 0.2s, 338K at 0.4s, and 298K again at 0.6s. The complimentary power curve is presented in figure 50 below.

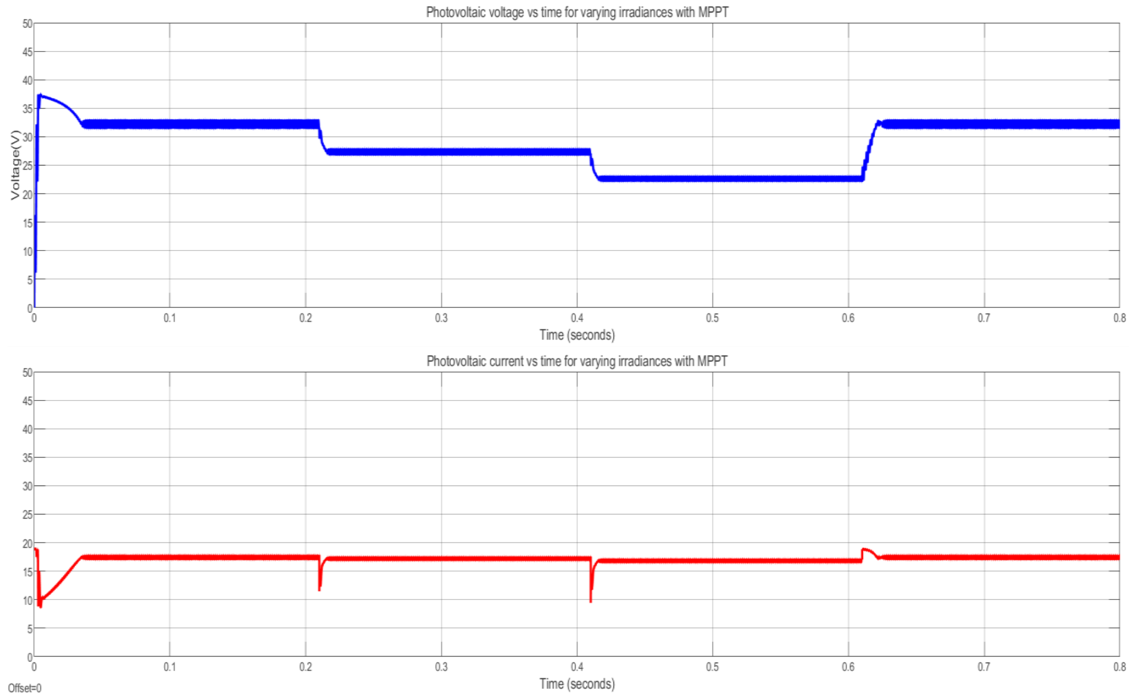


Figure 49: Photovoltaic voltage and current for varying temperature with MPPT

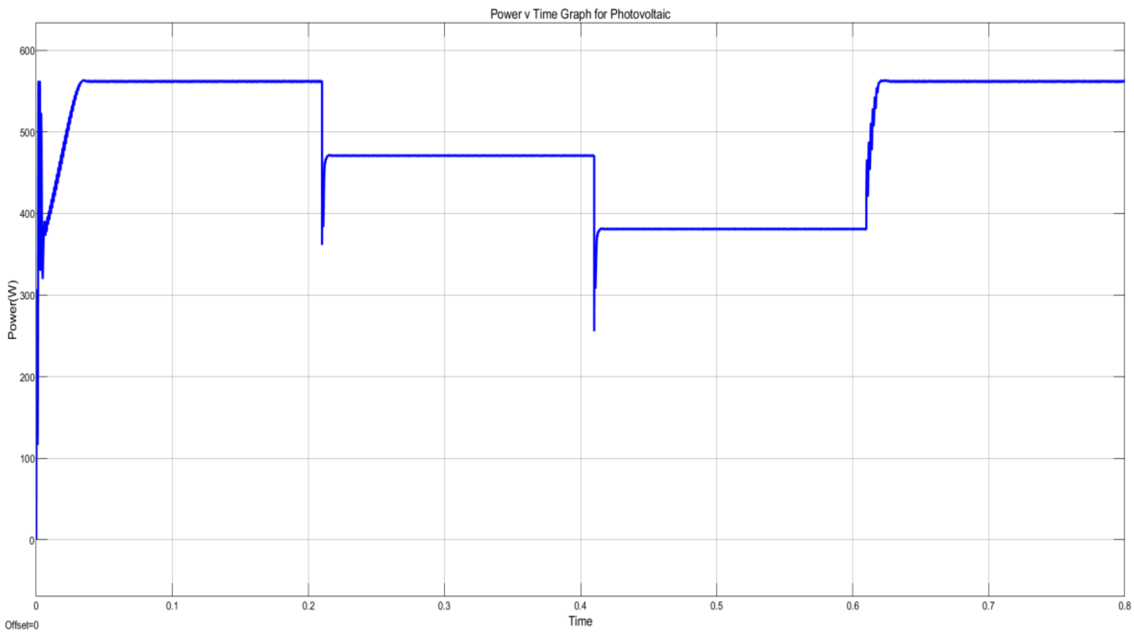


Figure 50: Power output of photovoltaic array with MPPT for varying temperature

8.4.3 MPPT Performance with Varying Resistive Load

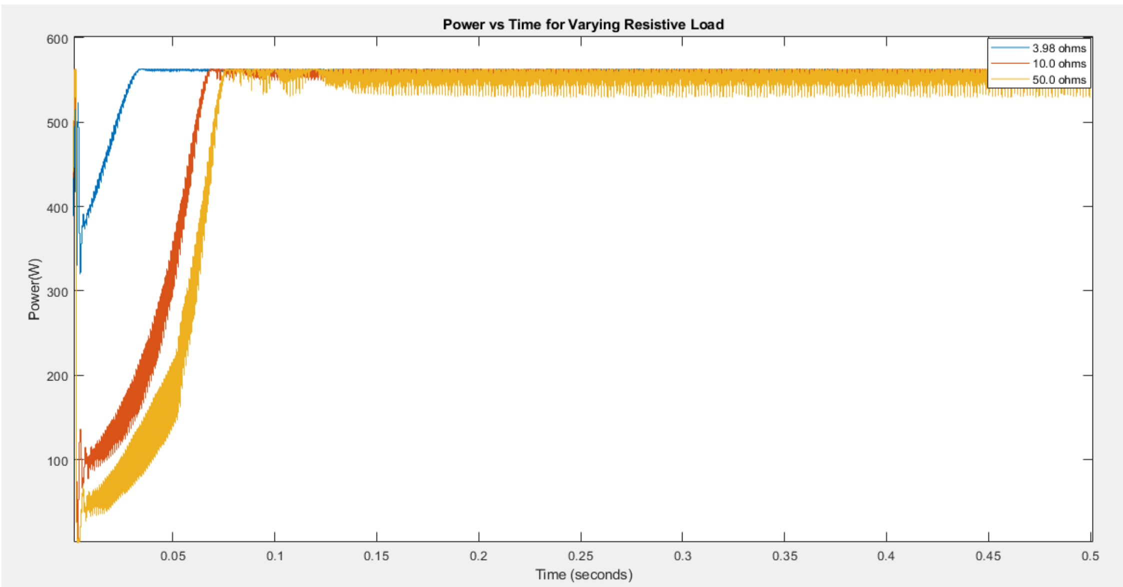


Figure 52: Power output for varying resistance with MPPT

Three resistive loads were used to analyse the effects of an increasing load on the power output. The system should be able to produce the same power output independent of the load by varying the voltage and current levels at the output of the boost converter. The three resistive loads that were used are 3.98Ω(which produces MPPT at STC), 10Ω and 50Ω. The results are seen above.

Figure 51 shows that the system is able to produce the same optimal power output regardless of the load because it solely depends on the irradiance and temperature. The duty cycle of the boost converter is varied to track the maximum power and transfer the power to the load. However, an increase in load resistance does force the system to exhibit increased oscillatory behaviour.

8.4.4 MPPT Efficiency

An irradiation curve which has the irradiation levels set at 333 $\frac{W}{m^2}$ at 0s, 666 $\frac{W}{m^2}$ at 0.2s, 1000 $\frac{W}{m^2}$ at 0.4s, 666 $\frac{W}{m^2}$ at 0.6s and 333 $\frac{W}{m^2}$ again at 0.8s was used for analysis with the temperature set at 297K. The results of the photovoltaic power output relative to ideal is seen below.

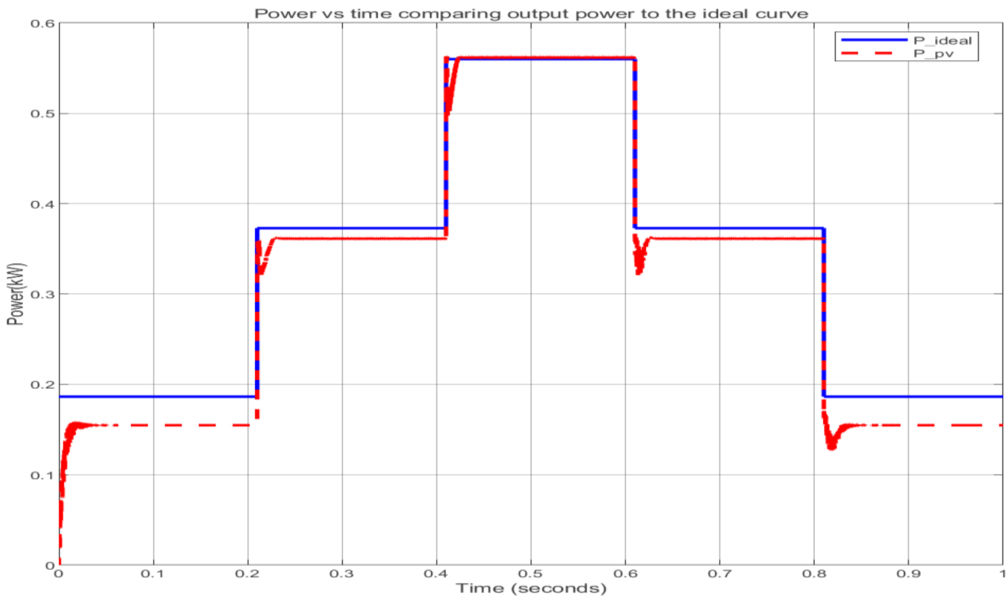


Figure 53: Comparison of photovoltaic power to ideal power curve

From figure 53, the efficiency of the system at lower irradiation values is less than that at higher values, hence it not being able to track the ideal power curve as perfectly as it does at STC. This is expected as it is characteristic of P&O algorithms as discussed in section 6.6.1. The mean efficiency is further analysed below.

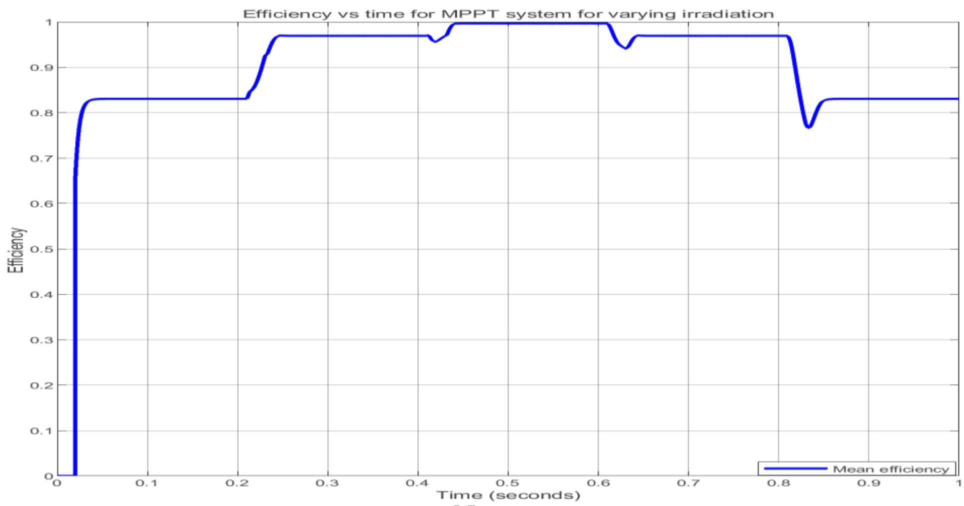


Figure 54: Mean efficiency of PV system with MPPT

The graph above shows that the efficiency ranges from 83.1% to 99.6% for the chosen irradiation input values with higher efficiency the result of higher irradiation input values.

8.5 Batteries

The performance characteristics of the designed battery model as well as the PV system in general after its integration into it are shown below.

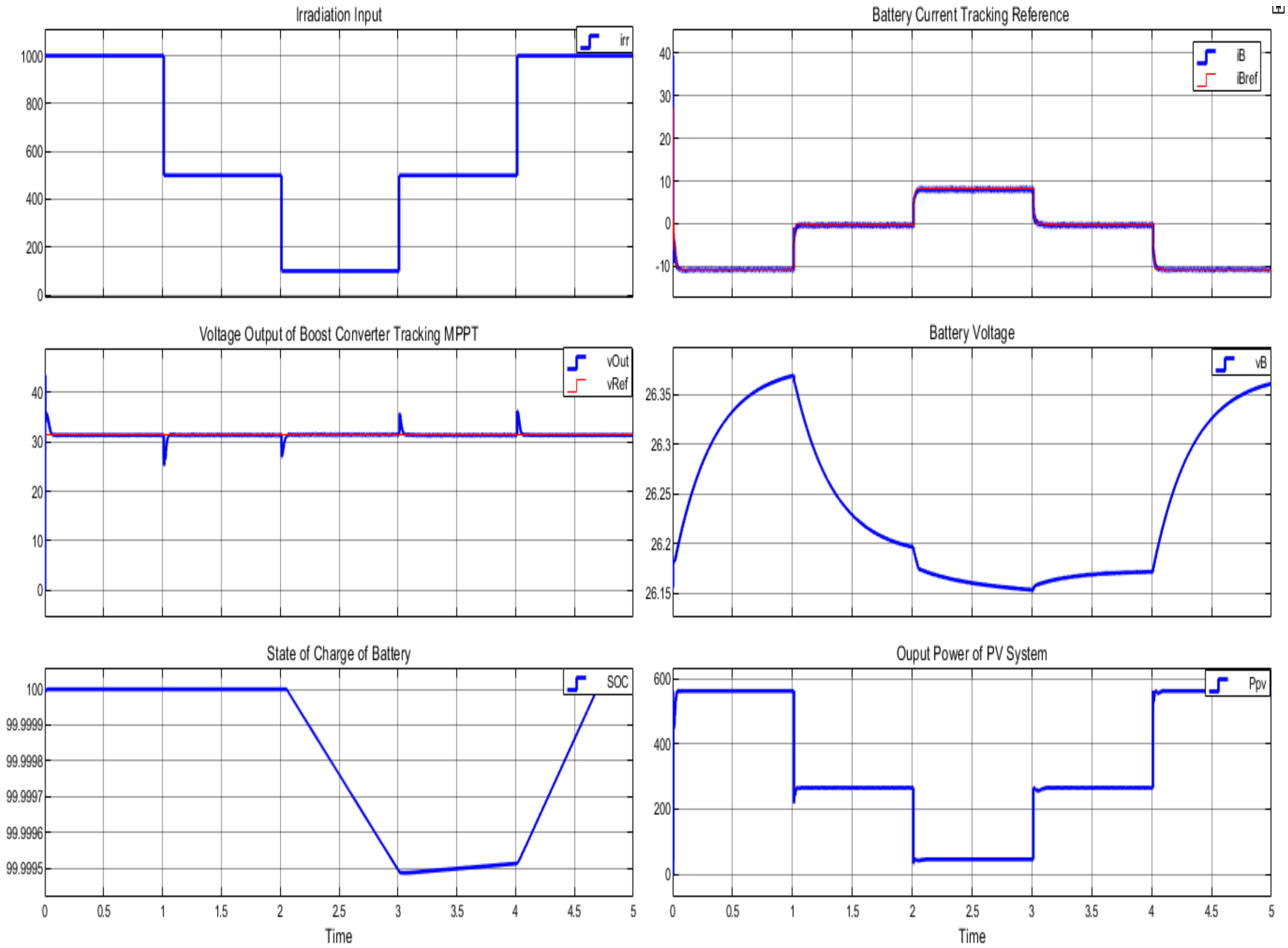


Figure 55: Performance of the PV system with integrated battery model

Figure 55 shows that, for this test, the irradiation was changed at 1s intervals from 1000 $\frac{W}{m^2}$ down to 500 $\frac{W}{m^2}$ and then to 100 $\frac{W}{m^2}$ before increasing again back to the initial value. The decrease in irradiation led to slight changes in battery voltage and significant changes in battery current to compensate for the change in power, as expected for changes in irradiation. The current and voltage values are able to track references near perfectly. The power output also decreases and increases accordingly relative to MPPT values.

