Techno-Economic Comparison of Standalone Microgrids for Rural Electrification in South Africa

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Abstract

Rural electrification is a global problem that primarily affects developing countries. The people worst affected are people living in sub- Saharan Africa. There are number of reasons why rural electrification is generally low. People in rural areas generally live in small communities, located far away or from the grid or in geographically tough terrain. As a result, it is not financially viable to extend the grid to these areas and therefore they remain unelectrified. Another dictating factor, is the fact that people in these areas are generally poor, and therefore this discourages any investment from the private sector. This dissertation focuses on rural electrification in South Africa specifically. Most people in South Africa affected by not being electrified live in rural areas on the border between the Eastern Cape and Kwa-Zulu Natal. As it is too expensive to extend the grid to these areas, off-grid options, such as microgrids were investigated.

A large amount of research has been carried out on hybrid microgrids as a solution to rural electrification. However, a limited amount of research has been carried out on single source microgrids. Furthermore, South Africa is fortunate to have an abundance of solar, wind and microhydro resources, however, it is unclear which resource would be cheapest based on the location of the rural area. As a result, the aim of thesis was to analyse the impact of the strength of the resource when implementing a microgrid and comparing the three different renewable resources systems against one another.

In order to carry out this analysis, three unelectrified villages were selected with each village located in an area of a strong resource, whether it be wind, solar or microhydro. i.e. one village was selected in an area with a strong solar resource, the second in an area with strong wind resource and the third in an area with strong microhydro resource. Once selected, a load for each village was modelled and the resource data for each village was obtained using open source sites. Solar-battery, wind battery and microhydro-battery systems were modelled for each village using HOMER.

From the results it was clear that when comparing the same resource in each of the villages, then the strength of the resource did affect the levelised cost of energy i.e. the stronger the resource, the less the lower the cost of energy which was as expected. However, when comparing the solar, wind and microhydro system in each village against each other, it was apparent that the strength of the resource did not dictate the type of technology to be used in that area. It was found that wind systems were not suited to small scale generation, whilst microhydro was the cheapest technology in each village, however, its implementation may be deterred by non-technical issues such as the social and environmental impacts of constructing a dam. The cost of the solar system was comparable to microhydro only when the irradiation was above a certain level. As solar systems are easier and quicker to implement it is possibly the best system in general for rural areas in South Africa.

Implementation of off-grid systems for rural electrification in South Africa is a viable option however, as the private sector is not incentivised to implement these systems, then government back in the form of grants and subsidies are required to implement these systems. However, as renewable technologies improve and get cheaper with time, this option to electrify rural areas is always becoming cheaper.

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1 Introduction

1.1 Background to the study

Rural electrification is a global problem that primarily affects developing countries. In the world, Africa has one of the lowest rural electrification rates. Most of these people without access live in rural areas. South Africa has one of the highest electrification rates in Sub-Saharan Africa; however, approximately 20% of all households still require electrification.

The electrification rate is not 100% in South Africa, as the remaining households that need to be electrified are situated far away from the grid, therefore a decentralised power solution is required. The two main decentralised forms of generation are Solar Home Systems (SHS) and microgrids, of which microgrids are the focus of this study as proposed solution to South Africa's rural electrification problem.

Microgrids are particularly advantageous for rural areas situated in difficult geographical terrain or rural areas located a great distance from the grid. They are a better option than SHS as a decentralised solution for the following reasons:

- They allow for inclusion of high powered loads [1]
- They are the better option financially as they take advantage of economies of scale. [2]
- They are easier to secure and therefore less likely to be vandalised [3]
- Furthermore, microgrids can aid in other economic activities as other loads beside domestic can be included in the demand profile. SHS's do not have this characteristic and are limited to domestic uses, with only business activities requiring light being aided in this regard.[1]

According to the research, [4]–[12] here are large amount of instances where microgrids were used in rural applications throughout the world. The Levelised Cost of Electricity (LCOE), defined as the average cost of per kWh of energy of useful energy produced by the system, was used to compare the different microgrid systems. From the microgrids systems reviewed, it was noted that LCOE ranged from $0.179/kWh - $2.797/kWh, depending on the location and the type of technology used. Most of these systems were located in developing countries. It was noted that microgrids for rural applications have not been implemented in South Africa. A pilot microgrid was implemented in Lucingweni village in 2007; however, it was concluded that the project was too expensive. [13]This was due to the high cost of renewables at the time and the fact that the system was overdesigned. In the last 10 years, the price of renewable technologies has dropped significantly due to advances in technology, therefore we expect the price to be more feasible at this stage, however this will depend on the renewable energy source selected.

It is important that the level of renewable resources available is good enough for the microgrid to provide sufficient energy. South Africa is blessed with an abundance of solar, wind and microhydro renewable resources with the strength of the resource depending on the location. Solar, wind and microhydro will be the main focus of this research.

It was noted that most of the research focused on hybrid microgrids and that a limited amount of research has been carried out on single source microgrids in general. As a result, this dissertation aims to provide better insight into technical and economic aspects of single source microgrids in South Africa versus other microgrids in other developing countries, as well as investigate how the strength of a resource in different areas affect the Levelised Cost of Electricity.

1.2 Objectives of this study

1.2.1 Problems to be investigated

South Africa is still to attain 100% electrification. The areas that are un-electrified are made up of mostly rural villages that are located a far distance from the grid, or in geographically rough terrain. This makes decentralised generation, the best option to power these rural villages.

A large amount of research has been carried out on hybrid microgrids as a solution to rural electrification. However, a limited amount of research has been carried out on single source microgrids. These microgrids have been found to be generally expensive in the past; however, based on the literature, there have been instances where they have been cheaper. [7], [14] Furthermore, limited research has been carried out in microgrids in South Africa. Earlier studies deemed them to be too expensive. But now since the price of renewables have dropped, this solution may be more feasible. The aim of this study is to show, how single source microgrids in South Africa, compare to other microgrids in developing countries, from a techno-economic standpoint. These results will give insight into whether these microgrids can be successfully implemented to solve South Africa's rural electrification problem.

Single source, stand-alone microgrids also make it easier to determine how the strength of a renewable resource will impact the general cost of electricity for a given microgrid in South Africa. As South Africa has a vast range of strong renewable resources, it is not clear, which would be the cheapest resource based on the location of the rural area. This thesis will therefore additionally aim to compare microgrids depending on the renewable resource selected in order to determine how much impact the type and strength of a resource has when implementing a microgrid.

1.2.2 Plan of the study

In order to achieve the above mentioned aims, three rural, un-electrified villages will be selected in different parts of South Africa. The villages will be selected such that the first one is located in an area of strong solar resource, the second one located in an area of strong wind resource and the third one located in an area of strong microhydro resource. The villages selected will be similar in size, in order to remove size of the village as a variable that will affect the cost.

HOMER, a micropower optimisation tool, will be used to simulate a single source solar, wind and microhydro-based microgrid in each area. In order to carry out this simulation the renewable resources and load of each village will need to be determined. A resource assessment will be carried out using various open source/free trial packages to determine the renewable resources in each rural village. The load profile will be generated and modelled based on the typical domestic, economic and social activities expected to be carried out in a village. Furthermore, the prices of the different components of the renewable systems will be obtained from online websites or any other open source sites. Further details of the components and costing will be covered in Section 3. All these variables will be input into HOMER.

The cost metrics in HOMER such as the Levelised Cost of Electricity (LCOE) and the Net Present Value (NPV) will be used to compare the different microgrids in each village, as well as comparing systems in different villages e.g. the comparison of the solar microgrids in all the villages. Further details on the comparisons to be carried out will be covered in Section 4. These comparisons will help determine how the strength of a renewable resource will impact the different cost metrics and energy parameters (unmet load, excess electricity, etc.), as well as determine whether single source, off-grid microgrids are a viable solution to South Africa's rural electrification problem.

In summary, the research goals are as follows:

- Comparison of the solar microgrids, wind microgrids and microhydro microgrids
- Comparison of the microgrids in each village separately
- Comparison of the microhydro systems with and without existing dam infrastructure.
- Determine whether single, source off-grid microgrids are a viable solution for rural electrification in South Africa

1.3 Scope and Limitations

The villages selected were un-electrified based on the map from the Scottish Power report written in 2003 [15]. However, based on information from the National South African Survey carried out in 2011, these rural villages were still un-electrified. No further information on whether these villages are currently electrified could be found. Therefore, for the purpose of this dissertation, these villages are considered to be un-electrified.

Furthermore, the selection of rural villages was limited to areas where renewable data was available. For solar and wind, data was easily available for any location, however microhydro data was only available in areas where measuring stations were placed, thereby limiting the choice of village.

The scope of this research is only limited to single source, off-grid microgrids with battery back-up. Hybrid microgrids will only fall under this scope for comparative purposes of which comparisons will be limited to hybrid microgrids covered in the literature review. Grid-connected microgrids are not considered in this research.

The price of the components, technical information and manufacturer datasheets were limited to information available public domain data on the internet. The exchange rate used was based on the date of which the prices were obtained, which in this case was mid-July 2016. Therefore, all costs achieved are based on the prices and rates as of that date.

1.4 Plan of development

Chapter 1 is an introduction to this thesis and provides a background to the research. Furthermore, the problem definition as well as a plan as to how the research aims are to be met are summarised here.

Chapter 2 presents the review of the literature. This includes a background into rural electrification in South Africa as well as a review of different microgrid technologies and their implementation in rural areas in other developing countries. The topic and focus of this dissertation is proposed based on the literature reviewed.

Chapter 3 discusses the research methodology. This section details how the villages were selected, how the load model and resource assessment was carried out, how this data and technical components were input into HOMER to simulate the different microgrid systems.

Chapter 4 covers the different case studies that will be carried out in order to achieve the research goals. This includes details of the different parameters that are to be compared and how these parameters are relevant to the research goals.

Chapter 5 presents a detailed analysis of the results of the above mentioned case studies. This will include all tables and figures relevant to the simulation results for discussion and explanation of the same.

Chapter 6 will provide conclusions and recommendations based on the results obtained. It will also be determined how the results tie in with the initial research aims and whether the project objectives were achieved.

2 Literature Review

2.1 Rural Electrification

2.1.1 Global

Unfortunately, not all people have access to electricity. According to the IEA Energy Outlook 2009 report [16], almost 1.3 billion people do not have access to electricity, which accounts for 15% of the world population.

According to a World Bank report, 12% of the world's population are made up of low income countries which consume only 1% of the total global energy [17]. The global distribution electricity access is shown in Table.2.1 below.

Table.2.1 Electricity access in 2009 [16]

	Population without electricity millions	Electrification rate %	Urban electrification rate %	Rural electrification rate %
Africa	**587**	41.8	68.8	25.0
North Africa	***2***	*99.0*	*99.6*	*98.4*
Sub-Saharan Africa	***585***	*30.5*	*59.9*	*14.2*
Developing Asia	**675**	81.0	94.0	73.2
China & East Asia	***182***	*90.8*	*96.4*	*86.4*
South Asia	***493***	*68.5*	*89.5*	*59.9*
Latin America	**31**	93.2	98.8	73.6
Middle East	**21**	89.0	98.5	71.8
Developing countries	**1 314**	**74.7**	**90.6**	**63.2**
World*	**1 317**	**80.5**	**93.7**	**68.0**
*** World includes OECD and Eastern Europe / Eurasia**				

From Table 2.1 it is noticed that most of the population without electricity access are from developing countries with 1,314 million people without electricity. The worst affected countries are located in developing Asia and Sub-Saharan Africa with 675 and 585 million people without electricity respectively. Even though developing Asian countries have so many people without electricity their electrification rate is high at 81% whereas Sub-Saharan Africa has the lowest electrification rates of 30.5%.

Even though the electrification rate is high, the rural electrification rates are lower globally, especially in Sub-Saharan Africa and South Asia. The world rural electrification rate is 68% whilst that of developing countries is 63.2%. This shows that most of the people that are not electrified are from rural areas of developing countries.

A further more detailed analysis of Sub-Saharan Africa is done in [18]. A graph of some of their electrification rates is shown in Figure 2.1.

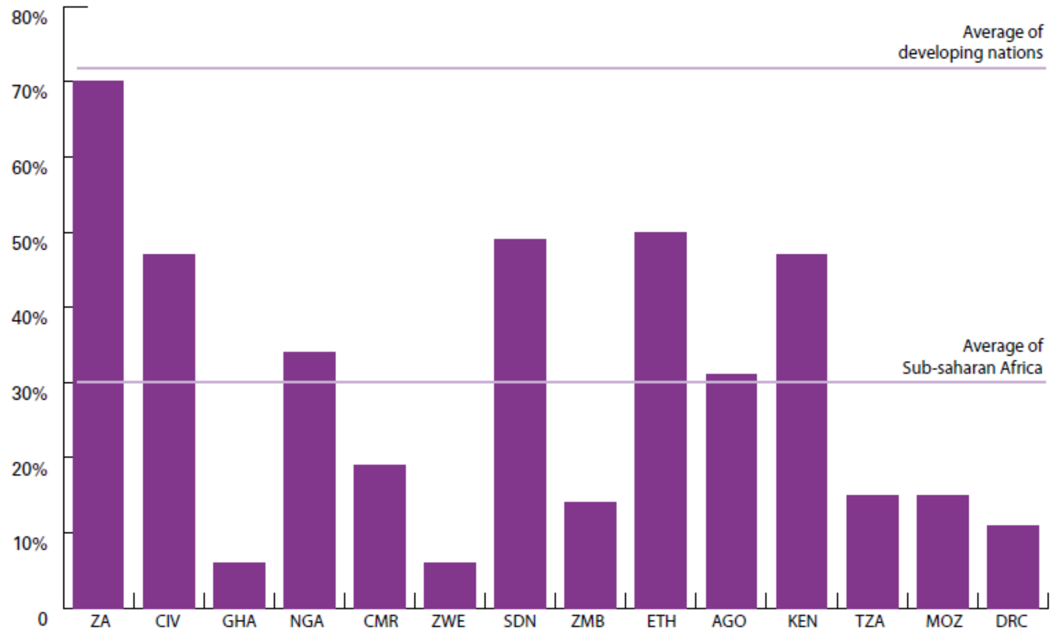


Figure 2.1 Graph of electrification rates of Sub-Saharan African countries [18]

From Figure 2.1 it is clear that not a single country is above the average of developing nations, though South Africa comes close with an electrification rate of 70%. Ghana and Zimbabwe have the lowest with electrification rates below 10%, whilst the average of Sub-Saharan Africa is 30%. According to [19], despite the high rates of urbanisation, Africa still has the highest share of rural population in the world. These rural areas are the biggest contributors to the low electrification rates.

A more detailed look at the trends of rural electrification rates from 1970 are shown in Figure.2.2 below.

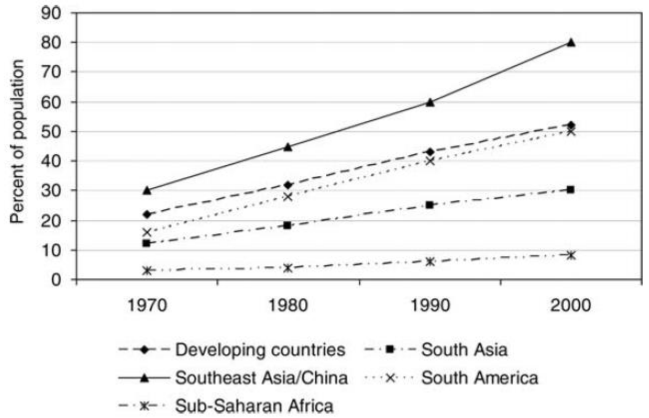


Figure 2.2 Access to electricity in rural areas of developing countries [19]

It is noted from Figure 2,2 that over the thirty year period, Sub-Saharan Africa's rural electrification rate was less than 10% [19]. It is clear that Sub-Saharan Africa has a rural electrification problem. The electrification rates are so low due to a number of inter-linking reasons.

2.1.2 Barriers to rural electrification

The primary reason why the electrification rate is so low in rural areas is because of distance from the grid. Grid connection has the advantage of providing a constant source of electricity depending on available resources, at a cheap rate wherever it is being connected. However, as the distance from the grid increases, longer transmission lines need to be built which greatly increase costs. Most rural areas are not electrified because of this reason. This is shown in [20] which compares distributed generation versus grid extension for Northern Ghana. For the given rural area that needed electricity the lifecycle cost of electricity was more expensive for the grid extension. The paper also concludes that the denser the village population the less the grid extension will cost, making it difficult to use this method for smaller, sparsely populated villages.

Besides distance from the grid another factor that leads to low electrification rates is that most people in rural areas are poor. This according to reference [21] makes it difficult for these rural consumers to pay the rates. These consumers then turn to cheaper, more traditional energy sources such as wood and paraffin. Reference [22] also mentions that the type of traditional energy source used is also dictated by income rate, with households with higher incomes using low pressure gas (LPG), whilst households with lower incomes will use crop waste and dung.