From the state of charge graph, the battery maintains a full capacity up until 2s because the solar levels provide enough energy to cater for the load. Thereafter and up until 3s, the battery discharges as the irradiation levels are now not enough to fully cater for the load and the battery acts as a secondary source of energy. The battery then recharges when irradiation levels are once again more than what the load demands.

8.6 Inverter

The results of the inverter simulation on the entire system for varying irradiation is shown below. The addition of the inverter results in increased overshoot and oscillatory behaviour in the system's control because of the DC to AC conversion, but the system is still able to track references comfortably and produces desirable results. This is seen in figure 56 below.

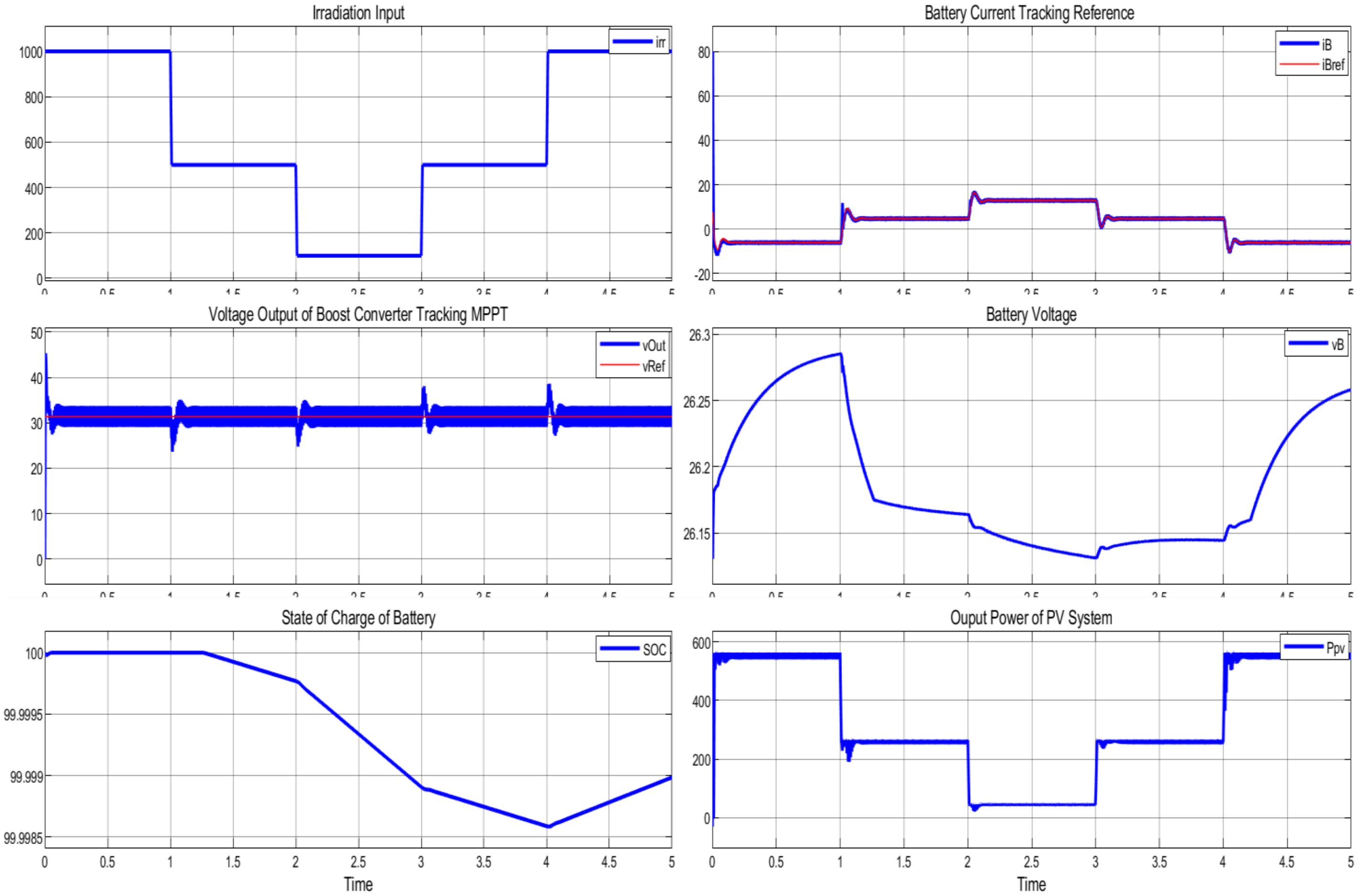


Figure 56: Performance of PV system with integrated inverter for varying irradiation inputs

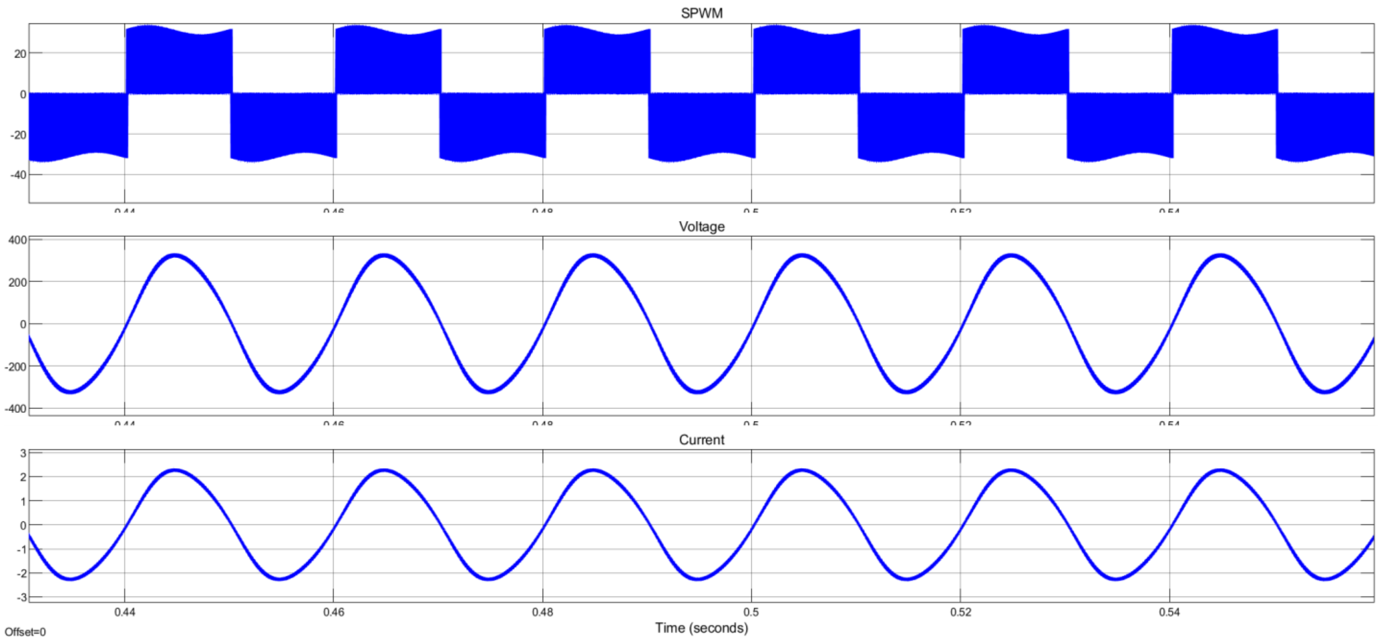


Figure 57: Voltage and current output across AC load

Figure 57 above depicts the PWM action in place, as well as the voltage and current across the AC load of the inverter. The peak of the sin wave voltage output falls at around 325V with a satisfactory total harmonic distortion of 3.6% from the simulation. This equates to an RMS voltage of exactly 230V, the necessary voltage required to run an AC load since $V_{rms} = V_p \times 0.7071$.

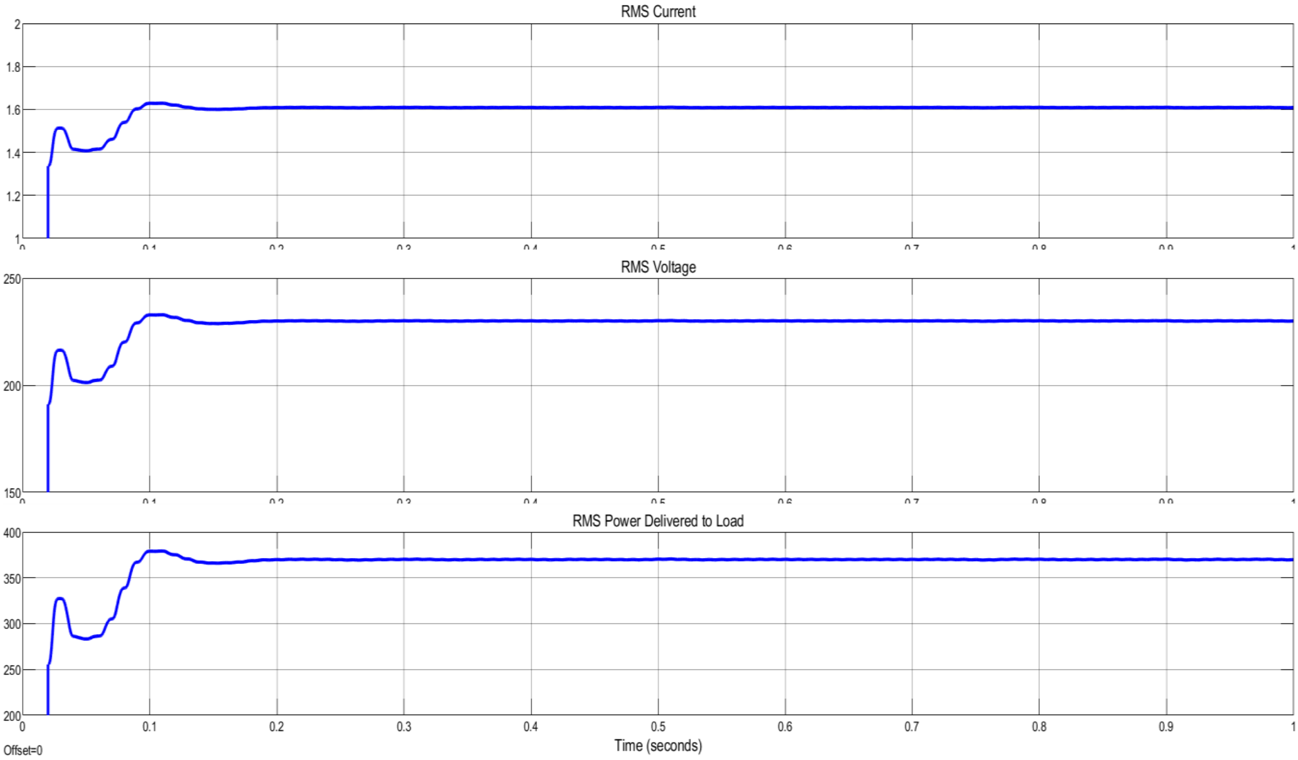


Figure 58: RMS voltage, current and power across the AC load

Figure 58 shows how the RMS values across the load settle within 0.2s. The power curve also suggests that the designed system is able to meet the maximum load requirement of 370W, the total wattage of all appliances connected to the PV system.

8.7 Full PV System Implementation

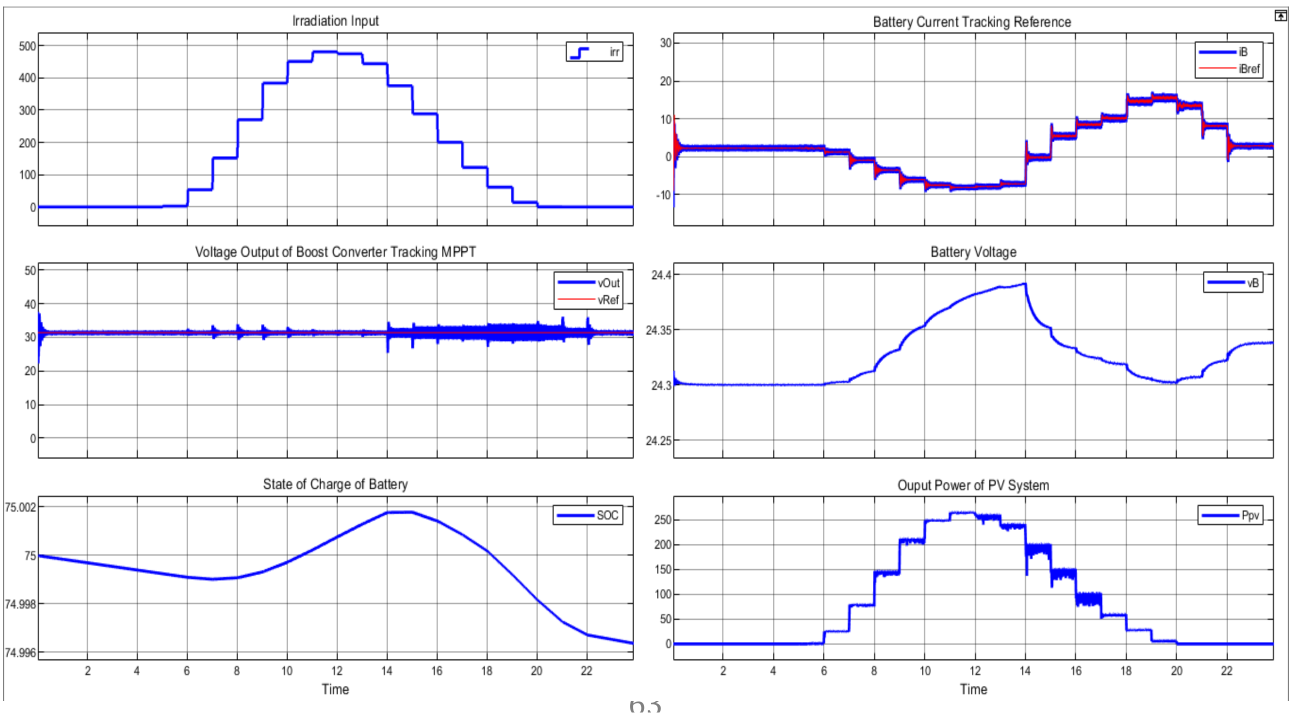


Figure 59: Simulation of designed PV system for an RDP house in Cape Town

In the case of Cape Town, figure 59 suggests that the system is able to meet the load demands without discharging the battery too rapidly. The voltage output of the boost converter experiences increased ripple at hour 14, which corresponds to 14:00 and when the load is in effect.