The fact that people are poor also means that rural electrification is not profitable for the private sector hence their reluctance to invest. People in rural areas would not be able to afford electricity if it was just provided by the private sector; therefore, it is up to the public sector and foreign donors to provide funding. Reference [19] highlights this fact and also the importance of costs and low returns in the medium run. Reference [23] compares rural electrification in Bangladesh and Thailand and details how the programs were carried out and determines why one was more successful than the other. In Thailand, the rural electrification rate increased from 7% in the 1970's, to 97% in 2000. In Bangladesh the rural electrification rate started out at a negligible amount in 1977, and increased to 19% in 2000. Both systems made use of Independent Power Producers (IPP's) to generate electricity and sell it to state enterprises in charge of transmission and distribution. Government funding played an important role in kicking-off these rural electrification programs.

Another important factor of low electrification rates in developing countries is that of political agendas. Politicians, who are tasked to make important decisions, may do so for their own political gain. Reference [24] notes that many politicians push for electrification of their districts or areas where they owe allegiance to. This is a barrier as people that are not in favour with politicians will not be electrified. It however can also be seen as a driver for those rural people in favour with politicians. In Bangladesh this has been a problem as indicated by reference [25], which concludes that political interference has a negative influence on system efficiency because of the reason mention above.

Another minor barrier to rural electrification mentioned in reference [24] that applied to Tanzania and Mozambique is traditional building techniques make houses unsuitable for electrification using current technical standards. These mud and grass houses can be electrified but at a more expensive price.

There are many barriers to rural electrification in developing countries but none that can be surmounted. There are some developing countries that have achieved high connection rates. The models used by these successful countries should be emulated and adjusted in order to gain success. The following section discusses the rural electrification situation in South Africa.

2.1.3 Rural electrification in South Africa

The barriers experienced by most developing countries were mentioned in Section 2.1.3 above. However, the barriers experienced by South Africa were a lot more different.

Before 1990, less than a third of the population had access to electricity. This was due to apartheid. The result of this caused a big racially defined wealth gap between black people and white people. This gap did not just include money, but infrastructure and services as well. 25% of non-urban black people were electrified as opposed to 97% of non-urban white households. This was the case even though there was a huge amount of excess supply due to the overbuilding in the 1980s [26].

Even though South Africa had apartheid as a barrier, they were fortunate to not face any of the other common problems faced by developing countries as indicated in the previous section. This was the case because of the excess electricity supply.

In the early 1990's, negotiations were carried out to roll out an electrification program called the National Electrification Programme (NEP). This program which started in 1992 was undertaken by Eskom. Eskom aimed at connecting 5 million people by 1997. The money for the connections was obtained through cross-subsidies, loans and grants. Therefore, during the period between 1994 and 1999, there were a high number of connections, especially in rural areas, however, until 2002 connections mostly occurred in urban areas. In 2002, responsibility for electrification shifted to the Department of Minerals and Energy (DME). In 2004, they started to face problems due to inadequate sub-transmission infrastructure, which lead to a big drop in the connection rate. [26] The distribution of areas not electrified in 2003 is shown in Figure 2.3 below and is denoted in black. [15]The red signifies the lay out of the MV network at the time.

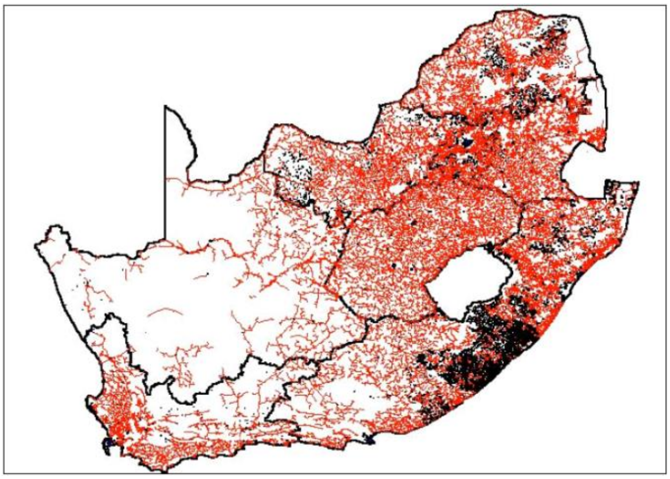


Figure 2.3 Areas not electrified in South Africa [15]

In 2004, the South African government set a goal of achieving "Universal Access" in South Africa by 2012. This would mean every household would have access to electricity by that time. However, with the resources at the time and the high financial cost, this goal was not achieved in 2013. [26]

In 1999, plans where set out to use off-grid solar as a technology to reach the remote rural areas as part of the Integrated National Electricity Programme (INEP). The INEP aimed to install over 300,000 solar home systems. The solar home system comprised the following:

- A photovoltaic panel (50Wp)
- Charge controller
- Wiring and outlets for small appliances
- A battery (105Ah)
- 4 compact fluorescent light bulbs (CFLs)

This system would equate to providing about 250Wh/day. The DME was to allocate concessions to private companies through a tender process to provide energy to these areas. These concessionaires would have the right to provide off-grid electrification to certain geographic areas. The concessionaires would use a fee-for-service model. Customers would pay a deposit and a monthly fee while the concessionaires would install the full system and provide maintenance. Government subsidy was a necessity for the program to be economically viable. Six concessions were selected of which five reached implementations. This program has not achieved its attended results due to government cut backs, therefore leading to concessionaires not being paid.[26]–[28]

The electrification rates as stated by the Department of Energy (DOE) in September 2013 were such that 5.7 million households were connected to the grid and a further 68,115 households were supplied by off-grid technologies. The DOE is still set on achieving the Universal Access goal. It is expected that 78% of all households will be electrified in 2014. A roadmap of achieving Universal Access using different technology options whilst varying the amount of investment is shown in Figure 2.4 below. [28]

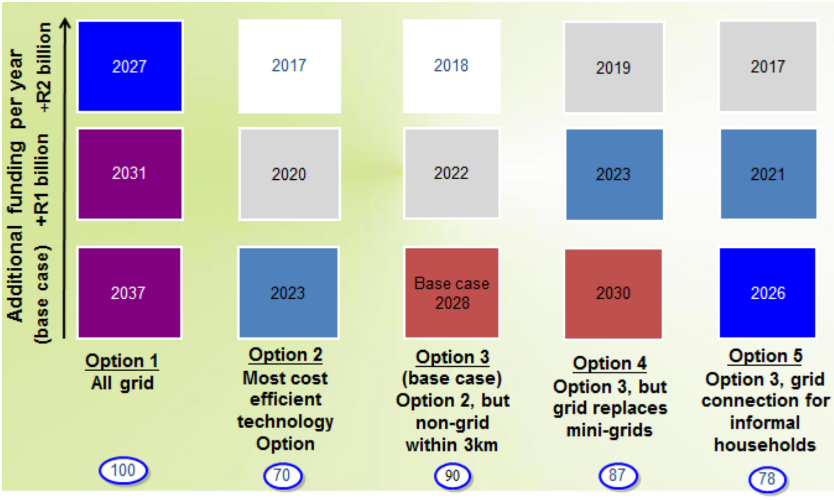


Figure 2.4 Roadmap to Universal Access [28]

In Figure 2.4, the numbers in the blue circle indicate the percentage of formal households that are connected to the grid. It is noted that Option 2 obtains Universal Access the fastest in all cases however Option 3 is what will be implemented. Figure 2.5 shows the off-grid potential. This shows that even at this time there is still a lot of scope in this field in South Africa.

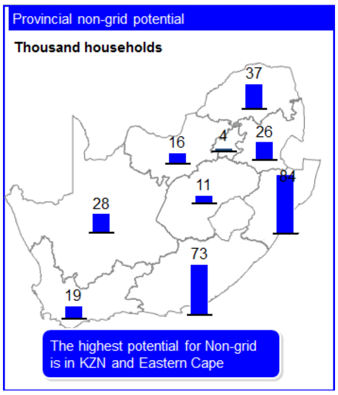


Figure 2.5 South Africa Off-grid potential [28]

2.2 Renewable Resources in South Africa

Most of the current generation mix in South Africa is made up of fossil fuels. According to reference [29], 92% of the electricity generated is from fossil fuels (coal, oil and gas). The generation mix in 2010 is shown in Figure 2.6

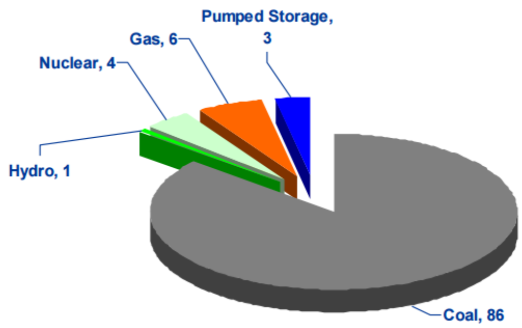


Figure 2.6 Generation mix in 2010 [29]

The high percentage of coal in the generation mix has led to the high carbon emissions experienced by the country. In order to counter these emissions and keep up with the increasing electricity demand, in 2010, DOE published the Integrated Resource Plan (IRP). The IRP provides a guideline to the proposed generation fleet for South Africa until 2030. According to the IRP, by 2030 the proposed generation mix is as shown in Figure 2.7 below. [30]

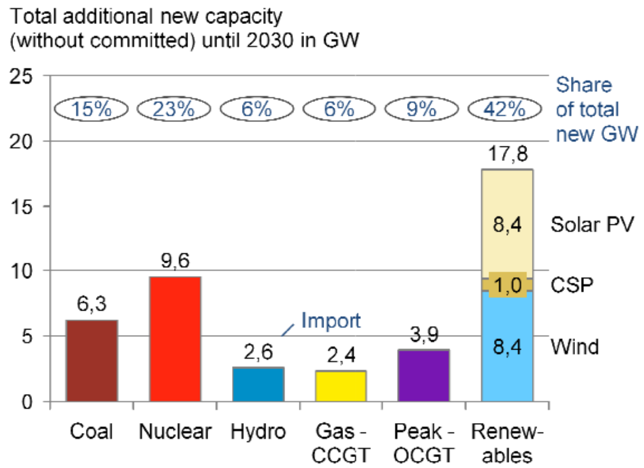


Figure 2.7 Proposed generation mix until 2030 [15]

The main point to note is the increase from 0% to 44.6% of renewable resources in the generation mix. This high contribution of renewables means that the renewable resources in South Africa are fairly good, especially wind and solar.

In order to execute this IRP, the DOE rolled out the Renewable Energy Independent Power Producer Procurement (REIPPP) programme. To date 79 privately developed utility scale projects have been allocated over the course of 4 rounds of bidding, which comes up to a total 5,243 GW of generation from only renewable sources. The bulk of the generation has come from solar and wind technologies. [31] The following sections discuss the renewable energy potential of South Africa.

2.2.1 Solar Energy

According to Figure 2.7 solar photovoltaic (PV) received 8.4 GW of allocation, whilst CSP received 1.0 GW [30]. The literature including [32]–[34], state that South Africa has good solar resources. Figure 2.8 below highlights this fact by showing the Global Horizontal Irradiation (GHI) across South Africa. The GHI is the total radiation from above that is received by a horizontal flat surface.

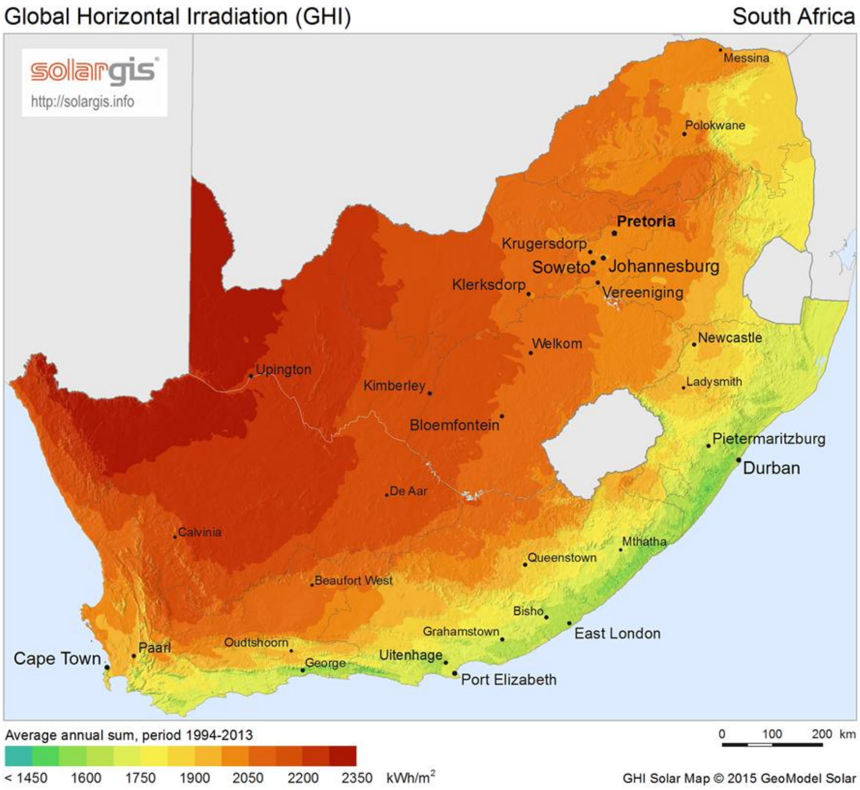


Figure 2.8 Global Horizontal Irradiation (GHI) South Africa [35]

From the diagram it is noted that the highest irradiation is experienced in the Northern Cape; therefore, this seemingly would be an ideal place to generate electricity using solar technology. An irradiation study was conducted in Durban which is in the region of lowest irradiation according to Figure 2.8. The study was conducted using various ground measured irradiation data for a year. It was concluded from the results that Durban had substantial solar resource [36]. This further proves the good solar potential of South Africa. Even in an area of lowest irradiation, the solar resource is still good enough for electricity generation.

However, generation of electricity from solar resources does not only depend on irradiation. Hot weather conditions as experienced in Durban will affect the performance ratio of solar modules. Conditions such as high temperature negatively impact performance thereby reducing yield. Therefore, the location with the best irradiation may not have the best performance ratio if temperatures are too high [33]. The average daily solar irradiation in the country varies from 4.5 – 6.5 kwh/m^2 [32].

There are 45 solar PV projects allocated under the first four rounds of the REIPPP program to date which comes up to approximately 2,315 MW. 33 of them are fully operational whilst the rest are in construction or waiting construction phase. Further still, 5 concentrated solar power (CSP) projects have also been allocated with a total of 300 MW. An additional CSP 100 MW plant which is to be built by Eskom is also awaiting construction. The positive action towards implementation of solar projects further compounds the great solar resources experienced by South Africa. [31], [37]

2.2.2 Wind Energy

There have been plenty of studies conducted to determine the wind potential in South Africa. The first was conducted by Roseanne Diab in 1995. Diab concluded that wind potential was generally good (mean annual speeds above 6m/s and power exceeding 200W/m^2) along the entire coast as well as other localised areas [38]. This is shown in Figure 2.9 below.

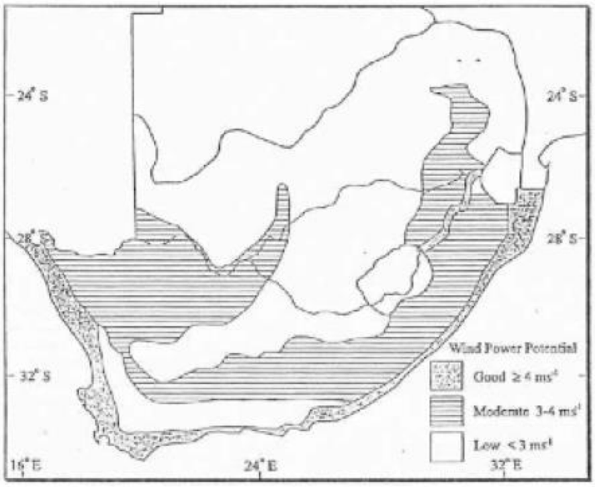


Figure 2.9 Diab's wind atlas [38]

After this in 2000 a joint effort was conducted by the DOE, Eskom and CSIR to produce a wind atlas using two different methods, one using circles to represent areas of differing wind resource and the other just focusing on the wind resource in the Eastern Cape.

In 2008, a mesoscale wind map was produced by Hagemann. An inland wind was discovered that was previously not detected in the other experiments. The results also showed that the wind resource is substantial even in the low case. This is the case especially in winter when electricity demand is at its highest. Hagemann further mentions the inconsistencies such as using inaccurate measurement instruments, human error and lack of a clear processing procedure in the previous studies [38]–[40]. Hagemann's atlas is shown in Figure 2.10 below.

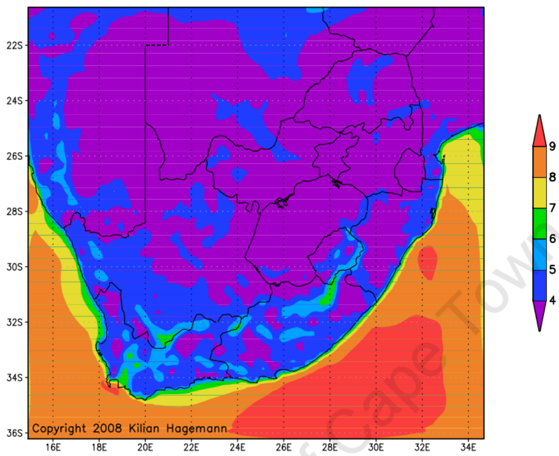


Figure 2.10 Hagemann's wind atlas [40]

These experiments give a rough idea of the wind potential in South Africa. It is noted that the wind potential prediction increased after each study. Diab predicted a potential of 7.9 TWh/ year, the DOE/Eskom/CSIR study predicted a potential of 26 TWh/year and Hagemann predicting a potential of 81 TWh/year. The large difference in results shows that there is a lot of uncertainty in terms of the wind potential. Therefore, a more conclusive study was necessary to obtain more accurate results. As a result the Wind Atlas of South Africa (WASA) project was carried out [40].

The WASA project was a collaboration between CSIR, the DOE, University of Cape Town (UCT), South African Weather Services (SAWS), South African National Energy Research Institute (SANERI) and Riso-Danish Technical University (Riso-DTU) to conduct a wind energy assessment for the South African Wind Energy Program (SAWEP). The aim of the project in a broad sense was to assess the wind resources in South Africa as well as promote wind development commercially and from a policy perspective in the country. The project was started in 2009, with the wind measurement masts being fully operational in 2010. The area the wind atlas will cover is shown in the shaded region of Figure 2.11 below. [38], [39]

Figure 2.11 Area selected for the wind atlas [38]

The project was split into 6 work packages:

- WP1 – Meso-scale modelling
- WP2 – Measurements
- WP3 – Micro-scale modelling
- WP4 – Application
- WP5 – Extreme Wind Atlas
- WP6 – Documentation and dissemination

Meso-scale and micro-scale modelling was conducted using KAMM/WAsP and Weather Research Forecasting (WRF) methods. Both modelling methods consist of taking large global meteorological conditions and down scaling them. WP2 consists of placing 10 wind measurement masts at different locations in the selected area for the wind atlas. The masts are 60 meters high and have high quality measurement instruments at varying heights along the masts. The measurements were taken for three years. The final results of the project were presented in April 2014 [38], [39], [41]. The resultant high resolution map of wind speed is shown in Figure 2.12 below.

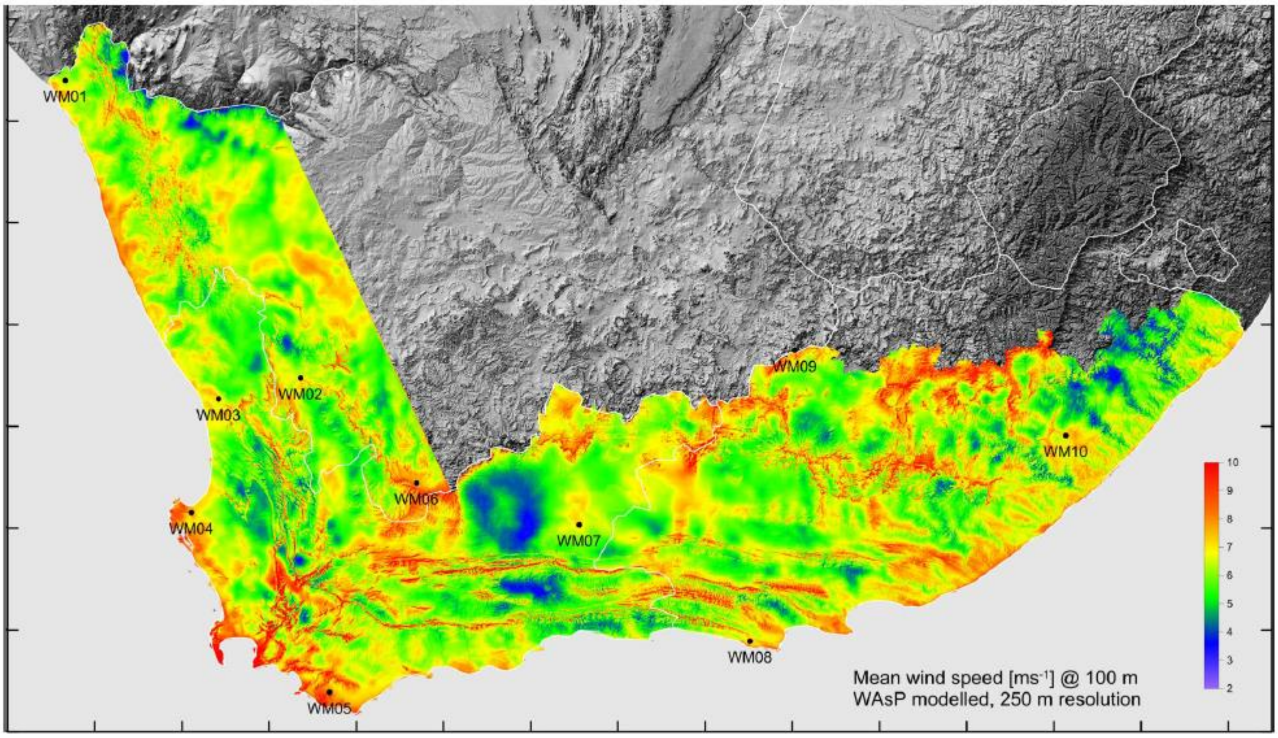


Figure 2.12 High resolution wind map of wind speed [41]

The labels in Figure 2.12 above indicate the position of the wind measurement masts. Looking at Figure 2.12 it is noted that there are many regions with a wind speed above 6 m/s therefore these regions have potential for good wind energy generation.

In terms of the REIPPP program 27 wind farms have been allocated which is a total of 2,660 MW. Eskom has further constructed a 100 MW wind farm, which is operational and currently supplying power to the grid. This information and the high predicted potential of 81 TWh show that South Africa has good wind resources. [31], [37]

2.2.3 Hydroelectric Resource

Hydroelectric power plants do not play big role in South Africa's current generation mix. There is a little potential in the country for large scale hydro power plants. However, most of the literature agrees that there is a lot of potential for small scale hydro, especially for rural electrification. [42]–[45].

Small hydro can be separated into mini-hydro (below 1 MW), micro-hydro (below 100 kW) and pico-hydro (below 20 kW) plants [44]. In South Africa, electricity was first provided by small scale hydro in Cape Town and Pretoria, until cheap coal was used to power the national grid which led to the decommissioning of these hydro plants. However, over the last few decades, South Africa has become more carbon-conscious; hence they have built more hydro power plants. There is currently an installed capacity of approximately 700 MW in the country, which is approximately 5% of South Africa's total installed generation capacity. Some examples of microhydro dams include Vanderkloof (240 MW), Gariep hydro (360 MW), Kakamas (10 MW), etc. The hydro potential in South Africa is shown in Figure 2.133 below [32].

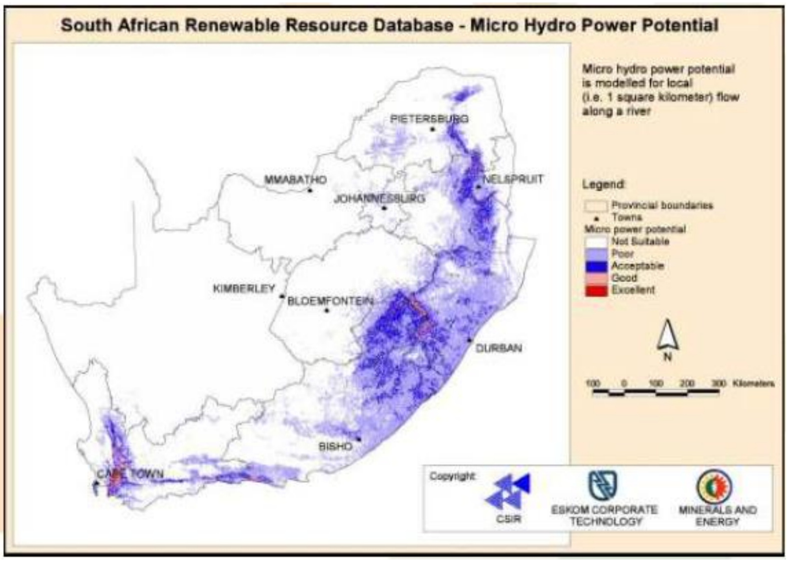


Figure 2.13 Hydro potential in South Africa [32]

For Figure 2.13, it is noted that there are plenty of areas with acceptable hydro resources, and a handful with excellent potential. A further small hydro study was carried out through GIS modelling for specifically the Eastern Cape Province. The resulting map is shown in Figure 2.14 below.

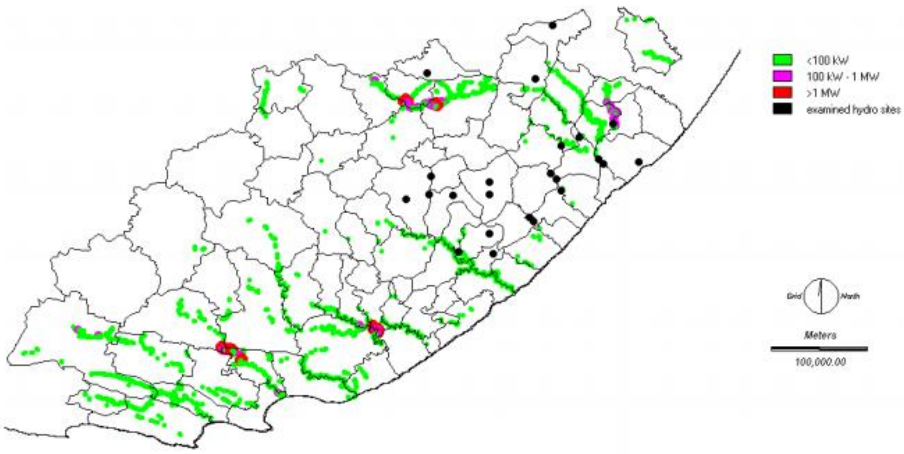


Figure 2.14 Small hydro potential in the Eastern Cape [46]

Reference [43] notes that according to a survey, there are about 8,000 sites with good small hydro potential in Kwa Zulu Natal and Eastern Cape provinces. A report by Barta in 2002, states that double the present installed small hydro capacity at that time could be implemented in rural areas of the Kwa Zulu Natal, Eastern Cape, Free State and Mpumalanga provinces [42]. Further still, there are about 450 media to large dams in South Africa, 100 of which of which are suitable for hydroelectric generation. South Africa hopes to increase their hydro resources by 300 MW by

2016, and by an additional 400 MW by 2020 [45]. All this data shows that South Africa has promising hydro resources that can be harnessed to provide renewable generation.

South Africa is abundant in solar, wind, biomass and hydro resources which will make a transition to renewable technologies a lot smoother. Even though most of the current capacity is only coal, South African government has shown its intent to change and lower its high carbon footprint through its implantation of its IRP through the REIPPP program. The main disadvantage with renewable resources is that they are location dependent, however because they are well spread out, these resources can be taken advantage of on a smaller scale for rural electrification purposes.

2.3 Distributed Generation (DG) Technologies

The previous section showed the renewable potential in South Africa as well as where these resources were strongest. In order to take advantage of these good resources, suitable distributed generation (DG) technologies should be selected. Solar, wind, biomass and microhydro technologies will form the main focus of this section.

2.3.1 Solar Energy Technology

The solar resources have proven to be good in South Africa. There are different methods of taking advantage of this resource in order to generate electricity. The two main ways are by either using solar thermal generation or solar photovoltaics.

2.3.1.1 Concentrated Solar Power (CSP)

This technology takes advantage of the heat from the sun and focuses it on to a receiver. The receiver contains a medium, such as water or molten nitrate salt, which is heated. This heated medium is used to generate steam that drives the turbines to generate electricity. Incorporation of thermal storage in the form of molten salt, can greatly increase the capacity factor, providing energy during the evening time. Molten salt can hold heat even after sunset and its amount of depends on the purpose and demand on the plant. Overall storage will improve grid integration and reduce the overall cost of electricity[47]–[49]. There are four main types of CSP technologies namely, solar tower, parabolic trough, Linear Fresnel reflector and parabolic dish.

2.3.1.1.1 Solar Tower

This technology uses mirrors (heliostats) that are arranged around a central tower. The heliostats individually track the sun over two axes and direct the sunlight to a receiver on top of the tower. The receiver contains the medium on the top of the tower that is heated. A diagram of the electricity generation process is shown in Figure 2.15 below.

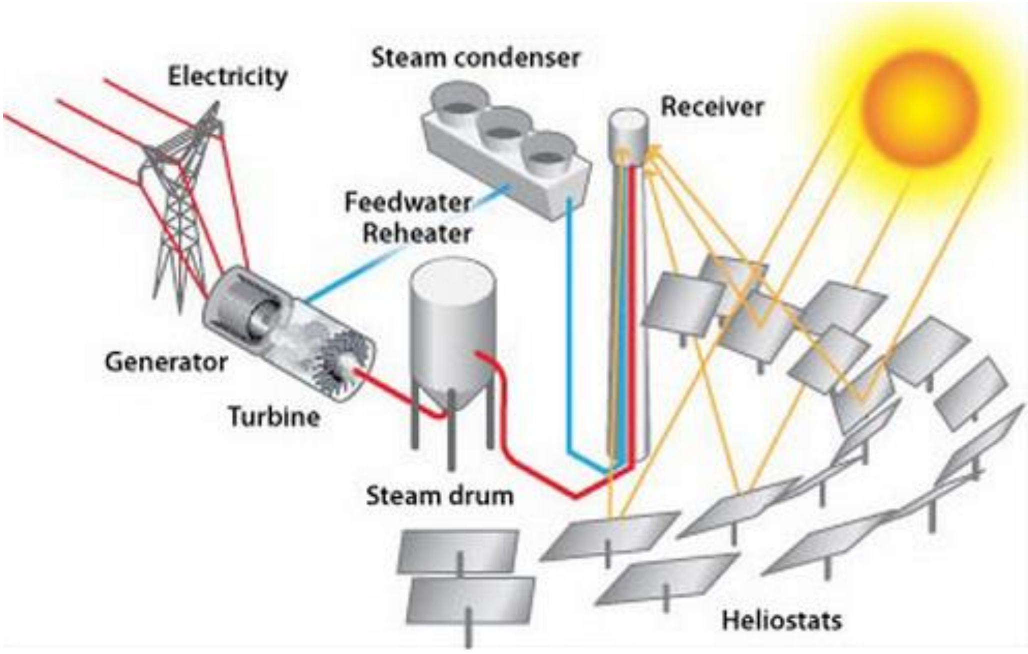


Figure 2.15 Solar tower generation system [48]

This technology achieves the highest temperatures as compared to the other CSP technologies. Depending on the heat transfer medium temperatures can range from 250°C–300°C for water/steam to 800°C using gases. The best medium to use is molten salt which is heated at 565°C. This has the advantage that it can be used for both heat transfer and storage [47], [48].

2.3.1.1.2 Parabolic Trough

This is the most popular CSP technology accounting for 90% of the current installed capacity according to reference [47]. This technology uses long rows of parabolic mirrors that concentrate the sun's heat on to a linear tube which is attached along the focal line of the mirror. These mirrors can be up to 100m long with a curved aperture of 5-6m. This is illustrated in Figure 2.16 below.