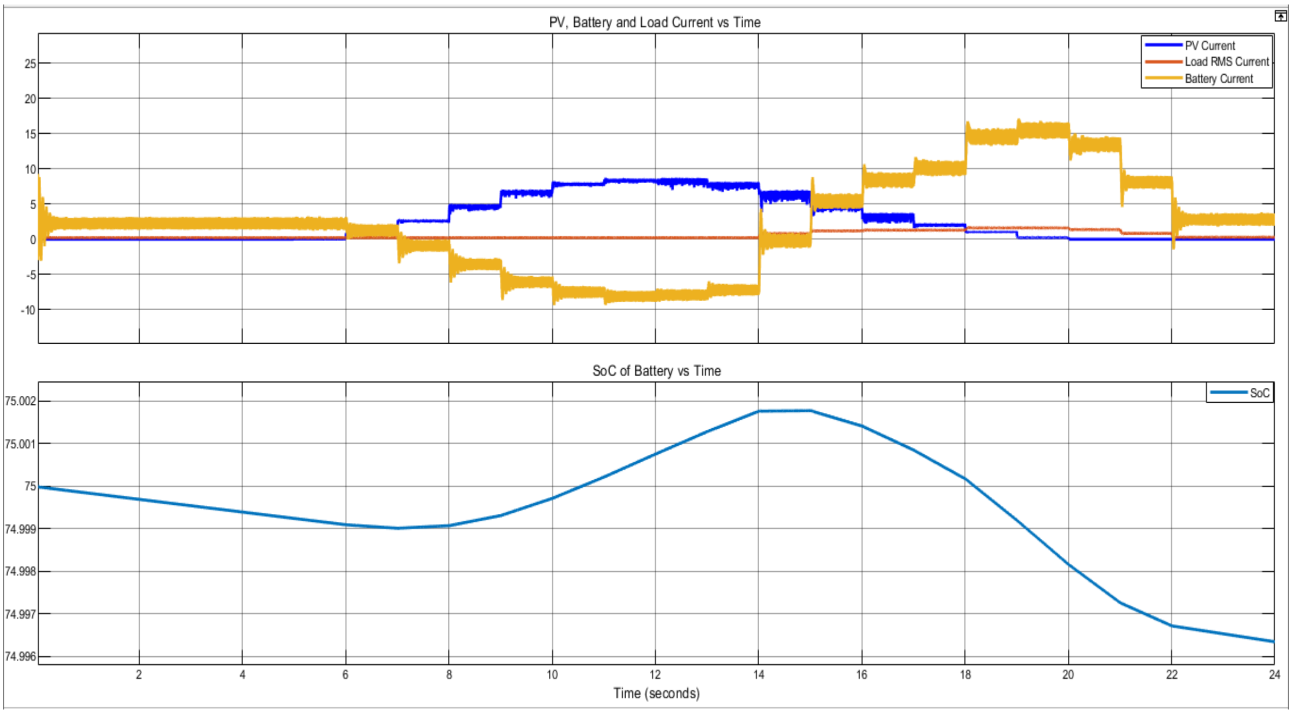


Figure 60: System current analysis for Cape Town

Figure 60 shows that between the hours of 07:00 up until 15:00, the irradiation levels are sufficient to charge up the battery. Thereafter, when irradiation levels drop, the battery power kicks in to provide the necessary power to the load from 15:00 up until midnight. The load current increases and decreases relative to the load profile and affects the battery bank current/PV current accordingly.

From the SoC curve, the battery bank can comfortably cater for the load demands. The battery is hardly affected by changes in the load and perhaps was oversized in design. This research believes that a smaller battery bank that meets system voltage requirements (2 x 200Ah connected in series) could have been considered and would substantially decrease the cost of the system.

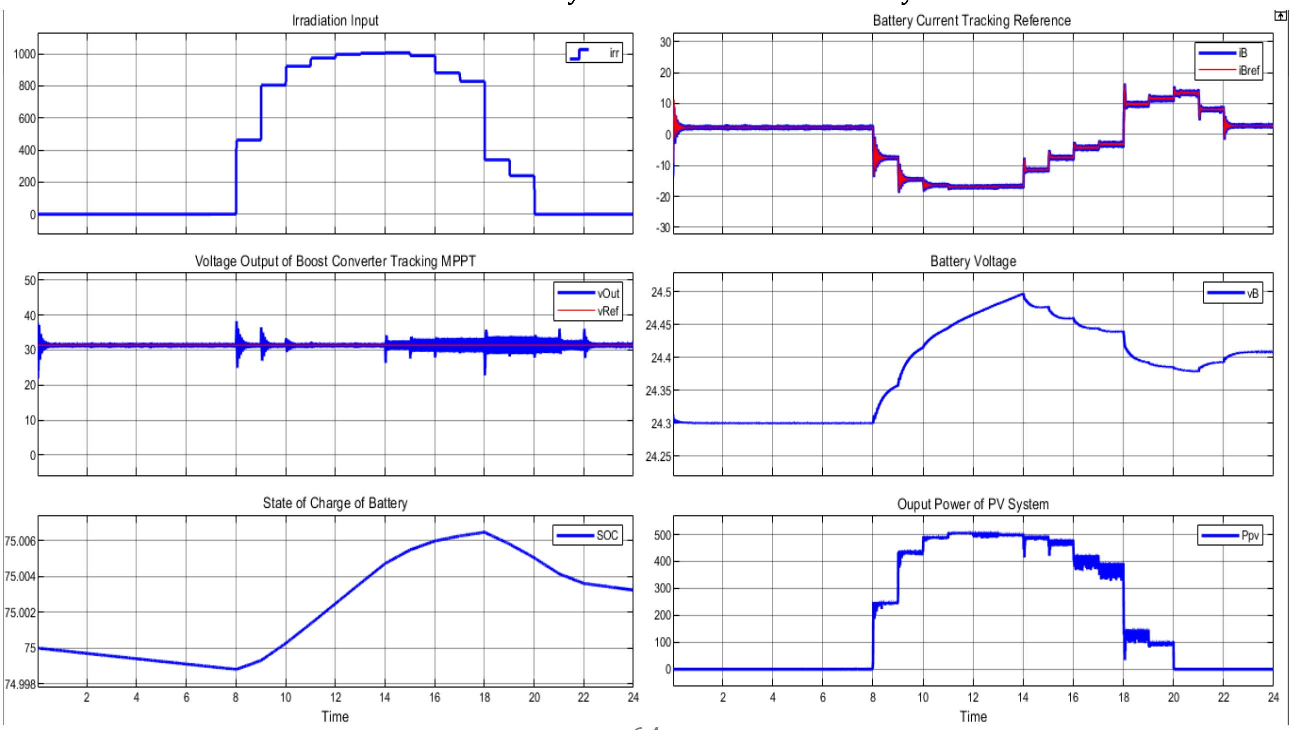


Figure 61: Simulation of designed PV system for an RDP house in Aggeneys

Figure 61 above shows that, for Aggeneys as well, the designed system meets the load demands. It's also evident that the battery ended off on a higher state of charge value than what it started at, meaning that for the given irradiation profile the DC power is enough to both meet the demands of the household and provide a net charge to the battery. This is further reason to suggest that the battery bank has been oversized. Even when the rate of discharge was at its peak between 18:00 and 20:00, the battery had only discharged by 0.002%.

Figure 62 shows how, again, the battery current is adjusted relative to the availability of PV current and demand of the load current.

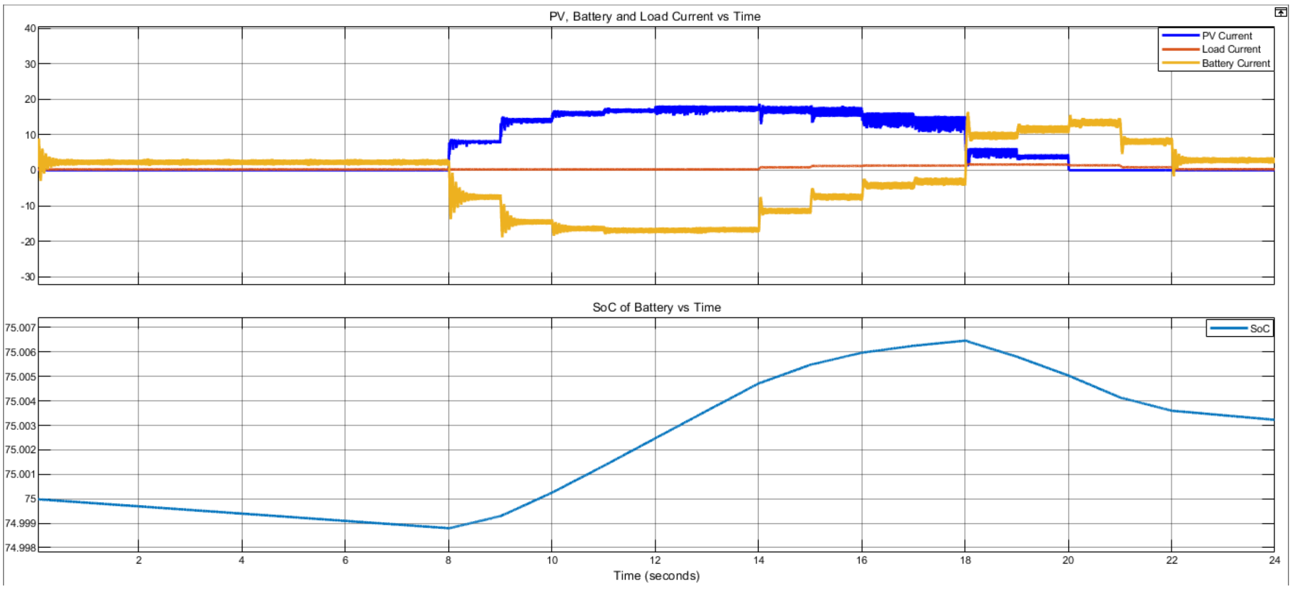


Figure 62: System current analysis for Aggeneys

9. Conclusions

9.1 Final Design Remarks

In this research, the study of a photovoltaic system for an RDP household with an integrated battery energy storage system has been developed. The results of the PV systems implementation show that the simulated system can meet the designs demands in both the case of Cape Town and Aggeneys. This is indicative that for areas with medium to high irradiance levels, the system will work.

Even though more simulations were not made to establish how long exactly the battery would be able to support the system in the event of the PV modules not supplying power due to clouded weather conditions, the results have discussed that the battery bank could have been oversized. Perhaps a battery bank consisting of 2 x 200Ah batteries would be a better fit for the system. The sizing of the inverter was ideal as it catered for the load requirements whilst ensuring that, unlike smaller inverters that were considered, its input voltage rating range catered for the DC voltage output of the panels. The charge controller was also sized well enough to accommodate for the maximum current provided by the PV modules. With proper load management in place, the household will be able to power up more small appliances during off peak hours if needed. The design has previously suggested that both water heating and cooking appliances should be still catered for by the grid or gas energy.

9.2 Overall System Feasibility

The cost analysis of the design suggested that it would cost the government R30 406,78 per system and it would take inhabitants 5 years and one month to pay the system off based on their current electricity expenditure. With the battery bank potentially being downsized, this would drastically reduce the cost of the system (by around R9000 as suggested in the feasibility section) making it even more affordable. This could also mean allowing for a potentially bigger system to be designed to for the same cost that might be able to cater for water heating or cooking appliances as well.

It is still unlikely that the government will find the resources to implement this given the current economic crisis it faces and the considerable decrease in solar water heating systems being rolled out. However, it was found that, if implemented, this would mean that Eskom would be saving on 2.73GW of coal-generated power every year just by RDP houses being powered by solar energy.

In conclusion, this system will be able to serve as an alternate means of providing energy to low-income households and lessen the burden on Eskom’s crippling grid.

9.3 Gaps in Knowledge

This research has worked on estimated figures for the development of the load profile and when analysing RDP electricity expenditure figures. There has been no attempt made to consult RDP inhabitants verify that these figures are accurate relative to their actual power usage and expenditure.

Further to this, this research worked on limited data with respect to the irradiation levels across parts of South Africa and could not establish a credible irradiation profile that would indicate the average hourly irradiation levels across all of South Africa.

Lastly, the design was not implemented in real life to further validate how well it meets requirements.

10. Recommendations

System Validation Through Experimentation

The designed PV system should be validated by procuring the actual physical components, building a physical off-grid system from them, and matching up experimental results under real-life testing conditions with the simulations.

Physical Gauging and Recording of Irradiation

Accuracy in irradiation data can be established by monitoring the irradiance levels across all South African provinces for a minimum period of at least a year. This will allow for a more credible irradiation profile to be developed for analysis and simulation.

Engagement with RDP Household Inhabitants

Engaging with people who come from low-income and RDP households in respect of their energy expenditure, minimum load requirements and willingness to consider non-renewable energy as a means of power generation is key. It will allow for this research to be developed based on more credible assumptions and allow for a more robust and informed design to be developed.

MPPT, Inverter and Battery Control

Better control engineering strategies can be used to further reduce the effects of voltage ripple and noise on the simulated system. The inverter could also make use of both voltage and current control for more desirable results as the current injected to the load will be regulated.

11. List of References

[1] A. Kriesch, “Load shedding: South Africa’s power cut problem,” *DW*, 2020. https://www.dw.com/en/load-shedding-south-africas-power-cut-problem/av-52767851#:~:text=Load shedding%3A South Africa’s power,electricity firm are to blame. (accessed Aug. 25, 2020).

[2] K. Ratshomo and R. Nembahe, “2019-South-African-Energy-Sector-Report,” 2019. [Online]. Available: http://www.energy.gov.za/files/media/explained/2019-South-African-Energy-Sector-Report.pdf.