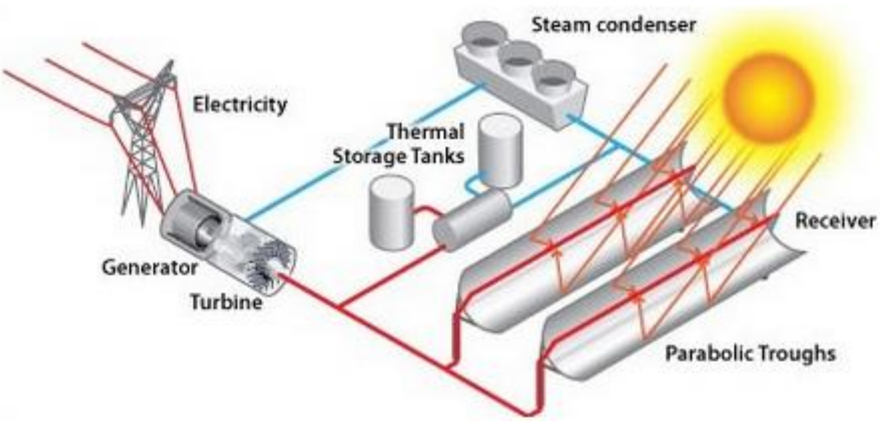


Figure 2.16 Generation using a parabolic trough [48]

The receiver consists of a tube that contains the heat transfer medium in it. The medium, which could be synthetic oil, or molten salt is used to heat water to steam that turns a turbine to generate electricity. The efficiency of these plants is between 14-16%, when synthetic oil is used as a medium at a maximum operating temperature of 390°C. [47]

2.3.1.1.3 Linear Fresnel Reflector

The linear Fresnel Reflector technology is very similar to the parabolic trough technology. It consists of flat mirrors that are arranged at different angles to reflect the sunlight to a linear, fixed receiver which is located a few meters higher than the mirrors. These mirrors use trackers to follow the sun and ensure sunlight is focussed on the receiver throughout the day. This is illustrated in Figure 2.17 below.

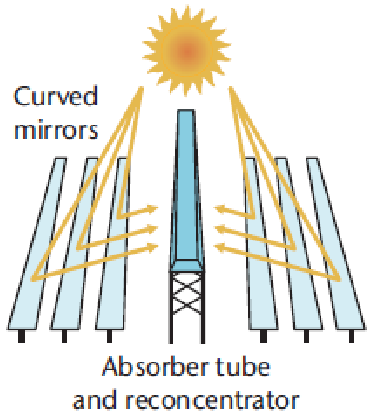


Figure 2.17 Linear Fresnel Reflector generation [49]

A secondary mirror may be placed on top facing downwards to refocus any reflected rays. The heat transfer medium used is water which is converted directly to saturated steam (Direct Steam Generation). One advantage of this technology is that the mirror is easier to manufacture as compared to the parabolic mirrors. This reduces the installation and material costs. However, the overall efficiency is lower than the parabolic trough system. It is still difficult to determine which one is cheaper as Linear Fresnel is a relatively new technology [47]–[49].

2.3.1.1.4 Parabolic Dish

This technology consists of a parabolic dish that focuses the sunlight to the dish's focal point which contains a Stirling engine or microturbine, which generates electricity from heat. This is illustrated in Figure 2.18.

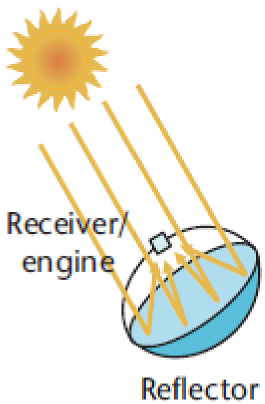


Figure 2.18 Parabolic dish

The system tracks the sun along two axes thereby leading to a high concentration factor. This system has the highest efficiency of all the other CSP technologies. A further advantage is their modular nature means more generation can be added when necessary. Even with the high efficiency, this technology has not been rolled out commercially because off the high costs and the storage difficulties [47]–[49].

CSP technologies take advantage of the heat from the sun to generate electricity. The advantages are that the cost of electricity could be cheaper as compared to other renewable technologies. However, there are huge capital costs involved when dealing with these plants. Further still, all the technologies require water which may be difficult to come by, especially in the hot, sunny regions like deserts, where this technology will thrive.

2.3.1.2 Photovoltaic (PV)

Solar PV generation makes use of sunlight to generate electricity using the photovoltaic effect. This happens when a photo-sensitive semiconductor absorbs photons from the sunlight. This works in a similar way to diodes.

This photovoltaic process takes place in a PV cell which is the basic building block of a PV panel. The cell is made up of an N-type and a P-type semiconductor joined together to form a P-N junction as shown in Figure 2.19 below. The photons which are ‘energy packets’, energise the electrons of the P-type semiconductor and the holes of the N-type semiconductor, giving them enough energy to be free. Thus the N-type region accumulates electrons while the P-type region accumulates holes. This creates a potential gradient across the P-N junction. When an external circuit is connected and the switch in Figure 2.19 is closed, a current will flow through the circuit [50], [51].

There are various types of cells available in the market, manufactured with different processes and materials, which leads to different cell characteristics such as cost and efficiency. The efficiency of the solar cell is the ratio of electricity generated by the cell versus the total solar energy received from the sun. These different cells are discussed in more detail in the following sections.

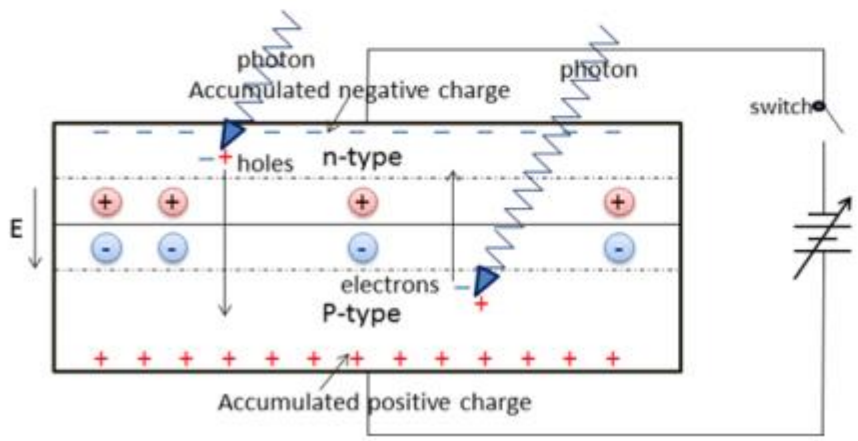


Figure 2.19 Electricity generation from a PV cell [50]

2.3.1.2.1 Crystalline Silicon

Silicon is the most popular semiconductor used in the manufacture of cells. The most popular are crystalline silicon cells. The two types of crystalline cell are monocrystalline and multi/polycrystalline.

A monocrystalline cell is manufactured by placing seed crystal into molten silicon, which is drawn from the liquid slowly. This results in a cylindrical ingot being formed. This ingot is then cut into thin wafers which are further cut into cells. This process is slow and energy intensive, therefore making these cells costly. Further still a lot of waste occurs during the cutting process [52]. Some of the best efficiencies documented for monocrystalline cells are upward of 20% [53].

A polycrystalline cell is made by casting the molten silicon into ingots. These lead to formation of multiple crystals. These multiple crystals are seen as imperfections therefore the efficiency is lower than that of the monocrystalline cells. However, the manufacturing process is a lot faster and not as energy intensive, therefore leading to a cheaper cell [52]. Most polycrystalline cells fall in the 13%-16% efficiency range; however these efficiencies are always increasing due to improved manufacturing processes [53].

2.3.1.2.2 Thin Film

Whilst crystalline cells use wafers, thin film PV modules are manufactured by depositing a thin layer of PV material such as amorphous silicon (a-Si), copper indium gallium selenide ($CuInSe_2$) or cadmium telluride (CdTe) on a substrate such as glass, metal or plastic. These modules are relatively easy to make and are manufactured in a single step, therefore making them cheaper. However, they have lower efficiencies as compared to crystalline cells. On average thin film cells have an efficiency of 5 – 13%. These thin film cells are similar to those found in calculators, mobile phones, computer monitors, etc. [54]

CdTe is also a good low cost cell and leads to a high efficiency thin film cell. The material is also highly tolerant to different deposition methods. In terms of market share of thin film, CdTe cells are the most used.

The a-Si cells are not as efficient as CdTe cells; however they have their own advantages. This material is abundant and non-toxic, not to mention it has low material requirements. Further still, this material can be deposited at lower temperatures meaning it can be deposited on flexible material such as plastics. A disadvantage of the cell though is they are highly affected by light induced degradation, which reduces the efficiency of the cell [55].

$CuInSe_2$ has a band gap of 1.53 eV making it an ideal material for photovoltaic cell. It is also one of the most absorbing materials. However, in terms of large scale production availability and cost of indium and gallium will become an issue as they are both expensive, rare metals further increasing the cost of manufacturing. [55]

2.3.1.2.3 Other Cells

Concentrator cells were developed to focus more on a smaller size cell. This is done using a lens to focus the light. This has the advantage that the cell area is less than is required for a different cell of the same power output; however, the sunlight collection area remains the same. A further disadvantage is the additional cost of the lens.

Single junction P-N cells only convert red and infrared light, whilst multi-junction cells convert other wavelengths of light into electricity. This is done using multiple layers of semiconductor, to match the differing wavelengths of light. This leads to an overall increase of efficiency as more light is converted to electricity. These cells can be made smaller by combining them with concentrators as mentioned above. This greatly increases these already efficient cells. The disadvantage of concentrators is that the efficiency drops drastically when there are clouds. They also require a tracker to ensure that the sunlight is always incident to the cell. This further increases fixed and maintenance costs. [52], [56]

The graph below in Figure 2.20 shows the laboratory cell efficiencies of the cells mentioned above. Multi-junction concentrator cells have attained the highest efficiency of just under 45%. It is noted that the efficiencies are either remaining constant or increasing which shows that there is gradual improvement in cell development. Most technologies are in their infant stage in terms of development; therefore, their efficiencies are low, though with time they will improve.

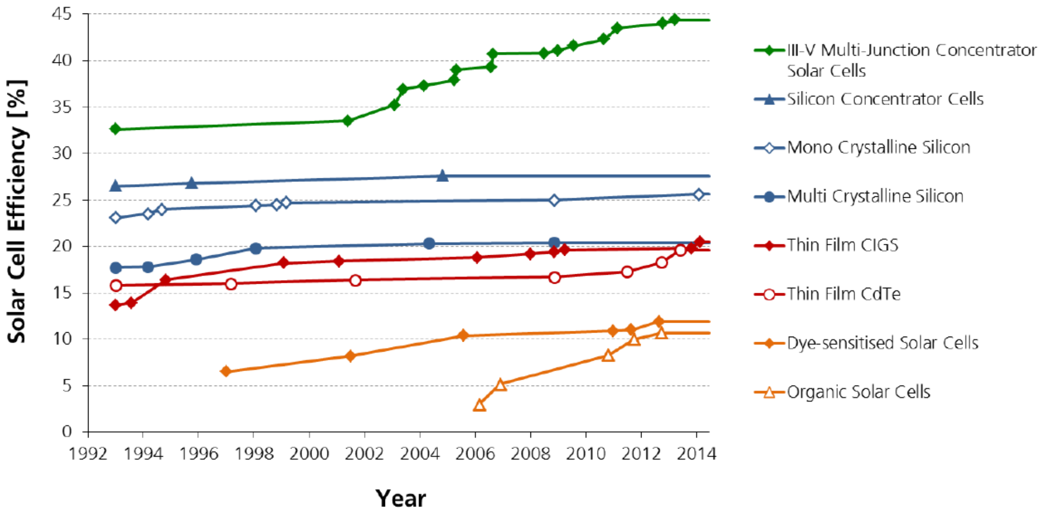


Figure 2.20 Laboratory cell efficiencies [57]

A module is made of a number of cells connected in series and parallel to increase the voltage and current respectively. These cells are then encased in a frame and covered with glass. To further increase the voltage and current, modules can be connected in series-parallel combination to form arrays. This is usually the case for ground mounted solar PV farms. The difference between a cell, module and array is illustrated in Figure 2.21 below [52].

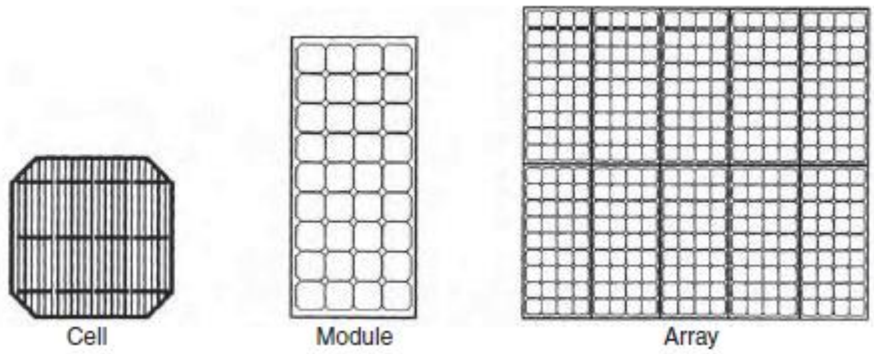


Figure 2.21 The different elements that make up an array [52]

A simple solar power system is shown in Figure 2.22 below. These arrays are placed on mounting structures. These structures may also have trackers to track the sun in either one or two axes. Trackers have the advantage that they greatly increase the efficiency of the overall system, however, they also increase the price. Therefore, if the price vs efficiency trade-off is economical then it will be viable to install trackers.

The direct current (DC) generated from the solar panels in Figure 2.22 then passes through a charge controller which is governed by certain rules. These rules determine whether the electricity generated is to be stored in the battery system or sent to the inverter to be converted to AC current. Details of the battery system will covered in more detail in Section 3.5.2.

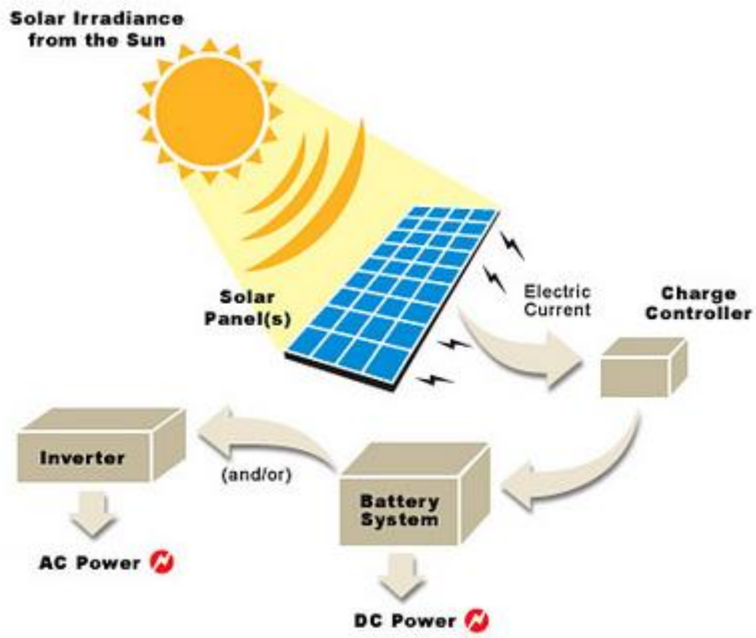


Figure 2.22 A simple solar power system

In rural systems, the aim is to keep the prices as low as possible as people in rural areas are generally poor. CSP systems are too big and capital intensive for this application. PV technology is ideal for these applications as the modules can be installed in a limited space in a short time.

Taking this into consideration the multi-junction concentrator modules, even though they have a high efficiency, are too expensive for rural application purposes. Therefore, the best option would be the polycrystalline modules. The steep drop in price of these modules over the last few years makes them even more attractive for this application. Fixed mounted solar panels are more suitable than panels with trackers for the same reason.

2.3.1.3 Mathematical Model PV

It was highlighted earlier how the PV cell generates electricity. However, in order to simulate a solar PV system for off-line academic or industrial research, a mathematical model is necessary. A simple circuit model of a PV cell is shown in Figure.2.23 below.

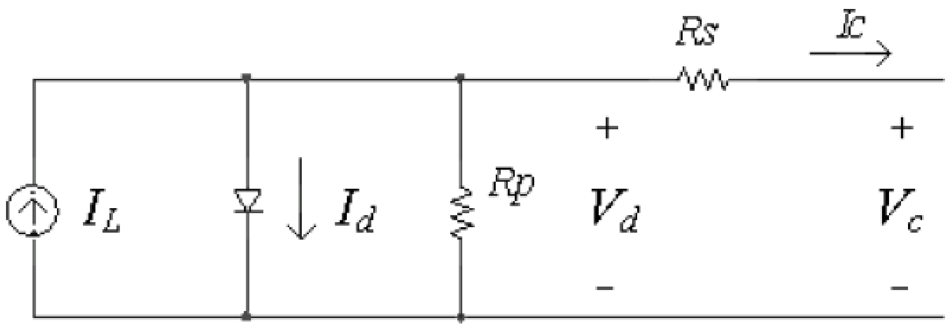


Figure.2.23 Simple circuit model of a PV cell

The current generated from the N-type and P-type semiconductors can be modelled as ideal current source, I_L, in parallel with the diode, with the diode current being I_d. Ideal models, however, do not work in the real world as they do not take into consideration the various losses that take place. Resistors are added to model these losses, with R_p taking into account the loss due to current leaking through the diode and R_s taking into account losses of the semiconductor and at the contact points. The voltage V_c out of the circuit is given by the equation (2.1) below [50].

$$\mathbf{V_c = V_d - (I_c \times R_s)} \qquad \textbf{2.1}$$

I_c is the output current from the PV cell and is given by the following equation (2.2):

$$\mathbf{I_c = I_L - I_o\left(e^{\frac{qV_d}{mkT}} - 1\right) - \frac{V_d}{R_p}} \qquad \textbf{2.2}$$

where Io is the diode reverse saturation current
q is the elementary charge
m is the diode ideality factor
k is the Boltzmann constant
T is the absolute temperature

Thus using the equations above, a PV cell, and hence PV array, can be modelled using a simulation software. Wind Energy Technology

In section 2.2.2, it was noted that the wind resources in South Africa was good. Therefore, wind distributed generation is also another electricity supply option. This can be done using with either vertical or horizontal axis wind turbines.

2.3.2 Wind

2.3.2.1 Turbine Operation

The two turbines are shown in Figure 2.24 below, with the horizontal axis turbine on the left and the vertical axis on the right. Both turbines are similar in the sense that they both make use of the wind to turn turbines, which further turn a shaft connected to a gearbox and a generator.

The main differences between the turbines are the axis that they spin on and the shape of the rotor blades. The vertical axis wind turbine has the advantage that it does not have to be facing any particular wind direction. This makes it more efficient, especially in areas with high wind variability. The main disadvantage though is that additional material is necessary in order to support the structure of the rotor. This additional material, and additional rotor blades means that the turbine turns at a slower speed but with a higher torque. Therefore, as a result, vertical axis turbines are less popular as a wind generation technology. [52], [58]

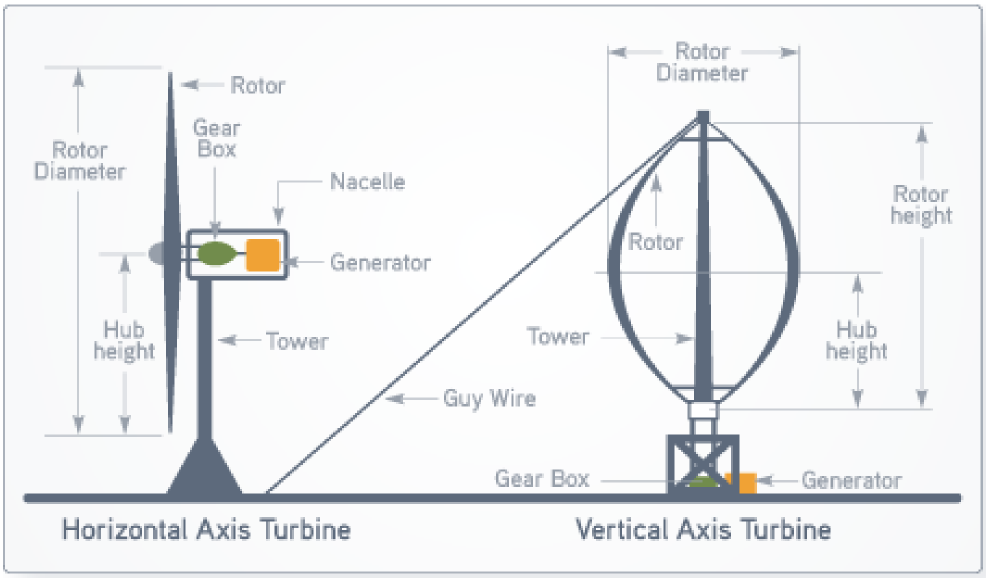


Figure 2.24 Horizontal axis (left) and vertical axis (right) turbines [58]

The main components of a wind turbine are the tower, rotor blades and nacelle. These different parts are shown in the horizontal axis turbine of Figure 2.24.

The tower can be made of steel or concrete. They must be at least 25 – 30m high to avoid any turbulence from trees and buildings. Structural design issue faced with tower construction is that the tower has to be able to handle the weight of the nacelle and rotor, whilst also avoiding wind resonant frequencies. The height of the tower is dependent on the power required as well as the height of obstacles such as trees and buildings. The wind speed is faster at higher heights; however increased heights mean increased costs, therefore the height of the tower would depend on the application and the project funding. Figure.2.25 below shows machine ratings and their typical heights. [52]

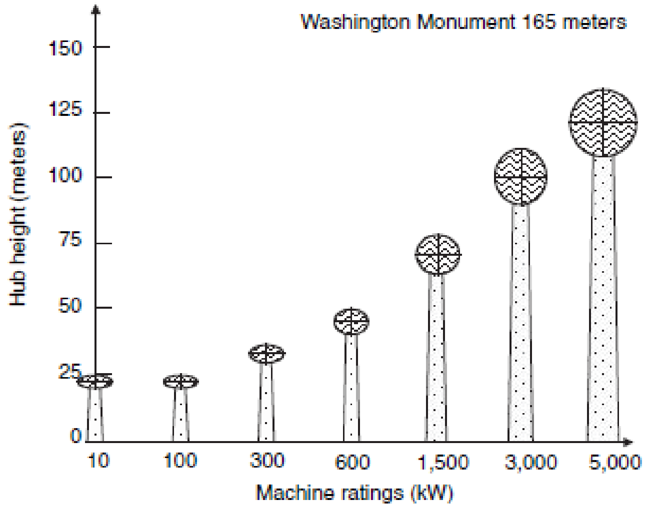


Figure.2.25 Hub height at different power ratings [52]

The rotor blades capture the wind and rotate, which in turn rotates a low speed shaft. The pitch of these blades can be changed in order to prevent the rotor blades from turning too fast or too slow due to the wind.

The nacelle houses all the important equipment necessary to generate electricity, from the gearbox to the generator. This equipment is shown in Figure 2.26 below.

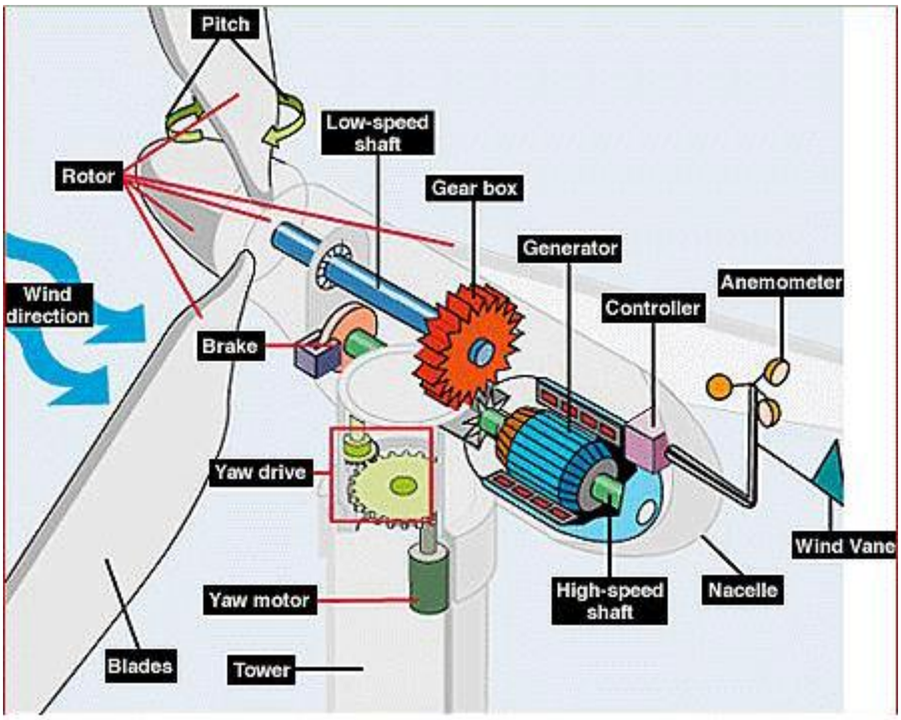


Figure 2.26 Schematic of nacelle of the wind turbine [59]

The low speed shaft rotates at 30 – 60rpm. This shaft is connected to a high speed shaft via a gearbox in order to increase the speed to value that will allow electricity generation. The speed of the high speed shaft is 1200 – 1800rpm. A typical induction generator is used to generate the electricity. Also housed in the nacelle is the yaw drive. This drive is necessary to ensure that the turbine is always facing the correct wind direction which is determined using the wind vane. The braking system is also included in the nacelle and is necessary to slow down the blades for optimum electricity generation or stop them completely for maintenance. [52]

2.3.2.2 Mathematical model

A wind energy conversion model is necessary to simulate wind power systems for simulation-based academic and industrial research. The wind model is mainly affected by the wind speed as shown in the equation (2.3) below.

$$\mathbf{P = \frac{1}{2}\rho A v^3} \qquad \mathbf{2.3}$$

where P is the mechanical power of the upstream wind (W)

ρ is the air density (kg/m^3)

A is the swept area of the rotor blades (m^2)

v is the wind velocity (m/s^2)

The power in the equation above is that of the upstream wind. The actual power extracted by the rotor blades that will drive the generator is dependent on the difference of the upstream wind and the downstream wind. This will lead to the following equation (2.4) below. [52]

$$\mathbf{P = \frac{1}{2}\rho A v^3 \boldsymbol{C_P}} \qquad 2.4$$

where C_p is called the power co-efficient and is given by equation (2.5)

$$\boldsymbol{C_P = \frac{(1+\frac{v_0}{v})(1-(\frac{v_o}{v})^2)}{2}} \qquad \mathbf{2.5}$$

where v_o is the downstream velocity

C_p is a function of the upstream and downstream wind with the value always being less than 1. When C_p is plotted against V_o/V a single maximum function with a theoretical maximum of 0.59 is obtained. C_p may also be expressed as a function of tip speed ratio (TSR), which is the linear speed at the tip of the rotor blades to the upstream wind speed. The rotor efficiency is the power translated from the wind to the shaft of the turbine. This rotating shaft is connected to a generator which will produce electricity. A graph of typical rotor efficiencies at different TSR's for different turbines is shown in Figure 2.27 below. [52]

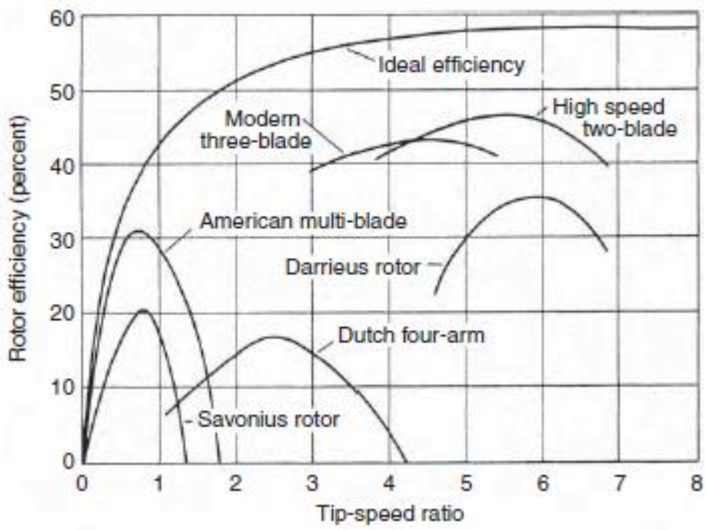


Figure 2.27 TSR vs Rotor Efficiency for various turbines [52]

It is noted that the high speed two blade turbine has the highest rotor efficiency at a given TSR followed by the modern three blade turbine.

2.3.3 Microhydro

The hydro resources in South Africa were found to be not as good as compared to solar and hydro, however there is scope for small scale hydro (micro-hydro and pico-hydro). This is ideal for villages in rural areas as their power requirements are not the highest. The differences between the different scales of hydro generation are shown in Table 2.2.

Table 2.2 Different scales of hydro generation [60]

Size	Description
Large	Any installation above 1 MW
Small	Capacity between 500 kW and 1000 kW
Mini	Capacity between 100 kW and 500 kW
Micro	Capacity below 100 kW
Pico	Capacity below 5 kW

2.3.3.1 Dams

The main basis of hydro power generation is converting the mechanical of moving water into electricity. The most common way of hydroelectricity generation is by building a dam to create a height difference and using the potential energy of falling water to generate electricity. An example of a dam hydro system is shown in Figure 2.28.

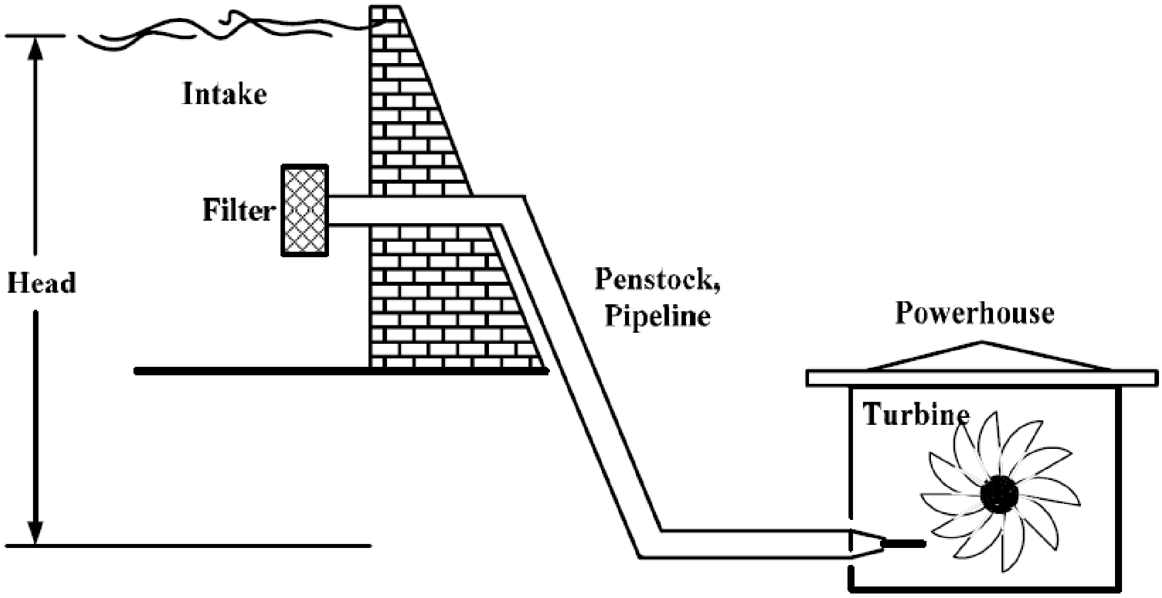


Figure 2.28 Dam hydro generation [60]

The water is directed via the penstock/pipeline, to the generator. The pressure of the water can be increased by narrowing the penstock as well as including a nozzle at the end of it just before the turbine.

The height of the water to the turbine, or the vertical height the water has to fall is called the head. The greater the head, the greater will be the potential energy, hence the greater the electricity generated. However, this vertical distance does not take into consideration the friction of the pipeline/penstock. Therefore, a more accurate measurement is given subtracting this friction from the head measurement to give the net head. The flow of the water is also another important factor which is the volume water moving at a certain point per unit time. The system output is given by Equation $\boldsymbol{Power\ (kW) = net\ head(m) \times\ flow\ rate\ (L/s)}$ 2.6. [61] This equation can be applied to and hydro system.

$$\boldsymbol{Power\ (kW) = net\ head(m) \times\ flow\ rate\ (L/s)} \qquad \textbf{2.6}$$

Hydro generation via a dam is more suited for large scale generation. Building a dam requires a substantial amount of civil work, not to mention a large catchment area for the water. This therefore will incur high costs and not the most feasible for small scale systems as would be required to electrify rural areas.

2.3.3.2 Run-off River Systems

For small scale hydro, run-off river systems are ideal as they do not require a dam to be built. An example of such a system is shown in Figure 2.29.