[3] “Coal Power.” https://www.eskom.co.za/AboutElectricity/ElectricityTechnologies/Pages/Coal_Power.aspx (accessed Aug. 26, 2020).

[4] “South Africa’s unemployment rate climbs to 30.1%,” *BUSINESSTECH*, 2020. https://businesstech.co.za/news/government/409897/south-africas-unemployment-rate-climbs-to-30-1/ (accessed Aug. 26, 2020).

[5] “How much you need to earn each month to be in the richest 1% in South Africa,” *BUSINESSTECH*, 2019. https://businesstech.co.za/news/wealth/336309/how-much-you-need-to-earn-each-month-to-be-in-the-richest-1-in-south-africa/ (accessed Aug. 26, 2020).

[6] “Small-Scale Embedded Generation (SSEG) Feed-In Tariff Map,” *Western Cape Government*. https://www.westerncape.gov.za/energy-security-game-changer/small-scale-embedded-generation-sseg-feed-tariff-map.

[7] “Electricity: Coal use inches lower as solar, wind and diesel rise,” *stats sa*, 2020. http://www.statssa.gov.za/?p=11292 (accessed Aug. 27, 2020).

[8] I. Vegter, “Mantashe is right: South Africa must build more nuclear energy,” *Daily Maverick*, 2019. https://www.dailymaverick.co.za/opinionista/2019-08-13-mantashe-is-right-south-africa-must-build-more-nuclear-energy/ (accessed Aug. 27, 2020).

[9] “Nuclear Power in South Africa,” *World Nuclear*, 2020. https://www.world-nuclear.org/information-library/country-profiles/countries-o-s/south-africa.aspx (accessed Aug. 27, 2020).

[10] “Wind vs. solar: A head-to-head comparison,” *Arcadia*. https://www.arcadia.com/energy-101/energy-sources/wind-vs-solar-a-comparison/ (accessed Aug. 27, 2020).

[11] “Renewable Energy,” *Department: Mineral Resources and Energy*. http://www.energy.gov.za/files/esources/renewables/r_solar.html (accessed Aug. 27, 2020).

[12] “Desalination plant to be installed at Koeberg Power Station,” *Credible Carbon*, 2018. https://www.crediblecarbon.com/news-and-info/news/desalination-plant-to-be-installed-at-koeberg-power-station/#:~:text=The Koeberg nuclear power station%2C located near Cape Town%2C currently,of fresh water per day. (accessed Sep. 30, 2020).

[13] “5 Advantages of Solar Energy on the Environment,” *ZENEnergy*, 2020. https://www.zenenergy.com.au/blog/five-advantages-of-solar-energy-on-the-environment/ (accessed Sep. 30, 2020).

[14] “Each Country’s Share of CO2 Emissions,” *Union of Concerned Students*, 2020. https://www.ucsusa.org/resources/each-countrys-share-co2-emissions (accessed Sep. 30, 2020).

[15] “When will solar and storage be cheaper than Eskom?,” *Power Optimal*, 2020. https://www.poweroptimal.com/will-solar-storage-cheaper-eskom/ (accessed Sep. 30, 2020).

[16] L. Joubert, “Energy ‘poverty’ still entrenched in SA,” *Energy Transition*, 2016. https://energytransition.org/2016/11/energy-poverty-still-entrenched-in-sa/ (accessed Sep. 30, 2020).

[17] Heinrich Boll Stiftung, “Energy Poverty and Gender in Urban South Africa,” 2016.

[18] SEA, “Tackling Urban Energy Poverty in South Africa,” *Sustain. Energy Africa*, vol. 9, pp. 1–20, 2014.

[19] O. S. Israel-Akinbo, J. J. Snowball, and G. Fraser, “An Investigation of Multidimensional Energy Poverty amongst South African Low-income Households. Israel-Akinbo, Sylvia ; Snowball, Jen and

Fraser, Gavin," *South African J. Econ.*, vol. 86, no. 4, pp. 468–487, 2018, doi: 10.1111/saje.12207.
[20] Sustainable Energy Africa, "Household Energy Use in Selected Areas in and around Cape Town," no. July, pp. 1–23, 2015.
[21] "RDP Housing In South Africa," *Loan Lenders*. https://www.loan-lenders.co.za/rdp-housing/ (accessed Sep. 30, 2020).
[22] "RDP Housing," *Klevabrick*. http://klevabrick.co.za/building-options/ (accessed Sep. 30, 2020).
[23] Human Sciences Research Council, "A survey of energy related behaviour and perceptions in South Africa: the residential sector," *Rep. Compil. Dep. Energy South Africa*, pp. 1–142, 2013.
[24] S. Africa, "Household energy access Overview," no. 2000, 2014, [Online]. Available: http://www.sustainable.org.za/userfiles/household.pdf%0Ahttp://sustainable.org.za/userfiles/household.pdf.
[25] J. D. Bethel Afework, Jordan Hanania, Kailyn Stenhouse, Brodie Yyelland, "Photovoltaic cell," *Energy Education*. https://energyeducation.ca/encyclopedia/Photovoltaic_cell (accessed Oct. 07, 2020).
[26] "What is a Solar PV Module?," *Electrical 4 U*, 2018. https://www.electrical4u.com/what-is-a-solar-pv-module/ (accessed Oct. 07, 2020).
[27] "PV Module Performance Characteristics," *PennState*. https://www.e-education.psu.edu/ae868/node/518 (accessed Oct. 07, 2020).
[28] D. K. S. Shakya and E. S. Raj, "Training Manual for Engineers on Solar PV System," *Minsitry Environ. Sci. Technol. Nepal*, no. July 2011, pp. 1–244, 2016, doi: 10.1080/09593980500213035.
[29] "How to choose the best battery for a solar energy system," *EnergySage*, 2020. https://www.energysage.com/solar/solar-energy-storage/what-are-the-best-batteries-for-solar-panels/ (accessed Oct. 07, 2020).
[30] "Solar Charge Controller," *Solar Advice*, 2020. https://solaradvice.co.za/solar-charge-controller/ (accessed Oct. 08, 2020).
[31] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," *IEEE Trans. Ind. Appl.*, vol. 41, no. 5, pp. 1292–1306, 2005, doi: 10.1109/TIA.2005.853371.
[32] S. Deshpande and N. R. Bhasme, "A review of topologies of inverter for grid connected PV systems," *2017 Innov. Power Adv. Comput. Technol. i-PACT 2017*, vol. 2017-Janua, pp. 1–6, 2017, doi: 10.1109/IPACT.2017.8245191.
[33] "Solar Power Starter Guide," *Solar Advice*. https://solaradvice.co.za/solar-inverter/#types.
[34] "DC/DC Conversion," *PennState*. https://www.e-education.psu.edu/eme812/node/713#:~:text=DC%2FDC conversion allows keeping,higher voltage to lower voltage. (accessed Oct. 08, 2020).
[35] S. Kolsi, H. Samet, and M. Ben Amar, "Design Analysis of DC-DC Converters Connected to a Photovoltaic Generator and Controlled by MPPT for Optimal Energy Transfer throughout a Clear Day," *J. Power Energy Eng.*, vol. 02, no. 01, pp. 27–34, 2014, doi: 10.4236/jpee.2014.21004.
[36] K. Zipp, "What are some common types of solar PV and storage installations?," *Solar Power World*, 2015. https://www.solarpowerworldonline.com/2015/10/what-are-some-common-types-of-solar-pv-and-storage-installations/#:~:text=There are three main types,get out of the system. (accessed Aug. 28, 2020).
[37] "Why is Intermittency a Problem for Renewable Energy?," *The Green Age*, 2019. https://www.thegreenage.co.uk/why-is-intermittency-a-problem-for-renewable-energy/#:~:text=Without a doubt%2C the biggest,only generated when it's sunny.&text=There are times at which,the energy we're generating. (accessed Oct. 01, 2020).
[38] I. ESTERHUIZEN, "Intermittency could limit solar PV market penetration - Thupela," *Creamer Media's Engineering News*, 2012. https://www.engineeringnews.co.za/article/intermittency-could-limit-solar-pv-market-penetration-thupela-2012-06-21/rep_id:4136 (accessed Oct. 01, 2020).
[39] "List of the Power Consumption of Typical Household Appliances," *DaftLogic*. https://www.daftlogic.com/information-appliance-power-consumption.htm#electric kettle (accessed Sep. 02, 2020).
[40] "How to Design Solar PV System," *Leonics*. http://www.leonics.com/support/article2_12j/articles2_12j_en.php (accessed Sep. 02, 2020).
[41] "What is a Solar PV system?," *SOLAREARTH*. https://www.solarearthsa.co.za/solar-

systems#:~:text=On average a 250-watt,is your panel generation factor. (accessed Sep. 02, 2020).
[42] J. Marsh, "What is a solar charge controller? Do you need one?," *EnergySage*. https://news.energysage.com/what-are-solar-charge-controllers-do-you-need-one/#:~:text=A solar charge controller is,loss of functionality over time.&text=Charge controllers are only necessary in a few specific cases. (accessed Sep. 09, 2020).
[43] "Why a Charge Controller?," *Blue Pacific Solar*. https://www.bluepacificsolar.com/charge-controllers.html#:~:text=Take the number of panels,%2B 25%25 %3D 29.18 amps. (accessed Sep. 10, 2020).
[44] "Question NW1367 to the Minister of Human Settlements," *PMG*, 2018. https://pmg.org.za/committee-question/11599/ (accessed Sep. 24, 2020).
[45] "Five reasons to invest in a gas stove," *East Coast Radio*, 2018. https://www.ecr.co.za/lifestyle/house-home/five-reasons-invest-gas-stove/ (accessed Sep. 25, 2020).
[46] "Solar water heater rollout programme gains momentum," *EE Publishers*, 2016. https://www.ee.co.za/article/solar-water-heater-rollout-programme-gains-momentum.html (accessed Sep. 25, 2020).
[47] T. Maeko, "Solar stuck where sun don't shine: State spends R289m to store solar water heaters," *Mail % Guardian*. https://mg.co.za/news/2020-07-30-solar-stuck-where-sun-dont-shine-state-spends-millions-on-storing-water-heaters/ (accessed Sep. 25, 2020).
[48] "Converting Part of Your Home to Solar or Battery Power," *Off Drid DIY*, 2015. https://offgriddiy.co.za/converting-part-of-your-home-to-solar-or-battery-power/ (accessed Sep. 25, 2020).
[49] "typical-layout-off-grid-residential-pv-system," *Solar Advice*, 2016. https://solaradvice.co.za/off-the-grid-solar-system/typical-layout-off-grid-residential-pv-system/ (accessed Sep. 26, 2020).
[50] "SAFE AND LEGAL INSTALLATIONS OF ROOFTOP PHOTOVOLTAIC SYSTEMS COMMERCIAL AND RESIDENTIAL - IN CAPE TOWN," *Electricity Services Department and Environmental Resource Management Department of the City of Cape Town.*, 2016. http://www.cityenergy.org.za/uploads/resource_371.pdf (accessed Sep. 26, 2020).
[51] "Protection of Off Grid Solar PV Systems," *Off Grid DIY*, 2015. https://offgriddiy.co.za/protection-of-off-grid-solar-pv-systems/ (accessed Sep. 27, 2020).
[52] "Frequently Asked Questions," *Solar Advice*. https://solaradvice.co.za/product/kodak-3kw-24v-oliter-1-2kwh-agm-solar-power-kit/ (accessed Sep. 28, 2020).
[53] I. Turok, "South Africa: SA Housing Policy Fails to Support Delivery," *allAfrica*, 2020. https://allafrica.com/stories/202006160321.html (accessed Sep. 29, 2020).
[54] T. BISCHOF-NIEMZ, "Opinion: Can low-income homes be made to benefit from the energy transition?," *Creamer Media's Engineering News*, 2019. https://www.engineeringnews.co.za/article/can-low-income-homes-be-made-to-benefit-from-the-energy-transition-2019-05-03/rep_id:4136 (accessed Sep. 29, 2020).
[55] P. Bracher, "Prescribed rate of interest is 7.75% from 1 June 2020," *Financial Institutions Legal Snapshot*, 2019. https://www.financialinstitutionslegalsnapshot.com/2020/09/prescribed-rate-of-interest-is-10-25-from-1-january-2019/ (accessed Sep. 29, 2020).
[56] T. Head, "Then vs now: How much Eskom's electricity prices have increased since 1970," *The South African*. https://www.thesouthafrican.com/news/eskom-electricity-prices-for-april-from-1970/ (accessed Sep. 30, 2020).
[57] S. Moolman, "2019 update: Eskom tariff increases vs inflation since 1988 (with projections to 2022)," *Power Optimal*, 2019. https://www.poweroptimal.com/2019-update-eskom-tariff-increases-vs-inflation-since-1988-with-projections-to-2022/ (accessed Sep. 29, 2020).
[58] A. M. Eltamaly, "Chapter 4 - Performance of MPPT Techniques of Photovoltaic Systems Under Normal and Partial Shading Conditions," in *Advances in Renewable Energies and Power Technologies*, I. Yahyaoui, Ed. Elsevier, 2018, pp. 115–161.
[59] X. H. Nguyen and M. P. Nguyen, "Mathematical modeling of photovoltaic cell/module/arrays with tags in Matlab/Simulink," *Environ. Syst. Res.*, 2015, [Online]. Available: https://environmentalsystemsresearch.springeropen.com/articles/10.1186/s40068-015-0047-9#:~:text=A mathematical model of PV,done in the following steps.
[60] E. Coates, "Boost Converters," *Learnabout Electronics*. https://learnabout-

electronics.org/PSU/psu32.php (accessed Oct. 14, 2020).
[61] Y. Koca, Y. Aslan, A. Yönetken, and Y. O. Ğ. Uz, “Boost Converter Design and Analysis for Photovoltaic Systems Boost Converter Design and Analysis for Photovoltaic Systems,” no. April, 2019.
[62] J. Betten, “Selecting Your Boost Converter Inductance Selecting Your Boost Converter Inductance,” *DesignNews*, 2014. https://www.designnews.com/selecting-your-boost-converter-inductance (accessed Oct. 15, 2020).
[63] B. Hauke, “Basic Calculation of a Boost Converter’s Power Stage,” *Texas Instruments, Appl. Rep. Novemb.*, no. November 2009, pp. 1–9, 2009, [Online]. Available: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Basic+Calculation+of+a+Boost+Converter’s+Power+Stage#0.
[64] M. Abdulkadir, A. S. Samosir, and A. H. M. Yatim, “Modelling and simulation of maximum power point tracking of photovoltaic system in Simulink model,” *PECon 2012 - 2012 IEEE Int. Conf. Power Energy*, no. December, pp. 325–330, 2012, doi: 10.1109/PECon.2012.6450231.
[65] S. G. Solanki, M. Ramasamy, S. Manzoor, and U. K. R. Ganesalingam, “Design & Development for off grid Solar Inverter,” *2018 IEEE 4th Int. Symp. Robot. Manuf. Autom. ROMA 2018*, 2018, doi: 10.1109/ROMA46407.2018.8986709.
[66] L. Mao, J. Chen, Y. Deng, and C. Wang, “A Novel Photovoltaic Off-grid Inverter Based on Boost Converter,” no. Ipemec, pp. 166–169, 2015, doi: 10.2991/ipemec-15.2015.33.
[67] D. K. Dileep and K. R. Bharath, “A Brief Study of Solar Home Inverters,” *2018 Int. Conf. Control. Power, Commun. Comput. Technol. ICCPCCT 2018*, pp. 334–339, 2018, doi: 10.1109/ICCPCCT.2018.8574265.
[68] “Solar Information,” *Eskom*, 2010. https://www.eskom.co.za/AboutElectricity/RenewableEnergy/Pages/Solar_Information.aspx (accessed Nov. 11, 2020).
[69] “Solar Radiation,” *Meteo Cape Town*. http://www.meteo.capetown/pages/station/climate.php?var=S (accessed Nov. 11, 2020).