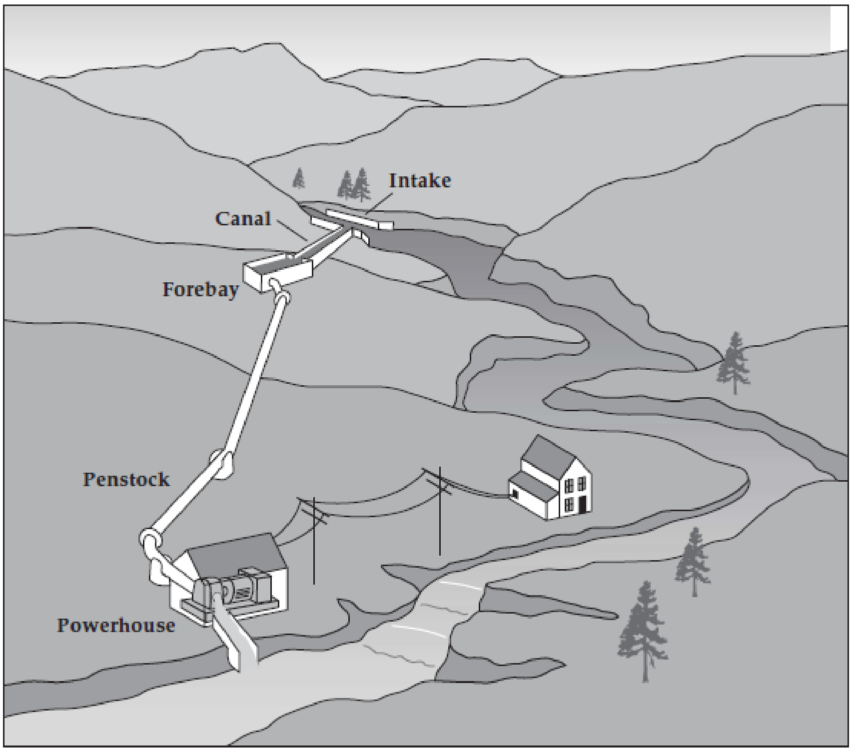


Figure 2.29 Run off river system for small scale hydro generation [61]

This system works by diverting part of a river and is known as a diversion system. There are two types of diversion systems called an open system and a closed system. An open system is characterised by a pipeline that is open which is more suited for high flow small head systems. Whereas the closed system consists of a closed pipeline, which will increase the head pressure, therefore it is more suited to high head, low flow systems.

As shown in Figure 2.29, the water is diverted at a high point in the river channel called the intake using a canal. The water from the canal collects in the forebay which acts a buffer. This serves the purpose of removing dirt and debris form the water and making sure that no air pockets form in the pipeline. The water will then flow through the penstock and turns the turbines which will generate electricity. The equations governing the power output are the same as mentioned for dam systems.

Even though this system does not require a dam, it still requires a fair amount of civil and mechanical work to construct the canal, forebay and penstock. Further still this technology is more advantageous in mountainous areas in order to give a greater head. These disadvantages lead to a variation of hydro generation that does not require a dam nor a diversion.

2.3.3.3 Hydrokinetic systems

Hydrokinetic generation is different from normal hydro generation in that it depends on the kinetic energy of the water as opposed to the potential energy. This form of generation has both oceans (wave and tidal) and rivers as its source, however, with regards to rural electrification rivers are the more likely choice [61].

A hydrokinetic system generates electricity using turbines in much the same way as with wind generation. The only difference is that for hydrokinetic generation the turbines are under water, therefore making use of the velocity of the river, or its flow, to generate electricity.

The turbines are either horizontal or vertical axis and are similar to those used in wind generation.

The differences between the two types of turbines are summarised in Reference [62]. Horizontal axis turbines are the preferred choice due to the lower efficiencies experienced by vertical axis turbines.

Whether it is horizontal or vertical axis, the general function of the turbine remains the same. The rotor blades are turned by the water, which further leads to a shaft connected to a gearbox being rotated. From the gearbox, the shaft of a generator is turned to generate electricity. Hydrokinetic systems are different from wind in that they can be supported in different ways. The turbines may be attached to a floating object, or fixed to the riverbed. The choice of support is dependent on the size of the turbine and its application.

The similarity between wind generation and hydrokinetic also extends to the power equation (2.6) as shown below.

$$\mathbf{P} = \frac{1}{2}\boldsymbol{\rho}\mathbf{A}\mathbf{v}^3\boldsymbol{C_P} \qquad 2.7$$

where ρ is the water density
A is the swept area of the turbine
v is the velocity of water
C_p is the turbine power co-efficient of efficiency

C_p has the same implication in wind generation and hydrokinetic generation and has a similar maximum theoretical value of 0.59. Hydrokinetic generation is different from wind however, in that, less velocity of water is required to get the same power output from turbines of the same size [62].

2.4 Microgrids

2.4.1 Introduction

It was noted in the first section that there were still plenty of rural areas that required electrification, and were not currently electrified mainly because of their geographic location and distance from the grid. The second section showed the renewable potential in South Africa as well as where these resources were strongest. The previous section looked at renewable generation technologies available in the market, as well as looking at their pros and cons. These sections can be tied together to solve the rural electrification problem by using microgrids.

A microgrid is a power system that has some form of distributed generation as a source of power (solar, wind, etc.) and a load to consume the power (building, village, etc.) that is capable of connecting to the main power grid if necessary, or operating isolated from it. Some microgrids may have storage devices such as batteries. An element of control is also necessary to tie all these aspects together and make sure the microgrid is running in the most efficient way. A diagrammatic representation of it is shown in Figure 2.30 below.

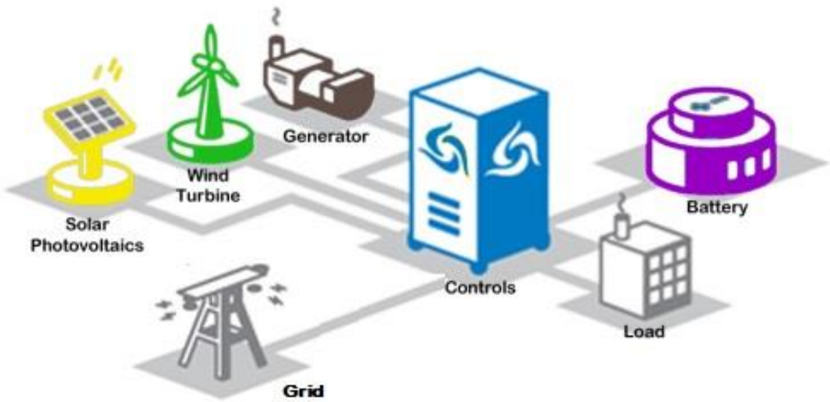


Figure 2.30 A simple microgrid (modified from [63]**)**

2.4.2 Modes of Operation

There are two modes of operation for a microgrid. When a microgrid is connected to the grid it is operating in grid-connected mode. If a grid-connected microgrid is disconnected from the grid, then the microgrid is said to be isolated from the main grid and is operating in islanded mode.

A microgrid can also operate in isolation from the main grid entirely. This scenario may arise due to bad geographical terrain or high costs in extending the grid. Therefore, whatever DG technology is used, it must be able to supply sufficient power to the load. In this scenario back-up generation or storage is a necessity, especially if a fluctuating renewable source such as solar or wind is used as the primary resource. Such a microgrid is known as an off-grid microgrid.

There are many advantages of using microgrids. The first is that there is no reliance to the main grid. Therefore, if there is a power cut/failure, the load will still be able to operate in islanded mode. This makes the microgrid more reliable especially in places where the main grid is not very reliable such is the case with most third world countries. Microgrids can also provide more cost effective option for areas far away from the main grid as mentioned in the previous point. This makes it ideal for rural areas that have some of these properties.

Microgrids can have more than one source to supply energy. These are known has hybrid microgrids. The advantage of such a system as compared to a single source microgrid is increased reliability; however, the disadvantage would be a more complicated control system. This thesis will only focus primarily on stand-alone, single source microgrids with solar, wind, and micro-hydro as the sources. Some of the technical issues experienced by these off-grid, independent microgrids are discussed in the following section.

2.4.3 Technical Challenges of Microgrids

There are various technical problems related to off-grid, independent microgrids. The main problem is that of reliability. This is particularly the case with solar, wind and microhydro as the driving technology. Any fluctuations in weather or river flow will lead to a fluctuating supply of energy and quality power which is not ideal for the end user. This is shown in [64] which looks at a study of an independent microgrid used to power an isolated island in Hong Kong. The study shows the difference in production and consumption at certain times throughout the day and at certain times consumption exceeds production.

With grid connected microgrids, when a fault occurs, voltage and frequency balance is controlled by the grid. In an independent off-grid system this is not the case. The imbalance between load and supply can lead to an unstable voltage and frequency of this system. A solution to this problem is using the inverters to balance out the load and supply [65].

Besides causing reliability issues, the fluctuations in renewable resources affect availability of energy supply. According to [66], there are different types of fluctuations related to renewable energy generation. Solar in particular is susceptible to cyclic fluctuations which occur over several minutes or less, such as due to cloud cover, or sustainable fluctuations which occur after a longer period, such as seasonal change. Solar as a result is termed as a low inertial system [67]. Wind-based microgrids have much more cyclic fluctuations as compared to solar. Wind power generated is a function of the wind speed cubed, meaning that a small fluctuation in wind speed can cause a large fluctuation in the power output of the wind turbine. These fluctuations will lead to voltage flicker and changes in frequency which can cause instability in the microgrid as well as reducing its power quality [68]–[70]. The water flow rate of a microhydro generator is also not constant therefore this will induce harmonics in the generated voltage [71].

Reference [72] looks at the advantages and disadvantages of different network topologies of off-grid PV-battery-generator systems. Some of the problems the different topologies had to take into consideration are energy management, in rush currents from motor loads and non-critical faults leading to nuisance tripping.

These are some of the more technical problems faced by independent microgrids. Most of these problems can be curtailed however by some form of storage and a suitable energy management system. The next section will look how microgrids compare to other rural electrification options as well as how they are implemented for rural applications.

2.5 Microgrids for Rural Applications

Microgrids are particularly advantageous for rural areas located in difficult geographical terrain or at great distances from the grid.

Another popular method of decentralised rural electrification is the Solar Home System. A comparison between microgrids and Solar Home System is discussed here to give a detailed account of microgrids for rural applications, whilst also highlighting why it is the preferred decentralised electrification option.

2.5.1 Microgrids vs Solar Home System

A Solar Home System (SHS) is an off-grid system that is powered by solar panels and batteries. The system is typically designed to power a few key components such as lights, TV, fan, etc. and therefore are generally very small (20 – 100 Wp). A typical system is shown in Figure 2.31 below.

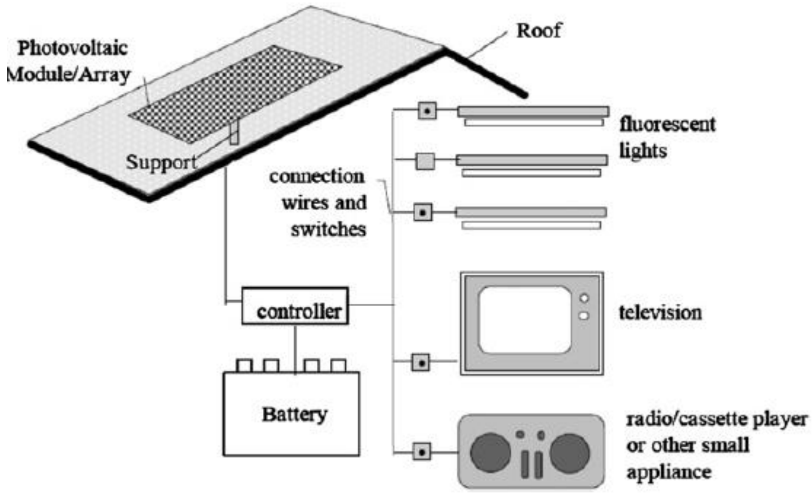


Figure 2.31 An example of a Solar Home System [73]

A detailed comparison between SHS's and PV microgrids is carried out in [2], which compares the design, cost, operations and maintenance, applications and efficiency of both systems. From a capital cost point of view, a microgrid will use bigger panels and batteries, which will mean a cheaper R/Wp or R/Ah rate. It must be noted that microgrids have additional costs to take into account such as inverters and a distribution network. Reference [2] concludes that from an financial point of view, a microgrid is a better option when the village being electrified is large and densely populated, whereas an SHS is cheaper option if the village is more sparsely populated and located in rough terrain.

Microgrids are more advantageous when it comes larger size and variability of the load. Due to their small size, SHS loads are limited to a few low power appliances as previously noted. Designing the system to include high powered appliances would cause the costs to escalate significantly. Therefore, SHS's are more suited to fairly basic domestic type systems and appliances, whereas microgrids are a better option when the loads include some high power appliances. Reference [1] carries out a comparison of SHS and microgrids for a rural are in South Africa. It is noted that microgrid systems can be designed to be large enough to not only supply domestic loads but to also commercial as well. This means that villages can use the electricity to carry out economic activities thereby giving them a source of income. SHS systems can only aid economic activities that require illumination.

SHS systems were implemented in South Africa on a fee-for-service concession system for selected areas in South Africa as noted in [27]. This programme did not work due to financial issues between government and the concessionaires. Reference [3] gives an assessment of the

South African SHS concession system by interviewing member of the rural households and the concessionaires. Household users noted that the SHS system did not cater for all their electricity needs. The illumination from SHS's provided a positive impact on communities by allowing productive activities to be carried out at night.

In terms of security, the panels of SHS systems are easy to steal. [27], [3] A microgrid on the other hand is easier to secure as most of the equipment will be installed in the same area, therefore making it easier to monitor and maintain.

Based on the information, we consider microgrids to be a better decentralised generation option, especially since the SHS system implemented in South Africa was not very successful. Therefore, microgrids for rural electrification applications is investigated in more detail.

2.5.2 Cost Analysis of Microgrids

According to reviewed literature, a great amount of research focusing on powering rural areas with microgrids has been carried out. In order to compare these different systems, the costs of the microgrids need to be analysed. There are two main ways of cost comparison, namely by evaluating the Levelised Cost of Electricity (LCOE) and the Net Present Cost (NPC). The LCOE is defined as the average price per kWh of useful energy produced any given system. The NPC is the full lifecycle cost of a microgrid, including the capital costs, operations and management costs (O&M), fuel costs and performance costs. [4] Both methods are a good way of comparing the economic performance of different microgrids using various forms of generation.

Cost is an important factor in determining the implementation of microgrids for rural electrification. The is due to the fact that many people living in rural areas are generally quite poor, therefore if the systems are too expensive then they will not be able to pay it off; hence the need of a cost analysis for rural microgrids. In this thesis the cost analysis will be limited to off-grid, single source and hybrid solar, wind, microhydro and diesel microgrids. This will provide a well-rounded review of the current costs of microgrids in various parts of the world, with prime focus being on developing countries, in order to be comparable with South Africa. The details of these systems are given in Table 2.3 below.

In this case NPC cannot be used for comparison purposes as the microgrids vary in size, which will lead to an increased NPC, i.e. the largest microgrid will automatically have the highest NPC. From Table 2.3, the most expensive system was found to be the wind/battery system in [5], with a LCOE of $2.797/kWh. The cheapest system was the microhydro/diesel system in [6] with a LCOE of $0.179/kWh. The estimated average LCOE of all the mentioned systems was $0.676/kWh. Quite a fair amount of research has been carried out on PV systems and all their different variants. Wind systems occur primarily in hybrid configurations and never only as a single source with a battery. Microhydro microgrids are the least investigated, however it was found to be the cheapest. In this case NPC cannot be used for comparison purposes as the microgrids vary in size, which will lead to an increased NPC, i.e. the biggest microgrid will have the highest NPC.