12. Appendices

Appendix A - Calculations

A.1 - Component Selection Calculations

i. Case A

Due to case A having the largest power demands between all cases, it would make sense for this system to be a grid-tied system in order for a more cost-effective solution to be designed, albeit at the expense of flexibility when it comes to Eskom power outages.

PV Power Demands:

$$Daily\ Power\ Needs\ \times Power\ Loss\ Factor = Power\ Consumption\ Demands$$
$$7.733\ \times 1.3 = 10.05kWh$$
The system to be designed would need to cater for **10.05kWh** daily consumption.

PV Module Sizing:

$$\frac{Power\ Consumption\ Demands}{Average\ Hours\ of\ Sunlight} = Total\ Array\ Wattage$$
$$\frac{10052.9}{4.8} = 2094.35Wp$$
The system to be designed would need enough panels to provide over **2094.35Wp** of power.

Inverter Sizing:

$$Total\ Wattage\ of\ Appliances\ \times Safety\ Factor = Inverter\ Wattage$$
$$\big((5\ \times 60) + 70 + 1200 + 2000 + 18.5 + (6 \times 4) + 770 + 2 + 150\big) \times 1.25 = 5668.12W$$
The designed inverter will have to be rated at anything larger than **5.67kW**.

Battery Sizing:

A 12-hour period can be used for the days of autonomy. This means that the batteries will be able to supply continuous energy for one half of a day without charging. Since this is a large, grid-tied system, there does not need to be too much emphasis on battery size since the battery only needs to cater for off-peak demand hours. The grid can step in to cater for some power needs on cloudy days or days with low solar irradiance if needs be.

$$\frac{Total\ Watt - hours\ per\ day\ used\ by\ appliances\ \times\ Days\ of\ autonomy}{(0.85\ x\ 0.6\ x\ nominal\ battery\ voltage)} = \ Battery\ Capacity\ (Ah)$$
$$\frac{10052.9\ \times 0.5}{0.85\ \times 0.6\ \times 48} = \ 205.33Ah$$
Finally, the battery bank should be rated 48V > **200Ah** for 12 hours of autonomy. Four 200Ah 12V batteries connected in series would suit this system.

Charge Controller Sizing:

No charge controller will be added to the system since it is grid-tied.

ii. Case B

The power demands of this case are relatively lower than that of A. To manage the cost-factor appropriately, this system will also be assumed as a hybrid grid-tied type with battery backup.

PV Power Demands:

$Daily\ Power\ Needs\ \times Power\ Loss\ Factor = Power\ Consumption\ Demands$
$3.933\ \times 1.3 = 5.11kWh$
The system to be designed would need to cater for **5.11kWh** daily consumption.

PV Module Sizing:

$$\frac{Power\ Consumption\ Demands}{Average\ Hours\ of\ Sunlight} = Total\ Array\ Wattage$$
$$\frac{5112.9}{4.8} = 1065.19Wp$$
The system to be designed would need enough panels to provide over **1065.19Wp** of power.
Inverter Sizing:

$Total\ Wattage\ of\ Appliances\ \times Safety\ Factor = Inverter\ Wattage$
$\big((5\ \times 60) + 70 + 18.5 + (6 \times 4) + 770 + 2 + 150\big) \times 1.25 = 1668.13W$
The designed inverter will have to be rated at anything larger than **1.67kW**.

Battery Sizing:

An eight-hour period can be used for the days of autonomy. This means that the batteries will be able to supply continuous energy for one third of a day without charging. This is also a grid-tied system the grid can still step in for solar production shortfalls. It is meant to be a cheaper alternative to case A albeit catering for less stored energy.

$$\frac{Total\ Watt - hours\ per\ day\ used\ by\ appliances\ \times\ Days\ of\ autonomy}{(0.85\ x\ 0.6\ x\ nominal\ battery\ voltage)} = Battery\ Capacity\ (Ah)$$
$$\frac{5122.9\ \times 0.33}{0.85\ \times 0.6\ \times 24} = 138.12Ah$$
Finally, the battery bank should be rated 24V >**139Ah** for 8 hours of autonomy. Two series connected 12V 150Ah batteries will suffice for this system.

Charge Controller Sizing:

No charge controller will be added to the system since it is grid-tied.

iii. ***Case C***

The power demands of this case are the lowest between all cases. This system will be assumed to be an off-grid system to assess the feasibility of some of the household components still being powered regardless of grid power disruptions.
PV Power Demands:

$Daily\ Power\ Needs\ \times Power\ Loss\ Factor = Power\ Consumption\ Demands$
$1.820\ \times 1.3 = 2.366kWh$
The system to be designed would need to cater for **2.366kWh** daily consumption.

PV Module Sizing:

$$\frac{Power\ Consumption\ Demands}{Average\ Hours\ of\ Sunlight} = Total\ Array\ Wattage$$
$$\frac{2366}{4.8} = 492.92Wp$$
The system to be designed would need a sufficient number of panels to provide over **492.92Wp** of power.
Inverter Sizing:

$Total\ Wattage\ of\ Appliances\ \times Safety\ Factor = Inverter\ Wattage$

$\left((5 \times 7) + 70 + 18.5 + (6 \times 4) + 150\right) \times 1.25 = 371.88W$

The designed inverter will have to be rated at anything larger than **0.37kW**.

Battery Sizing:

A two-day period can be used for the days of autonomy. This means that the batteries will be able to supply continuous energy for two continuous days. The reason why this period is extensive relative to the previous two cases is because this system does not have the grid to fall back onto if the PV system does not provide enough power.

$$\frac{Total\ Watt - hours\ per\ day\ used\ by\ appliances\ \times\ Days\ of\ autonomy}{(0.85\ x\ 0.6\ x\ nominal\ battery\ voltage)} = \ Battery\ Capacity(Ah)$$

$$\frac{2366\ \times 2}{0.85\ \times 0.6\ \times 24} = 386.60Ah$$

The battery bank should be rated 24V >**387Ah** for two days of autonomy. This system would require 4 200Ah 12V batteries configured in a series-parallel connection for successful operation.

Charge Controller Sizing:

Since this system is small, the panels needed to cover the peak power required can be configured in a single PV array. It is assumed that 2-250W panels will be used in the array. Therefore,

$$\frac{No.of\ Panels\ \times Watts\ of\ Each\ Panel}{Battery\ Bank\ Voltage} \times 1.25 = Charge\ Controlller\ Rating(A)$$

$$\frac{2\ \times 250}{24} \times 1.25 = \mathbf{26.04A}$$

Finally, the charge controller should have a rating higher than **26.04A.**

A.2 - Cost Comparisons for Each Case

i. *Case A*

Sustainable

Description	**Price**
6 x 380W JA Solar Panels	R15,204
1 x Infini Solar E5.5kW 48V Hybrid Inverter	R27,169
4 x Leoch LPGS12-200 12V 200Ah Hybrid GEL Battery	R23,472
	R65,845

Solar Shop

Description	**Price**
6 x 380W JA Solar Panels	R13,200
1 x Deye 5kW Hybrid Inverter	R22,850
4 x Deep Cycle 200Ah 12V Gel	R23,960
	R61,010

Solar Panel Energy

Description	**Price**
6 x 370W CNBM Monocrystalline Solar Panels	R13,500
1 x Sofar 6000-ES 6kVA/6kW Hybrid Inverter	R19,750
4 x 200Ah GEL-VRLA Allgrand Deep Cycle Battery	R17,600
	R50,850

From the above 3 tables, the package offered by Solar Panel Energy for R50 850 is the most feasible solution. It is also the only solution that meets all sizing requirements.

ii. *Case B*

Sustainable

Description	Price
3 x 380W JA Solar Panels	R6,600
1 x Growatt SPF 3000TL HVM-24 3kVA/3kW 24V Hybrid Inverter	R10,402
4 x Varta LFD75 75Ah 12V Professional Deep Cycle Battery	R13,216
	R30,218

Solar Shop

Description	Price
3 x 365W Canadian Solar Poly KuMax	R6,240
1 x Deye 5kW Hybrid Inverter	R23,510
2 x Deep Cycle 200Ah 12V Gel	R11,980
	R41,730

Solar Panel Energy

Description	Price
3 x 370W CNBM Monocrystalline Solar Panels	R6,750
1 x Growatt SPF 3000TL HVM-24 inverter	R7,850
2 x 150Ah GEL-VRLA Allgrand Deep Cycle Battery	R6,600
	R21,200

For Case B, once again the package offered by Solar Panel Energy for R21,200 is the most feasible solution. It also meets all sizing requirements. Solar Shop had a significantly higher figure than its competitors mainly because of its limited range in small hybrid inverters and small batteries.

iii. *Case C*

Sustainable

Description	Price
2 x 250W Renewsys Deserv Solar Panels	R3,794
1 x IPower 800W 24V Inverter	R3,774
4 x Leoch LPGS12-200 12V 200Ah Hybrid GEL Battery	R23,472
1 x Microcare 30 Amp LED MPPT Charge Controller	R2,135
	R33,175

Solar Shop

Description	Price
2 x JA Solar 280W Poly Large Wafer	R3,200
1 x Axpert RCT 1K 1kW 24Vdc	R5,520
4 x Vision Deep Cycle 200Ah 12V Fully Sealed AGM Technology 6FM100Z-X	R23,960
1 x Victron BlueSolar MPPT 100/30	R3,570
	R36,250

Solar Panel Energy

Description	Price
2 x CNBM 270W Polycrystalline Solar Panels	R3,652
1 x Synapse 3.0V+ 24V Off-Grid Inverter	R5,650
4 x 200Ah GEL-VRLA Allgrand Deep Cycle Battery	R17,600
1 x SC 4860: 60A MPPT for Growatt inverters	R5,000
	R31,902

In this case, again Solar Panel Energy beats its competitors in providing the most economical solution. This is despite its lack of variety in both other competitors in their respective off-grid inverter and charge controller options.

A.3 - Boost Converter Component Sizing Calculations

Based on the selected input parameters, the components are sized as follows [63].

iv. ***Inductance***

$$L \geq \frac{V_{in} \times (V_{out} - V_{in})}{\Delta I_L \times f_s \times V_{out}} = \frac{31.38 \times (47.07 - 31.38)}{5.35 \times 10000 \times 47.07} = 195.51uH$$

v. ***Input Capacitance***

$$D = 1 - \frac{V_{in}}{V_{out}} = 0.33$$

$$C_{in} \geq \frac{I_{out(\max)} \times D^2}{0.02(1 - D) \times f_s \times V_{in}} = \frac{11.90 \times 0.33^2}{0.02(1 - 0.33) \times 10000 \times 31.38} = 308.19uF$$

vi. ***Output Capacitance***

$$C_{out} \geq \frac{I_{out(\max)} \times D}{f_s \times \Delta V_{out}} = \frac{11.90 \times 0.33}{10000 \times 0.01 \times 47.07} = 834.39uF$$

Here, ΔV_{out} is the output ripple voltage and is assumed to be 1%.

Appendix B - Simulink Block Diagrams

B.1 - PV Module Simulations

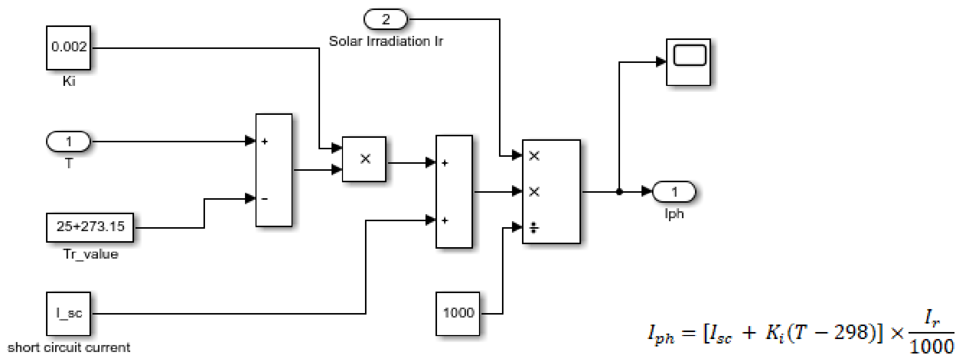


Figure 63: Photon current equation represented in Simulink

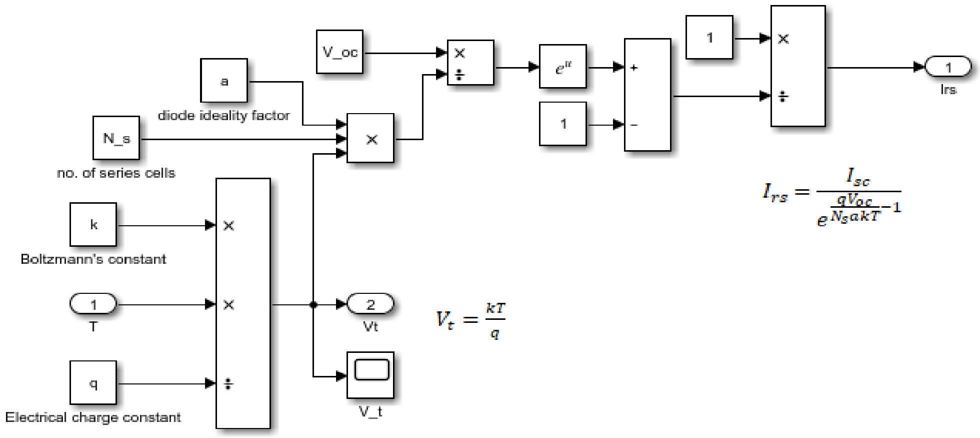


Figure 64: Reverse saturation current and thermal voltage represented in Simulink