Table 2.3 Details of different off-grid microgrid systems

Ref.	Publication Year	Description	Location	Load Consumption (kWh/day)	Type of System	LCOE ($/kWh)	NPC ($)
[4]	2015	6 villages were selected from 6 geopolitical zones in Nigeria. Each village had the same load and was compared with 7 combinations of the following sources; PV, wind, diesel and battery. Out of the 7 systems, the PV/diesel/battery system was found to be the cheapest for all the sites whilst the wind/diesel system was the most expensive	Tambo, Nigeria	Wet season (8 months) – 101.94 Dry season (4 months) – 58.12	PV/diesel/battery	0.547 - 0.66	229,941
			Ngo, Nigeria				251,151
			Ete, Nigeria				Not provided
			Onilu, Nigeria				Not provided
			Zalau, Nigeria				232,226
			Gubio, Nigeria				238,174
[7]	2013	In this paper the optimal sizing standalone PV system carried out using an intuitive method and numerical method in Matlab. The numerical method was found to be more accurate as it compared the load vs the energy resource on an hourly basis, providing a more precise sized battery bank.	Sohar, Oman	6.13	PV/battery	0.196	Not provided
[8]	2014	A hybrid microgrid system was implemented for a remote island. A techno-economic analysis of this system was carried out using HOMER with a sensitivity analysis on load consumption and energy resource. The complimentary nature of wind and solar was also shown in this paper.	Hong Kong	250	PV/battery/wind	0.595	693,114
[9]	2013	4 variations of microgrid systems were modelled on Homer for a village in Nigeria. The variations consisted of the different	Jos, Nigeria	1,500	PV/diesel/battery	0.364	3,441,282

		combinations of the following sources; PV, diesel and battery. The PV/diesel/battery system was found to be the optimal whilst the diesel/battery system was found to be the least optimal. A sensitivity analysis was carried out on the interest rate and its effects on the optimal system were noted.					
[10]	2015	An economic comparison of 3 off-grid power systems for a remote rural village in Burkina Faso were modelled. It was noted that the hybrid system was cheapest in terms of NPC and LCOE.	Pissila, Burkina Faso	711	PV/diesel/battery	0.500	1,494,844
					PV/battery	0.750	2,025,003
					PV/diesel	0.770	2,151,995
[11]	2016	HOMER was used to investigate the potential of a PV/wind/diesel/battery system in a village in Tunisia. It was noted that a wind/diesel/battery system was found to be the most economical. It was also noted that this hybrid system is more optimal than grid extension.	Bizerte, Tunisia	34	Wind/diesel/battery	0.260	57,320
[12]	2014	8 renewable systems were modelled and compared for a rural village in south Africa. Each system was comprised of atleast one of the following sources; PV, wind, hydrokinetic, diesel and batteries. The hydrokinetic/diesel/battery system was found to be the most economical. It was further noted that, the portion of power provided by the diesel generator increased during months of low water resource.	Kwa-Zulu Natal, South Africa	35	Hydrokinetic/diesel/battery	0.265	43,599
[14]	2010		Southern Iraq	31.6	PV/battery	0.238	60,735

		Systems compromising of a combination of PV, diesel and battery sources are compared for a health clinic in rural Iraq. The load for the clinic was modelled and the system was simulated on HOMER. The cheapest option was found to be the PV/battery system.			PV/battery/diesel	0.272	78,212
[6]	2015	A PV/microhydro/diesel/battery system was compared to a microhydro/diesel system on HOMER for a rural village in Southern Bangladesh. Two different sized generators were used to cater for low and high loads. It was noted in the results that most of the power of the system was contributed by the microhydro turbine and diesel generator. The microhydro/diesel system was found to be cheaper in terms of NPC and LCOE at the expense of higher carbon emissions.	Southern Bangladesh	255	PV/microhydro/ diesel/battery	0.206	240,506
					Microhydro/diesel	0.179	191,084
[5]	2016	Off grid and grid connected wind systems are compared in two areas in Brazil and one area in United States of America. The results of the off-grid system are shown.	Campinas, Brazil	37	Wind/battery	2.797	435,564
			Cubatao, Brazil			1.835	285,783
			Roscoe, USA			1.373	213,783

While comparing hybrid with the single source microgrids, it is noted that in two instances single source PV/battery microgrids are relatively cheap at a cost of $0.196/kWh and $0.238/kWh for [7] and [14] respectively. However, the wind/battery microgrid was the most expensive as noted in the previous paragraph. The cheapest technology was the hybrid microhydro/battery system, however in general the other hybrid systems varied in price from $0.179/kWh to $0.770/kWh. [10] compares 3 systems both hybrid and single source for the same load. The PV/diesel/battery system LCOE was $0.500/kWh whilst the PV/battery system LCOE was $0.750/kWh. This indicates that the hybrid system is cheaper that single source microgrids.

This price variation between the microgrids is also due to different social and economic factors. Some of these affect the LCOE indirectly whilst other affect the electricity user. The factors affecting the implementation of microgrids are investigated in the following section.

2.5.3 Social and economic factors affecting rural microgrids

Location is the most determining factor of the cost of microgrid, due to the fact that it determines the amount of renewable resource that the system will receive and inevitably determine the type of renewable system to implement as well as the number of components required. The renewable resources available in South Africa is covered in more detail in section 2.2. The rising cost of diesel over the years is makes renewable generation a more attractive option. Besides resources, location also dictates other costs such as capital, labour, taxes, etc. The cost of components of maybe cheaper if the country implementing the system has facilities manufacturing these components. e.g. for a microgrid in South Africa, it could possibly cheaper to buy solar modules manufactured in South Africa as opposed to importing them from China. These differing costs make it difficult to give a fair comparison of different renewable systems in various countries.

Government subsidy also plays a big role in making renewable energy more systems more affordable as rural areas are made up of predominantly poor people. This subsidy is dictated by the government policy being implemented in a country. The policy usually translates to an electrification program being implemented. [74] looks at the state of rural electrification in countries in South Asia and the Pacific Islands. It is noted that most of the rural electrification programs implemented, would not have been implemented had it not been for government backing. In [75], decentralised solar systems were installed in Chhattisgarh due to CREDA. In Senegal, microgrids are designed for rural areas as part of the Intelligent Energy – Europe Programme. [76], [77] These are some examples of electrification programs that have promoted rural electrification. An offshoot of this is government corruption as discussed in section 2.1.2.

The user's load demand affects the size of the system implemented. This has a direct effect on the cost. Additionally, though if the user's load demand is restricted, as in with SHS systems, then this will lead to users who are not happy with their systems as noted in [3]. Therefore, the system has to be large enough, as well as adaptable in order to cater for the user's demand, and not just supply basic electric needs. A higher demand can also lead to greater economies of scale, which will lead to an overall lower LCOE. However, a balance must be attained with the system being affordable in terms of what users are willing to pay [78] whilst also being big enough to cater for their requirements.

These factors all affect the implementation of microgrids in rural areas. The next section looks at how these factors tie in to the South African context by investigating a case study of a pilot rural microgrid system in the country.

2.5.4 Case Study: South Africa

Two pilot hybrid and off-grid microgrids were implemented as a possible solution to rural development in South Africa, one at Hluleka Game Reserve and the other at Lucingweni village, both located in the Eastern Cape province. The projects were started in 2001. Reference [13], a report by the Department of Minerals and Energy (DME), gives an in-depth analysis of the technical and socio-economic viability of these projects in order to determine the replication potential of microgrids in South Africa. The report was obtained via the public domain and therefore no permission for use was sought.

Both systems consisted of solar panels, wind turbines and batteries; however, Hluleka had a diesel generator whilst Lucingweni did not. The details of both systems are given Table 2.4 below.

Table 2.4 Hluleka and Lucingweni system details [13]

	Hluleka	Lucingweni
Primary Load	12 guest chalets, Administration block, Staff quarters, Street lighting	120 Domestic load, Carpentry workshop, Metal workshop
Daily Load (kWh)	85.77	508.64
Solar Panels (kWp)	5.6	56
Wind Generators (kW)	5	36
Diesel Generator (kVA)	5[1]	-
Batteries (kWh)	139.20	557.70
Deferrable Load (kWh)	50.00	66.57

Any excess electricity was sent to a deferrable load which consisted of water pump and filtration plant for Hluleka and water pump, ice maker and battery charger for Lucingweni. It is noted that the system for Lucingweni was designed for 220 households, however, only 120 households were connected. [13]

The system cost for Hluleka was found to be R200,000/kW, which was considered to be expensive by the DME. It was also noted that the system was too small for the load, which led to shortfall of generation and related problems. Furthermore, issues such as vandalism, lack of a sufficient diesel switching system and inadequate operations and maintenance, led the DME to conclude that this model should not be replicated. [13]

As noted above, the Lucingweni system was over designed and therefore a substantial amount of power was used on the deferrable load. The cost of electricity was found to be R14.26/kWh including the recovery capital and reticulation costs and R4.88/kWh only including the recovery of the operational costs. The capital and reticulation costs were not expected to be covered, as is the case with most rural electrification programs, however the operational costs should be covered. This was still considered as expensive by the DME. Besides cost, however, socio-economic issues also played a role in the failure of this program. It was noted that people had not fully adopted the system as they were uncertain as to who owned the system. This resulted in a lack of operation and maintenance as it was not clear whose responsibility this was. Furthermore, users expecting a service similar to that of being grid connected were disappointed as their electricity usage was more limited. [13]

According to [1], due to these high costs, the hybrid system was only run for 3 months after the plant was commissioned, due to the high cost of energy. Even though Lucingweni was eventually stopped, the

[1] An additional 75 kVA back-up generator was kept in case of plant failure.

authors argue that the microgrid systems, as a form of rural electrification in South Africa, can still be implemented successfully. In order to prove this, a hybrid microgrid was simulated for Lucingweni and Thlatlaganya village. Both microgrid systems were designed to support domestic, social and economic activities. The system implemented consisted of solar, wind, microhydro and diesel generation sources. The LCOE was found to be $0.08/kWh (R0.99/kWh) and $0.41kWh (R5.10/kWh) for Lucingweni and Thlatlaganya respectively. The system at Lucingweni had a lower LCOE as microhydro was the dominant generation source, whilst for Thlatlaganya it was a diesel generator. It is noted that the LCOE for Lucingweni was found to be a lot cheaper than initially stated in [13]. The inclusion of hydro as a generation source has significantly reduced the LCOE, furthermore the cost of components such as panels and turbines have significantly reduced since the Lucingweni was initially implemented which has further contributed to the reduced costs.

It is concluded that the Lucingweni project was initially found to be expensive, however this was not solely due to the high cost of renewables at the time, but also poor implementation and management after the plant was built, from a technical and social point of view. Reference [1] has shown that the cost has been significantly reduced, and that microgrids are still a suitable option for powering un-electrified rural areas if planned and implemented correctly, taking into consideration the available resources. It is clear that users have a willingness to pay but, the systems should provide more than just basic electricity but should also promote economic activities in order to alleviate the community.

2.6 Proposed Research

It is clear from the literature review, that rural electrification is still a problem that needs to be solved in South Africa. It has reached a stage where the remaining villages that require electrification are located at a great distance from the grid; therefore, off-grid generation is the most suitable option.

Off-grid generation is made more attractive with the abundance of renewable resources available in South Africa. There are various renewable resources that can be taken advantage of in South Africa, however this thesis will primarily focus of solar, wind and microhydro generation.

There are two primary off-grid generation options available, namely SHS and microgrids. SHS's were found to be generally cheaper, however they are only ably to provide basic electricity, whereas microgrids can be designed to provide more energy, not only powering domestic households, but also providing energy to promote economic activity. Therefore, microgrids are found to be a more suitable option to electrify rural households, albeit more expensive.

There are different microgrid topologies that can be implemented. Due to the distance of the un-electrified rural areas from the grid, only off-grid microgrids will be investigated. A fair amount of research has been carried out on hybrid technologies, however a limited amount has been carried out on single source microgrids. By selecting single source, off-grid microgrids it will be easier to compare the different renewable resources against one another, giving an insight into how the strength of a resource will relate to the LCOE and NPV, specifically for microgrids within the South African context. Furthermore, the cost metrics of the single source microgrids, can be compared against microgrids in South Africa and other developing countries.

In order to carry out this investigation, 3 villages in South Africa will be selected. The first village will be selected in an area with strong solar resources, whilst the second village will be selected in an area of strong wind resources, and the third village will be selected in an area with strong microhydro resources. Once selected, a solar, wind and microhydro system will be simulated in each village using HOMER modelling software. The LCOE and NPV cost metrics produced by HOMER will be used to compare each resource in each village, as well as note how different villages compare to one another. The same will be done from a technical point of view.

These results will give insight into whether these microgrids can be successfully implemented to solve South Africa's rural electrification problem. The next chapter will look at how the different villages were selected.

3 Methodology

3.1 Introduction

Based on the literature reviewed, for the purpose of this research, it was decided that single source solar, wind and microhydro-based microgrids would need to be analysed in order to determine if they are a viable solution for rural electrification in South Africa.

Suitable software is required in order to model these microgrids and conduct relevant analyses. Reference [79] reviews different software designed to analyse hybrid energy systems. These systems are more complicated than single source systems, therefore, the same software can be used for analysing the feasibility of single source microgrids. From the review it was determined that HOMER (Hybrid Optimisation of Multiple Electric Renewables) was best suited for carrying out the simulations as it provided the required tools to carry out a techno-economic analysis, whilst also providing useful additional information such as capacity shortage, excess energy generation, etc., which was not provided by the other mentioned packages.

HOMER was developed by the National Renewable Energy Laboratory (NREL) based in the United States of America. The software, as its name states, is used to simulate different types of hybrid renewable energy systems based on resource, load, technology and cost inputs and then for optimising these systems based on user set parameters in order to provide the best solution to a problem. Sensitivity analyses can also be carried out, allowing the user to test how a change in a certain variable (fuel cost, wind speed, discount rate, etc.) will affect the overall system. A diagrammatic depiction of how HOMER can be used to solve problems is shown in Figure 3.1 below. [80]

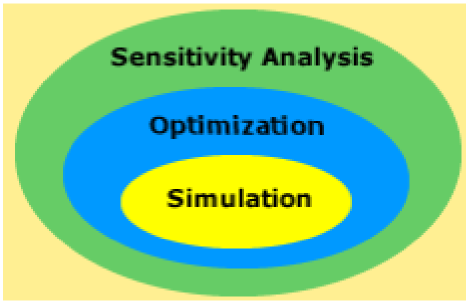


Figure 3.1 Representation of how HOMER works [80]

HOMER can be used to model many different types of systems, ranging from both conventional and renewable technologies. In order to simulate these systems, HOMER requires the following inputs; renewable resource data, system component details and the load. The renewable resources that need to be input will depend on the component selected, i.e. if a wind turbine and PV system are to be modelled then the wind speed and irradiation of the area will be required. Once all the details are input, the simulation can be run. HOMER will then perform energy balance calculations for each configuration of the system using the input values. HOMER conducts these calculations by comparing the load with the energy generated for every time step. The different feasible solutions will then be provided at the end of the simulation with the lowest cost solution being noted first. [80]

For each simulated solution, HOMER outputs different cost metrics in order to aid the user in analysing the feasibility of each microgrid. The LCOE and the NPC are the best indicators for determining the cost feasibility of a modelled microgrid. The LCOE is defined as the average cost of per kWh of energy of useful energy produced by the system and is given by the following equation [81]:

$$LCOE = \frac{\left[\frac{i(1+i)^N}{(1+i)^N - 1}\right].C_{NPC}}{E_{served}} \quad \textbf{(3.1)}$$

Where,

i – annual real discount rate
N – Lifetime of the system
C_{NPC} – Total Net Present Cost
E_{served} – total electrical load served

The total NPC of a system is defined as the present value of all the costs that the system incurs over the lifetime of the project, minus the present value of all the revenue that it earns over its lifetime. In order to determine the NPC, HOMER creates a cash flow table with annual costs and revenues over the lifetime of the system [81].

There are different versions of HOMER that have been released. The version that was selected to be used for this dissertation is HOMER Pro 3.6.3.0. At the time of selection this was the latest version of HOMER that was available.

This dissertation will focus on single source solar, wind and microhydro off-grid microgrids. As these microgrids have a single source, this makes storage an important aspect of the system configuration. As a result, each system will also consist of a battery bank in order to provide energy when the renewable resource level is inadequate to cater to the load demand. The following sections will look at how the HOMER inputs were derived. The first step in this process involved the identification and selection of villages with solar, wind and hydro resources.

3.2 Village Selection

The first step in carrying out this investigation was to select three villages, in which the off-grid microgrid systems would be modelled. The villages were selected such that one was in an area with strong solar resource, the second was in an area with strong wind resource and the third was in an area with strong microhydro resource. This differentiation between the three villages was specifically made so that it would be possible to determine how the different technical and economic metrics of the simulated microgrids were related to the strength of the resource in each respective area. Furthermore, each village was selected in a way that made it possible to simulate a solar, wind and microhydro system for all the villages, therefore resource data had to be available for all of them. Solar and wind resources were easy to obtain for any selected site, however the microhydro data was limited to areas with available gauge stations which contained flow rate data. Details on how the river data was obtained are covered in section 3.4.3. Furthermore, the villages selected had to be unelectrified -in order for off-grid microgrid system to be relevant for them. In order to carry out this task, Google Earth and its overlay tool was used.

In addition to having the required resource data, each village had to be of a similar size in order to maintain consistency between the simulation results. Therefore, it was decided that only villages between 40 and 70 households in size, would be considered.

Scottish Power conducted a study on rural electrification in South Africa to assess the mini-grid potential in South Africa. [15] A part of the study was identifying which rural areas were unelectrified. In order to do this, a map of the MV network in South Africa was combined with a map of villages in South Africa as shown in Figure 2.3 in section 2.1.2. The finalised map of all the unelectrified rural areas (signified as black dots) is given in Figure 3.2.

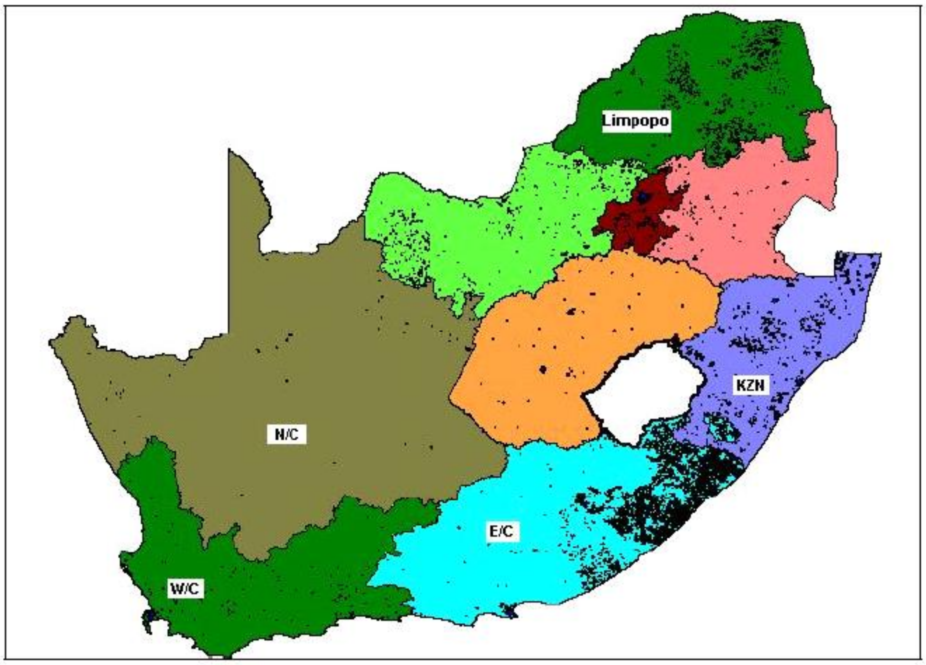


Figure 3.2 Map of unelectrified areas in South Africa [15]

This map was overlaid on to the map of South Africa in Google Earth, in order to easily determine the location of these unelectrified villages. Having easily located the unelectrified villages, the next step was to determine each village based on the strength of the resource. The process for selection of each village is covered in the following sections.

3.2.1 De Grens – Solar Village

The village was selected by identifying areas in South Africa with high solar irradiation. To do this the Global Horizontal Irradiation map in Figure 2.8 in section 2.2.1 was overlaid over the map of unelectrified rural areas (Figure 2.3) in Google Earth. This is shown in Figure 3.3 below.

Figure 3.3 Overlaid GHI and unelectrified village map in Google Earth

From Figure 3.3 it is noted that the highest solar irradiation is experienced along the Northern parts of South Africa, with the Northern Cape being the best placed. When Comparing these high irradiation areas with the unelectrified villages (signified by the black dots), it is noted that the areas circled in red were flagged as possible solar villages.

After identifying/selecting the four circled locations in Figure 3.3, Area A was checked first since it was in a location with the highest irradiation, followed by Area B which had the second highest irradiation. Areas C and D fell in the same irradiation band so they were checked last. On closer inspection, Area A and B were discarded. Despite the fact that the irradiation was highest in these areas, there was no river with suitable measurement data running through these areas, which made it impossible to model microhydro systems for any of the villages. The same was the case for Area D. This left Area C, which is reviewed in more detail in
Figure 3.4 A more detailed view of Area C below.

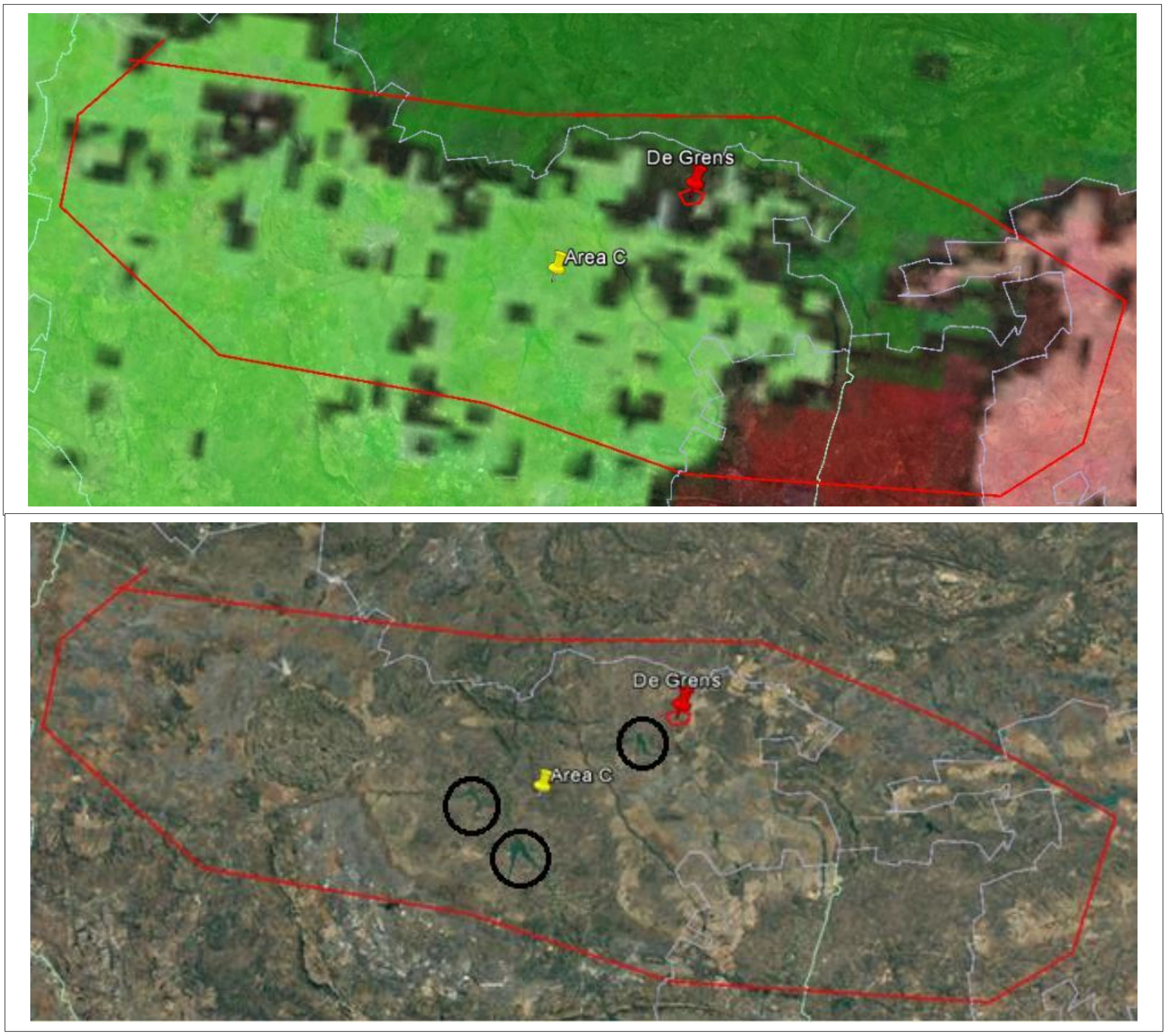


Figure 3.4 A more detailed view of Area C

Figure 3.4 A more detailed view of Area C shows the unelectrified areas within Area C whilst the second gives terrain view of the same area. All the unelectrified areas were reviewed. From the terrain view, it was noted that there were a few big enough dams (signified by the black circles) in the area suitable for microhydro generation. Based on the available dam flow rate data in each station and the assumed village size parameters, it was found that De Grens village (as shown in the figure) was the most ideal.

De Grens village is located in the Moretele municipality, within the North West province. A more detailed look at the village parameters is given in section 3.2.4.

3.2.2 Emntla – Wind Village

The wind village was selected in a similar way as the solar village, the only difference being that the wind maps in Figure 2.10 and Figure 2.12 in section 2.2.2 were used. Looking at Hagemann's wind map in Figure 2.10, it is clear that most of the areas with fast inland wind speeds are located in the Eastern

Cape and Western Cape. A more updated wind speed map at higher resolution of these above mentioned areas was given in Figure 2.12. Therefore, this map was used as an overlay to select the wind speed village as shown in Figure 3.5 below.

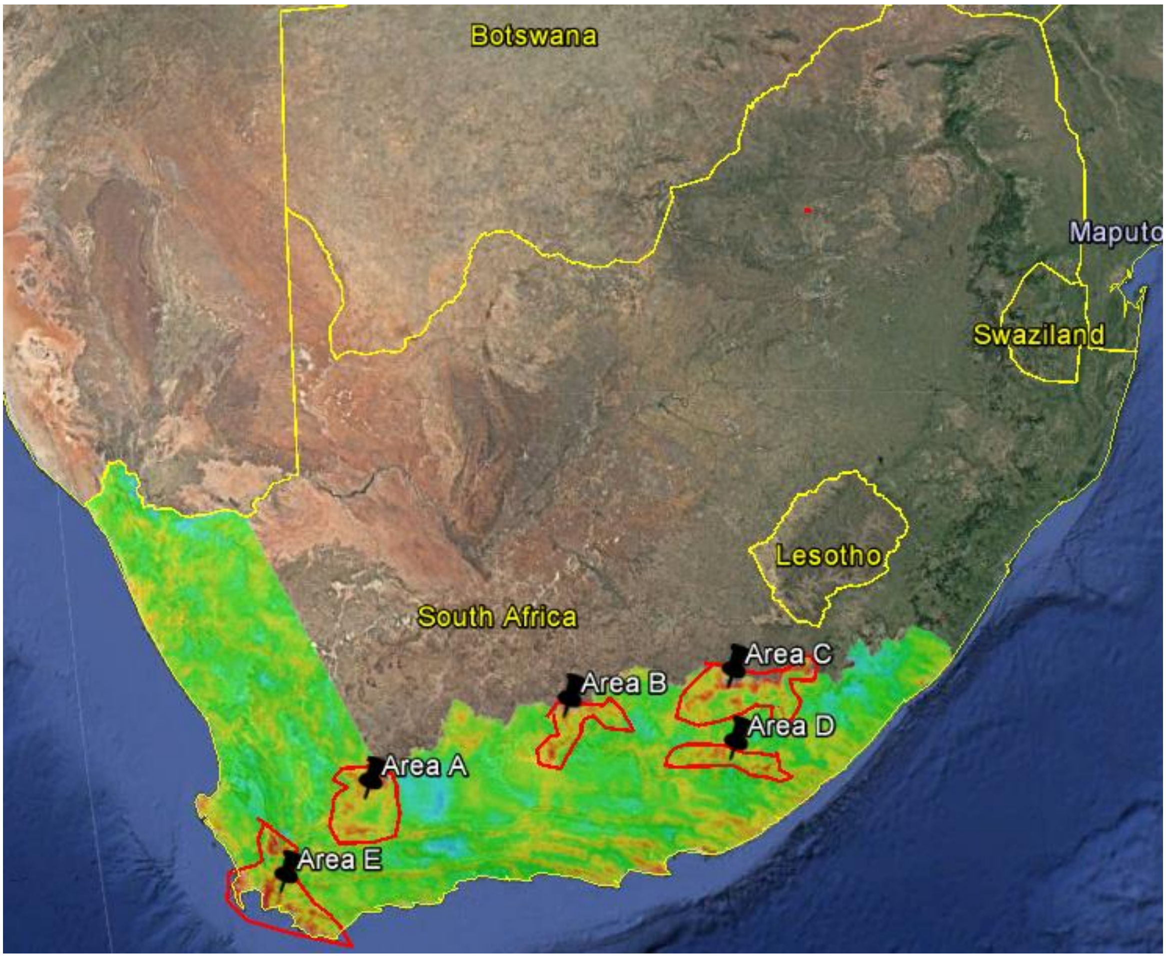


Figure 3.5 Map showing areas of high wind speed

From Figure 3.5 it was noted that 5 areas of high wind speed existed which are identified by the red shading. The next step was to combine the map of unelectrified rural areas (Figure 2.3) to determine which area had the highest concentration of unelectrified villages. The unelectrified villages are represented by the collection of black dots in Figure 3.6 below.

Figure 3.6 Map showing unelectrified areas as compared to areas with strong wind

As indicated in Figure 3.6 Areas A, B and C were excluded/eliminated? due to the lack of unelectrified villages in those areas. This left Areas C and D. Areas D and E were excluded as there was no useable dam/river data to implement a microhydro system. This left Area C, which is reviewed in more detail in Figure 3.7 below.

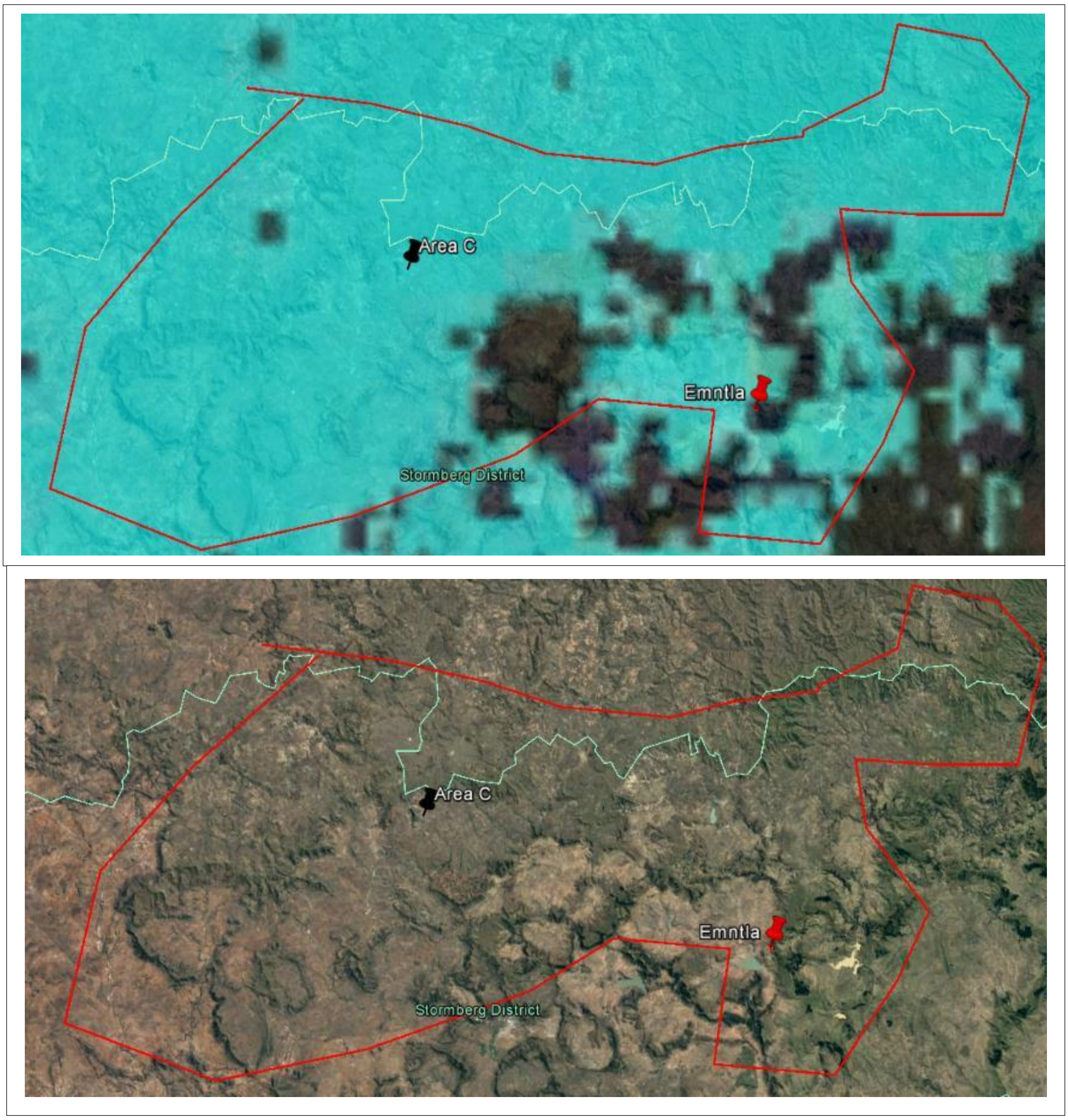


Figure 3.7 Unelectrified and terrain view of Area C

From the terrain view it was noted that Area C was very mountainous, however there were only a few dams and no notable rivers within this area. Based on the information and village size parameter, Emntla village was selected as the wind village.

Emntla village is located in the Intika Yethu municipality, within the upper parts of the Eastern Cape. A more detailed review of the village parameters is given in section 3.2.4.

3.2.3 KwanGqikiza – Microhydro Village

The final village to be selected was the one with a strong microhydro resource. Figure 2.13 in section 2.2.3, gives a map of the hydro potential in South Africa. The area around the border of the Eastern Cape and Kwa-Zulu Natal was selected as the area of interest due to the high density of potential microhydro sites located there, as well as a high concentration of unelectrified villages in these areas.

A slightly different approach was taken in selecting a suitable the microhydro village. Hydrology data for various surface water bodies has been collected by the Department of Water and Sanitation of South Africa(DWAS). The data was made available for use by anyone in the public domain, through their website [82]. Part of their data collection included mapping most of the rivers in South Africa. The rivers were mapped on Google Earth and split into various orders depending on whether they were classified as main rivers or just different tributaries. For the purpose of finding the most suitable microhydro village, only the main river systems were selected as they had faster flow rates than their subsequent tributaries. The different rivers are shown in Figure 3.8 below.