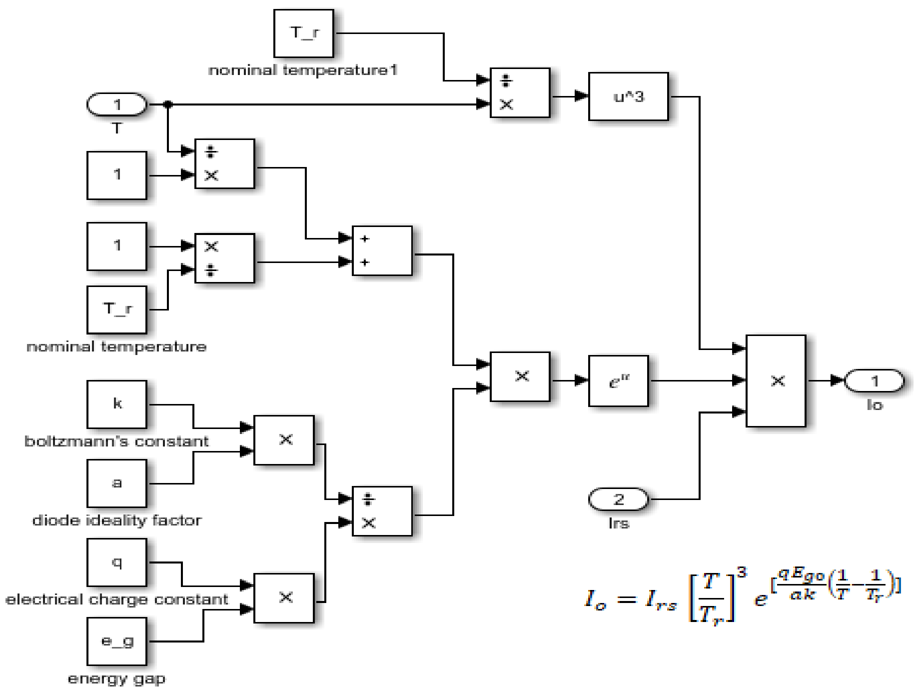


Figure 65: Saturation current represented in Simulink

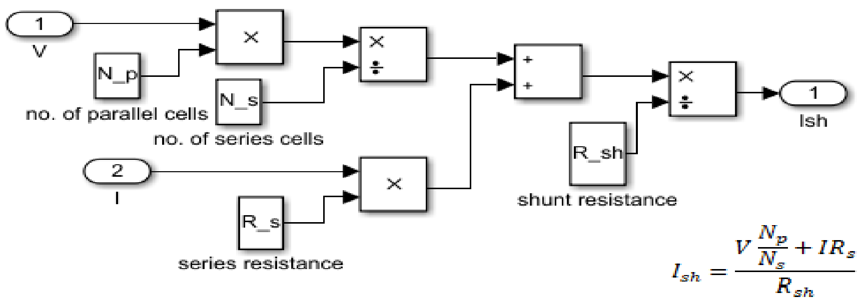


Figure 66: Current through shunt resistor represented in Simulink

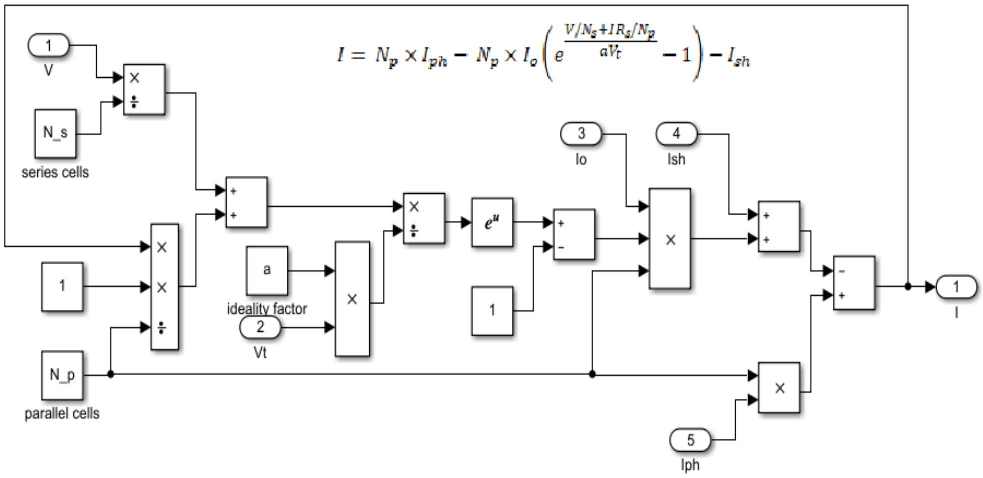


Figure 67: Output current represented in Simulink

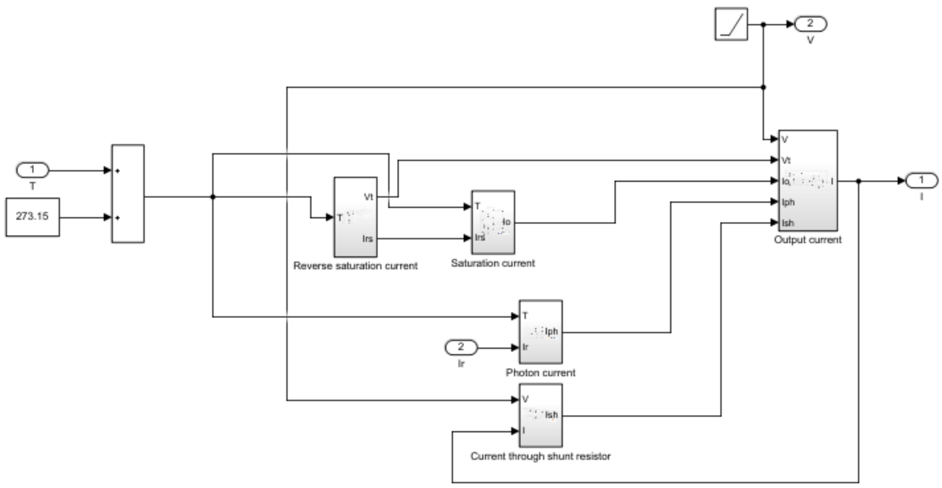


Figure 68: Simulink block diagram modelling a PV module

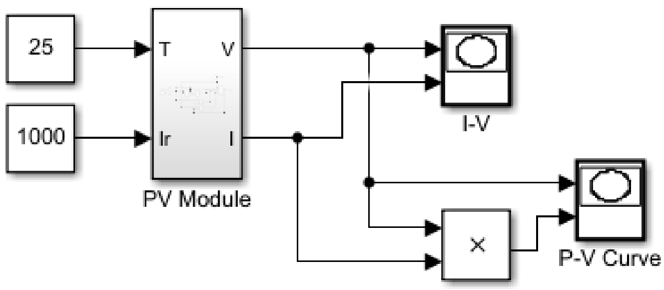


Figure 69: Simulink model of PV module to determine characteristic curves

B.2 - PV Array Simulations

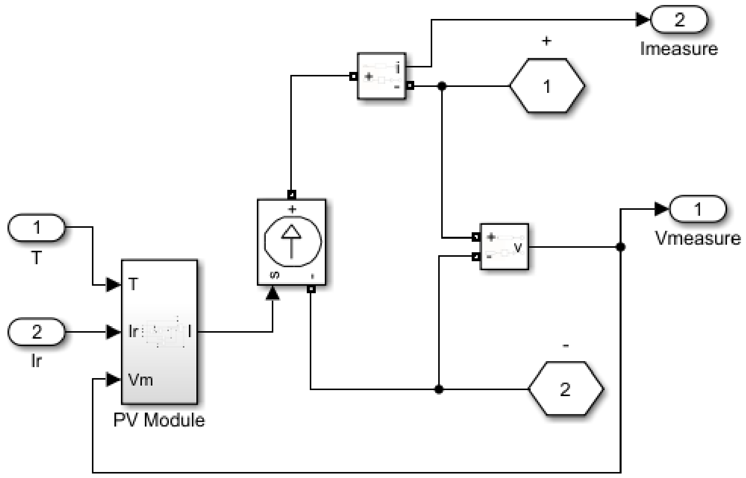


Figure 70: PV module subsystem in Simulink

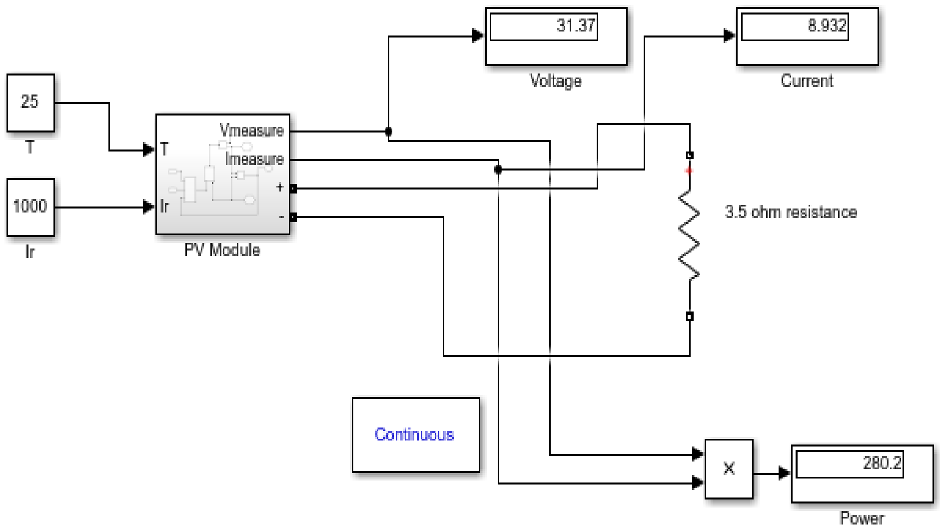


Figure 71: PV system with a single module in Simulink

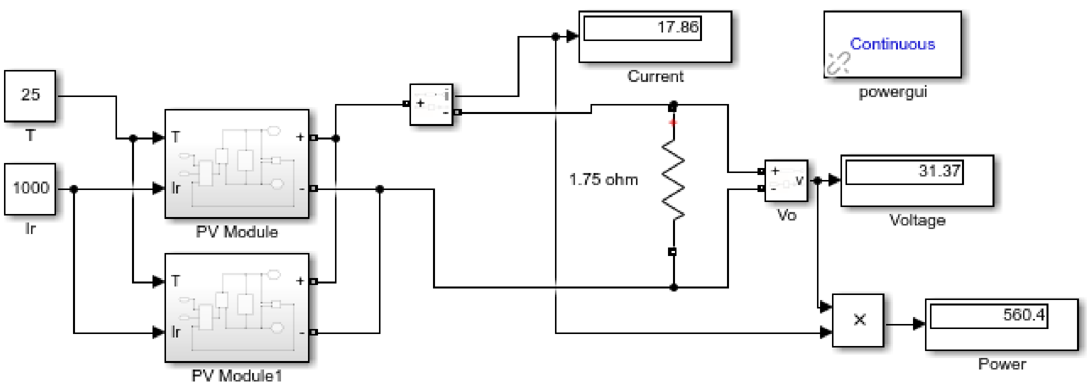


Figure 72: Simulink block diagram representing two 280W modules connected in parallel

B.3 - Boost Converter Simulations

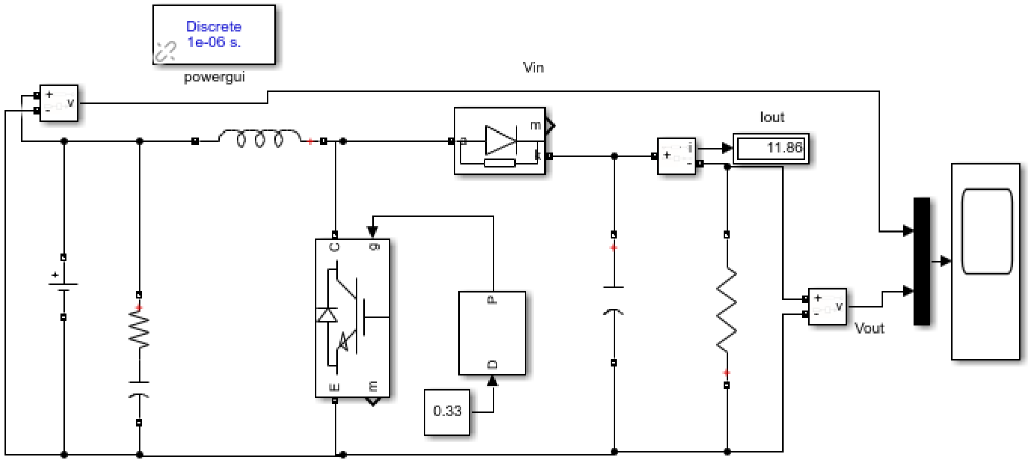


Figure 73: Simulink block diagram of a boost converter

B.4 - Charge Controller Simulations

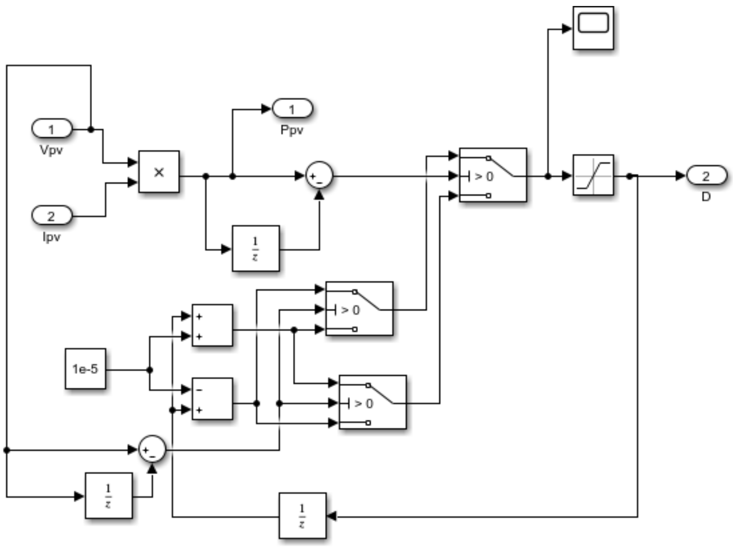


Figure 74: Simulink block diagram of P&O algorithm

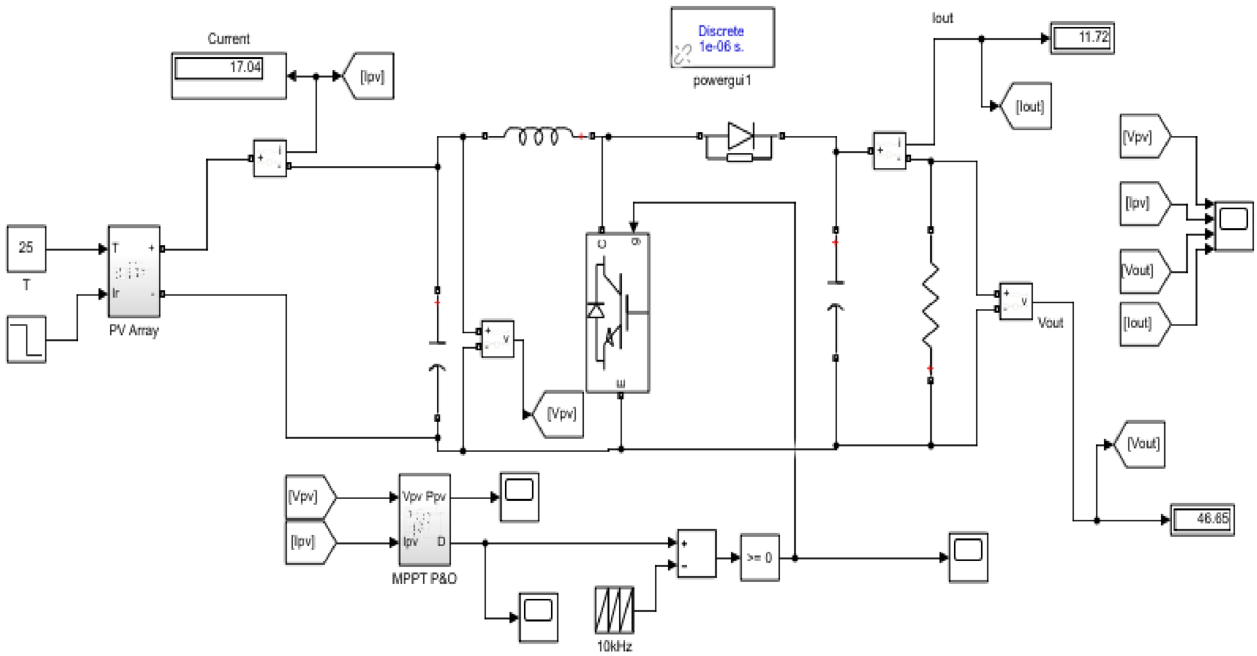


Figure 75: Simulink block diagram of MPPT integrated PV system

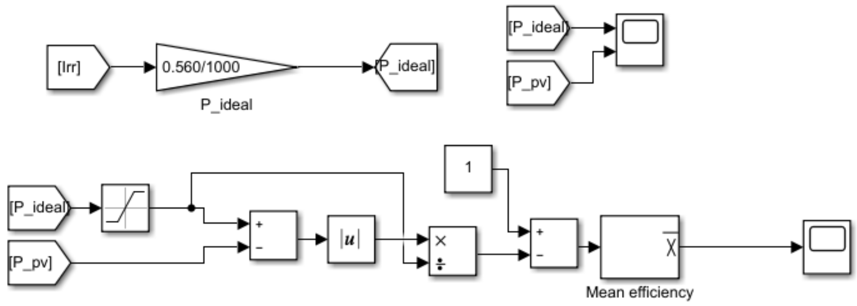


Figure 76: Simulink block diagram used to compare PV power to ideal and calculate MPPT efficiency

B.5 - Battery Bank

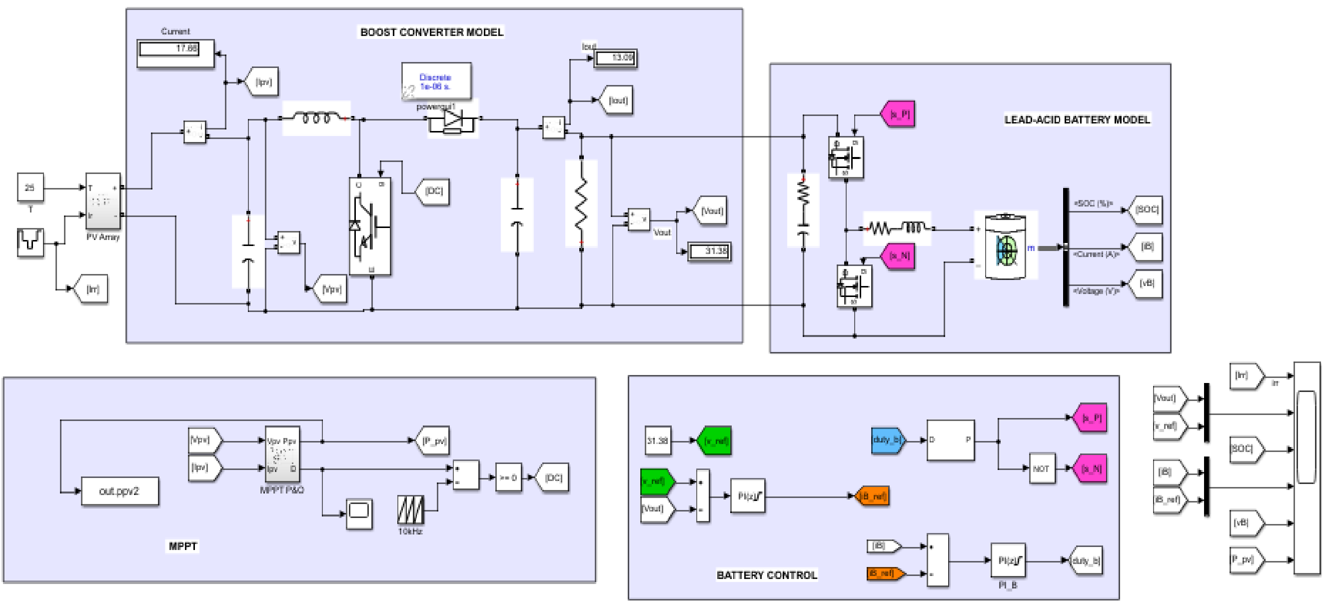
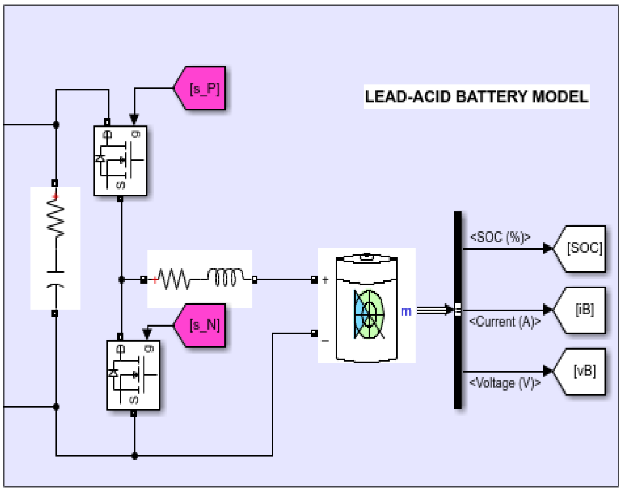


Figure 77: PV system model with integrated lead-acid battery pack



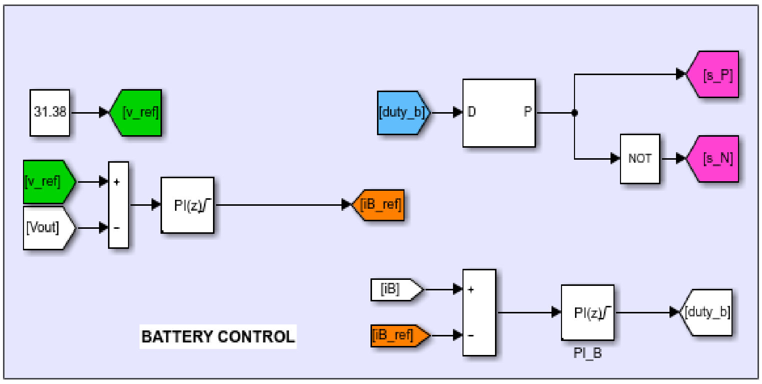


Figure 78: Close-up view of the battery model and its respective control circuit for charging and discharging

B.6 - Inverter

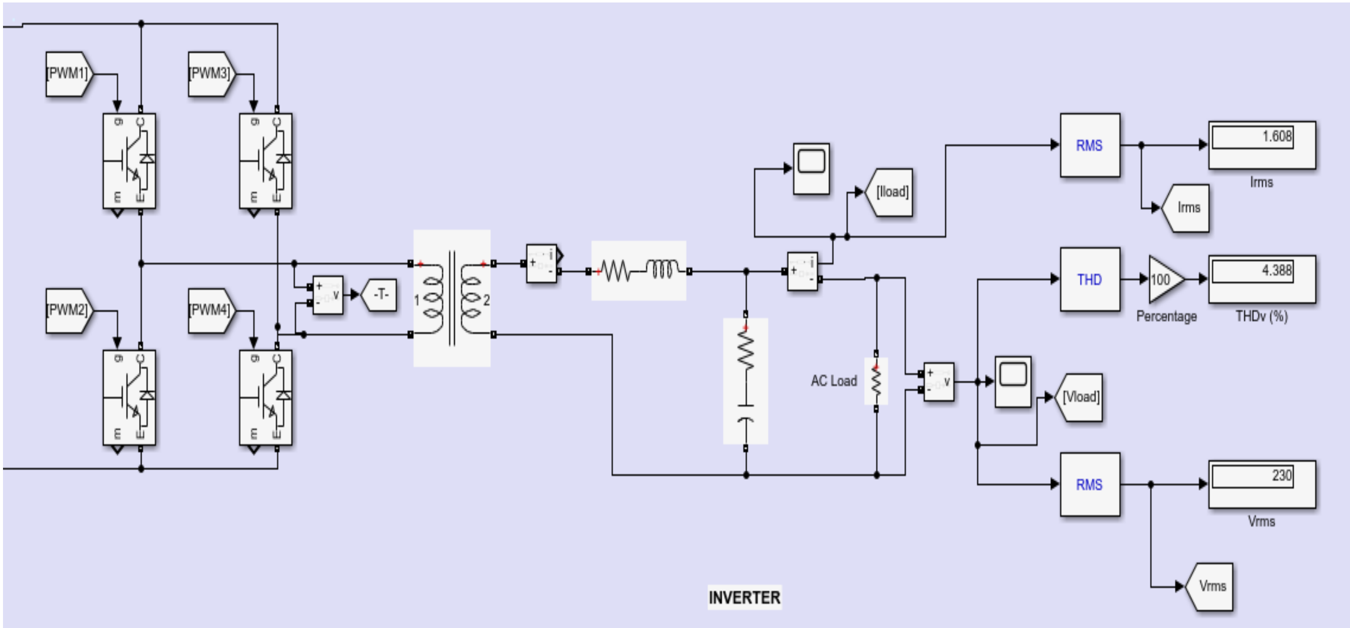


Figure 79: Simulink block diagram of DC-AC inverter

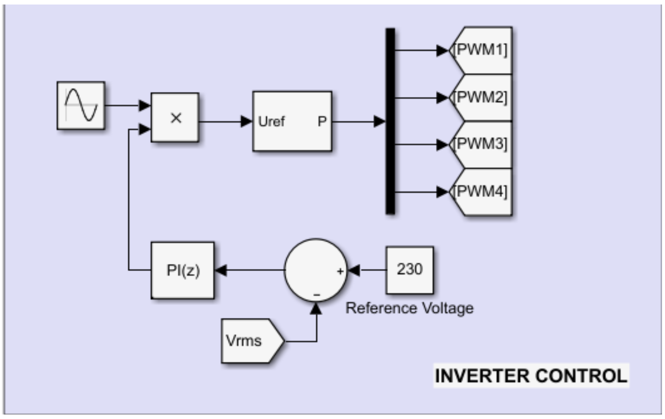


Figure 80: Inverter voltage control block

B.7 – Full PV System Implementation

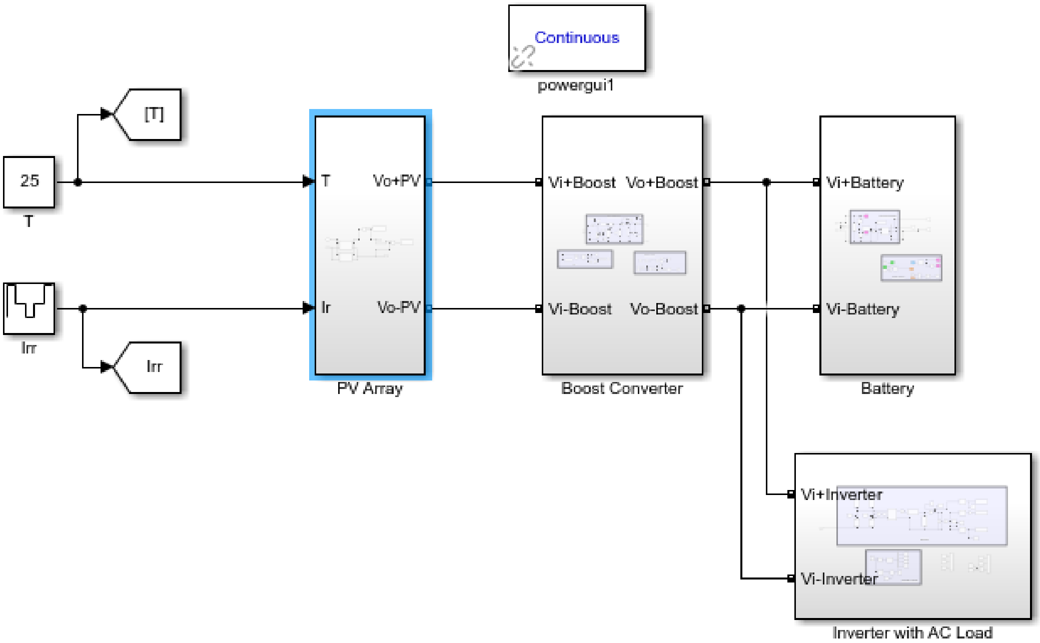


Figure 81: Simplified Simulink diagram of entire PV system with integrated component subsystems

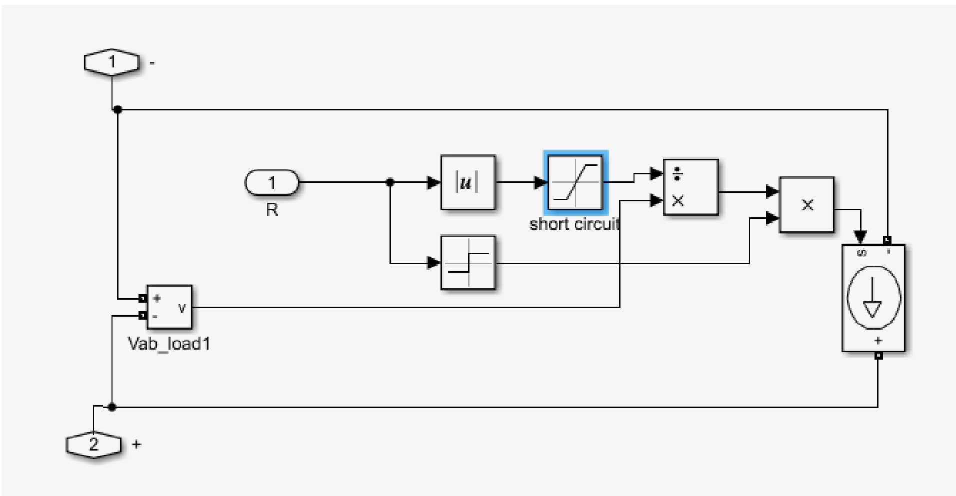


Figure 82: Variable resistor block used as dynamic load

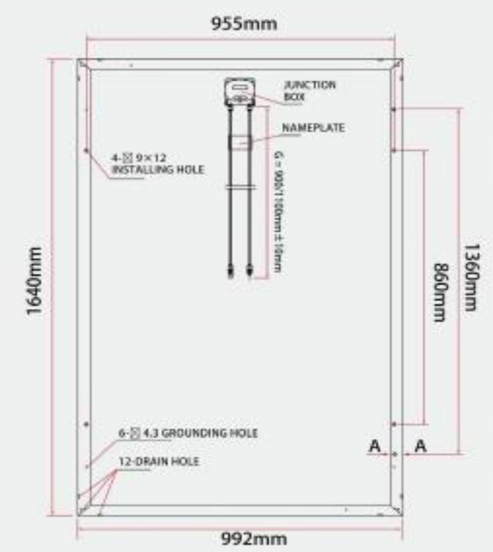
Appendix C – Datasheets

C.1 PV Modules

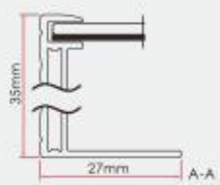
CLEAR EARTH, CLEAR LIFE

www TheSunPays co.za

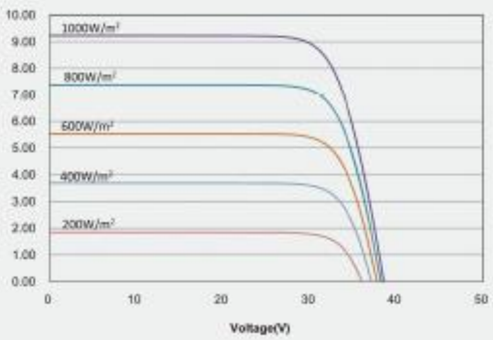
DIMENSIONS OF PV MODULE 6P60 SERIES



Back View



I-V CURVES OF PV MODULE 6P60 SERIES



Dealer Information

ELECTRICAL DATA @ STC	SP-P270W	SP-P275W	SP-P280W	SP-P285W
Peak Power Watts-P_{MAX} (Wp)	270	275	280	285
Power Output Tolerance-P_{MAX} (%)	0/+5	0/+5	0/+5	0/+5
Maximum Power Voltage-V_{MPP} (V)	31.72	31.99	31.38	31.56
Maximum Power Current-I_{MPP} (A)	8.52	8.60	8.93	9.04
Open Circuit Voltage-V_{OC} (V)	38.10	38.25	39.12	39.35
Short Circuit Current-I_{SC} (A)	8.86	8.92	9.45	9.56
Module Efficiency η_m (%)	**16.5**	17.0	17.2	17.5

STC: Irradiance 1000 W/m², Cell Temperature 25°C, Air Mass AM1.5 according to EN 60904-3.
Average efficiency reduction of 4.5% at 200 W/m² according to EN 60904-1.

ELECTRICAL DATA @ NOCT	SP-P270W	SP-P275W	SP-P280W	SP-P285W
Maximum Power-P_{MAX} (Wp)	196	199	206	210
Maximum Power Voltage-U_{MPP} (V)	28.49	28.68	28.7	28.9
Maximum Power Current-I_{MPP} (A)	6.88	6.96	7.18	7.27
Open Circuit Voltage-U_{OC} (V)	35.15	35.46	35.6	35.7
Short Circuit Current-I_{SC} (A)	7.17	7.23	7.54	7.63

NOCT: Irradiance at 800 W/m², Ambient Temperature 20°C, Wind Speed 1 m/s.

MECHANICAL DATA	
Solar Cells	Multicrystalline 156 x 156 mm
Cell Orientation	60 cells (6 x 10)
Module Dimensions	1640 x 992 x 35 mm
Weight	18.2 kg
Glass	High Transparency, Anti-Reflective, AR Coated and Heat Tempered Solar Glass - 3.2mm
Backsheet	White
Frame	Silver Anodized Aluminium Alloy (Black Available)
J-Box	IP 67 rated
Cables	Photovoltaic Technology cable 4.0 mm², 900mm(Customized Available)
Connector	MC4 Compatible

TEMPERATURE RATINGS	
Nominal Operating Cell Temperature (NOCT)	44°C (±2K)
Temperature Coefficient of P_{MAX}	-0.41%/K
Temperature Coefficient of V_{OC}	-0.32%/K
Temperature Coefficient of I_{SC}	0.05%/K

MAXIMUM RATINGS	
Operational Temperature	-40 to +85°C
Maximum System Voltage	1000V DC (IEC)
Max Series Fuse Rating	15A
Mechanical Load	5400pa
Wind Load	2400pa

PACKAGING CONFIGURATION	
Modules per box:	30 pieces
Modules per 40' container:	840 pieces
Modules per 20' container:	360 pieces

WARRANTY
12 year Product Workmanship Warranty
30 year Linear Performance Warranty

(Please refer to product warranty for details)

INSURANCE
Product liability insurance with CHUBB Group
Product performance(E&O)insurance CHUBB Group

C.2 Inverter

IPOWER 800W 24V INVERTER

Excl. Tax: **R 3,281.74** Incl. Tax: **R 3,774.00**

IPower series is a pure sine wave inverter which converts 12/24/48VDC to 220/230VAC. The new industrial design, compared with the civil design, has a wider operating temperature, easy installation and operation. The wide input voltage range is ideal for solar system application.
The inverter can be applied in many fields, such as household emergency lighting system, vehicle mounted system and small field power supply etc.

Please note, this product is currently available on backorder with lead time of 2 - 3 weeks.

Please download full specifications sheet here.

Add to Wishlist | Add to Compare

DESCRIPTION

Features

Safe design with input and output electrical isolation.
Adoption of advanced SPWM technology, pure sine wave output.
Optional output voltage 220/230VAC, choosing by DIP switch.
LED indicators for fault status and working status.
Lower No-load consumption.
Max. efficiency up to 95%.
Input protection: Over voltage protection, low voltage protection.
Output protection: Overload protection, short circuit protection.
Over temperature protection: Temperature-controlled Fan Ventilation; Inverter turns off automatically when overheating.

Technical Specification

Model: IP1000-22.
Rated Input Voltage: 24VDC.
Input Voltage Range: 21.6 to 32VDC.
Input surge voltage: □40VDC.
Output Voltage: 220VAC (± 5%), 230VAC (-10% ~ + 5%).
Output Frequency: 50/60±0.1Hz
Output Continuous Power: 800W.
Power Factor: 0.2-1(VA lower than output continuous power).
Output Wave: Pure sine wave.
Overall dimension: 284.7mm × 231.5mm × 98.5mm.
Net weight: 3.9 kg.

C.3 Batteries

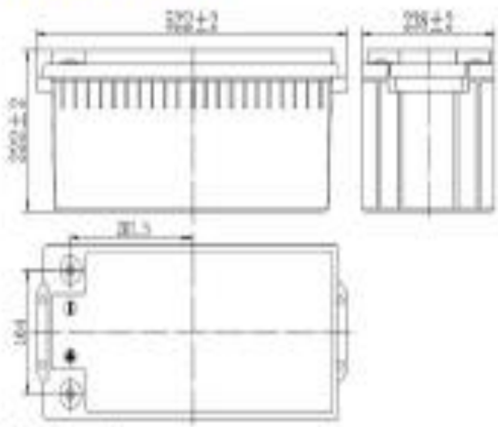
CHAMPION

Champion Battery Stoarge Limited

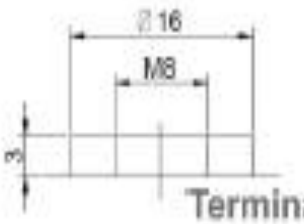
6FM200G

Normal Voltage		12V
Capacity (25℃)	10HR(10.8V)	200 Ah
	5HR(10.5V)	176 Ah
	1HR(9.6V)	124 Ah
Dimension	Length	522±2mm (20.55inch)
	Width	238±2mm (9.37inch)
	Height	222±2mm (8.74inch)
	Total Height	222±2mm (8.74inch)
Approx. Weight		56.5 Kg ± 2%
Terminal type		T11
Internal resistance (Fully charged, 25℃)		Approx. 3.3mΩ
Capacity effected by temperature 10HR	40℃	103%
	25℃	100%
	0℃	88%
	-15℃	70%
Self-discharge (25℃)	3 month	Remaining Capacity: 94%
	6 month	Remaining Capacity: 88%
	12 month	Remaining Capacity: 75%
Nominal operating temperature		25℃±3℃(77℉±5℉)
Operating temperature range	Discharge	-15℃~50℃(5℉~131℉)
	Charge	-10℃~50℃(14℉~131℉)
	Storage	-20℃~50℃(-4℉~131℉)
Float charging voltage(25℃)		13.50 to 13.80V Temperature compensation: -18mV/℃
Cyclic charging voltage(25℃)		14.10 to 14.40V Temperature compensation: -30mV/℃
Maximum charging current		40A
Terminal material		Copper
Maximum discharge current		1600A(5 sec.)
Designed floating life (20℃)		15 years

Dimensions



Terminal



Terminal F14

Applications

- Telecommunication system
- Railway station
- Ship Equipment
- Military Equipment
- Medical treatment equipment
- Alarm system
- Control systems
- Emergency lamp
- Firefighting equipment
- Standby power supply
- UPS and solar power

General Features

- Wide operating temperature range from -25°C to 45°C
- No memory effect, thick flat plate with high Tin low Calcium alloy
- Long Service Life, Both for Float and Cyclic use
- Sealed and maintenance free operation
- ABS containers and covers
- Safety valve installation for explosion proof

C.4 Charge Controller

1. Electric Parameters

Parameter	Value		
Model	ML2420	ML2430	ML2440
System voltage	12V/24VAuto		
No-load loss	0.7 W to 1.2W		
Battery voltage	9V to 35V		
Max. solar input voltage	100V(25℃) 90V(-25℃)		
Max. power point voltage range	Battery Voltage+2V to 75V		
Rated charging current	20A	30A	40A
Rated load current	20A		
Max. capacitive load capacity	10000uF		
Max. photovoltaic system input power	260W/12V 520W/24V	400W/12V 800W/24V	520W/12V 1040W/24V
Conversion efficiency	≤98%		
MPPT tracking efficiency	>99%		
Temperature compensation factor	-3mv/℃/2V (default)		
Operating temperature	-35℃ to +45℃		
Protection degree	IP32		
Weight	1.4Kg	2Kg	2Kg
Communication method	RS232		
Altitude	≤3000m		
Product dimensions	210*151*59.5mm	238*173*72.5mm	238*173*72.5mm

2. Battery Type Default Parameters (parameters set in monitor software)

Parameters cross-reference table for different types of batteries				
Voltage to set Battery type	Sealed lead-acid battery	Gel lead-acid battery	Open lead-acid battery	User (self-customized)
Over-voltage cut-off voltage	16.0V	16.0V	16.0V	9~17V
Equalizing voltage	14.6V	—	14.8V	9~17V
Boost voltage	14.4V	14.2V	14.6V	9~17V
Floating charging voltage	13.8V	13.8V	13.8V	9~17V
Boost return voltage	13.2V	13.2V	13.2V	9~17V
Low-voltage cut-off return voltage	12.6V	12.6V	12.6V	9~17V
Under-voltage warning return voltage	12.2V	12.2V	12.2V	9~17V
Under-voltage warning voltage	12.0V	12.0V	12.0V	9~17V
Low-voltage cut-off voltage	11.1V	11.1V	11.1V	9~17V
Discharging limit voltage	10.6V	10.6V	10.6V	9~17V
Over-discharge time delay	5s	5s	5s	1~30s
Equalizing charging duration	120minutes	—	120minutes	0~600minutes
Equalizing charging interval	30days	0days	30days	0~250D (0 means the equalizing charging function is disabled)
Boost charging duration	120minutes	120minutes	120minutes	10~600minutes

13. Table of Figures

14. EBE Faculty: Assessment of Ethics in Research Projects

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zulpha Geyer (Zulpha.Geyer@uct.ac.za; Chem Eng Building, Ph 021 650 4791).Students must include a copy of the completed form with the final year project when it is submitted for examination.

Name of Principal Researcher/Student: TAREEQ SALEY **Department:** ELECTRICAL ENGINEERING

If a Student: YES **Degree:** MECHATRONICS **Supervisor:** PAUL BARENDSE

If a Research Contract indicate source of funding/sponsorship:

Research Project Title: RESIDENTIAL PV SYSTEM DESIGN

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	YES	NO
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	YES	NO
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	YES	NO
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	YES	NO

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:

	Full name and signature	Date
Principal Researcher/Student:	**TAREEQ SALEY**	11 November 2020

This application is approved by:

Supervisor (if applicable):	**PAUL BARENDSE**	11 November 2020
HOD (or delegated nominee): Final authority for all assessments with NO to all questions and for all undergraduate research.	**Janine Buxey**	11 November 2020
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above		

ADDENDUM 1:
Please append a copy of the research proposal here, as well as any interview schedules or questionnaires:

The purpose of my research is to design and simulate a residential PV system consisting of an inverter and battery energy storage system. This PV system will be designed around the needs of low income South African households and will try and find an approach to allow for these households to benefit from solar energy whilst allowing Eskom to become less reliant on sourcing energy from fossil fuels.

ADDENDUM 2: To be completed if you answered YES to Question 2:

It is assumed that you have read the UCT Code for Research involving Human Subjects (available at http://web.uct.ac.za/depts/educate/download/uctcodeforresearchinvolvinghumansubjects.pdf) in order to be able to answer the questions in this addendum.

2.1 Does the research discriminate against participation by individuals, or differentiate between participants, on the grounds of gender, race or ethnic group, age range, religion, income, handicap, illness or any similar classification?	YES	NO
2.2 Does the research require the participation of socially or physically vulnerable people (children, aged, disabled, etc) or legally restricted groups?	YES	NO
2.3 Will you not be able to secure the informed consent of all participants in the research? (In the case of children, will you not be able to obtain the consent of their guardians or parents?)	YES	NO
2.4 Will any confidential data be collected or will identifiable records of individuals be kept?	YES	NO
2.5 In reporting on this research is there any possibility that you will not be able to keep the identities of the individuals involved anonymous?	YES	NO
2.6 Are there any foreseeable risks of physical, psychological or social harm to participants that might occur in the course of the research?	YES	NO
2.7 Does the research include making payments or giving gifts to any participants?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues:

ADDENDUM 3: To be completed if you answered YES to Question 3:

3.1 Is the community expected to make decisions for, during or based on the research?	YES	NO
3.2 At the end of the research will any economic or social process be terminated or left unsupported, or equipment or facilities used in the research be recovered from the participants or community?	YES	NO
3.3 Will any service be provided at a level below the generally accepted standards?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues:

ADDENDUM 4: To be completed if you answered YES to Question 4

4.1 Is there any existing or potential conflict of interest between a research sponsor, academic supervisor, other researchers or participants?	YES	NO
4.2 Will information that reveals the identity of participants be supplied to a research sponsor, other than with the permission of the individuals?	YES	NO
4.3 Does the proposed research potentially conflict with the research of any other individual or group within the University?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues: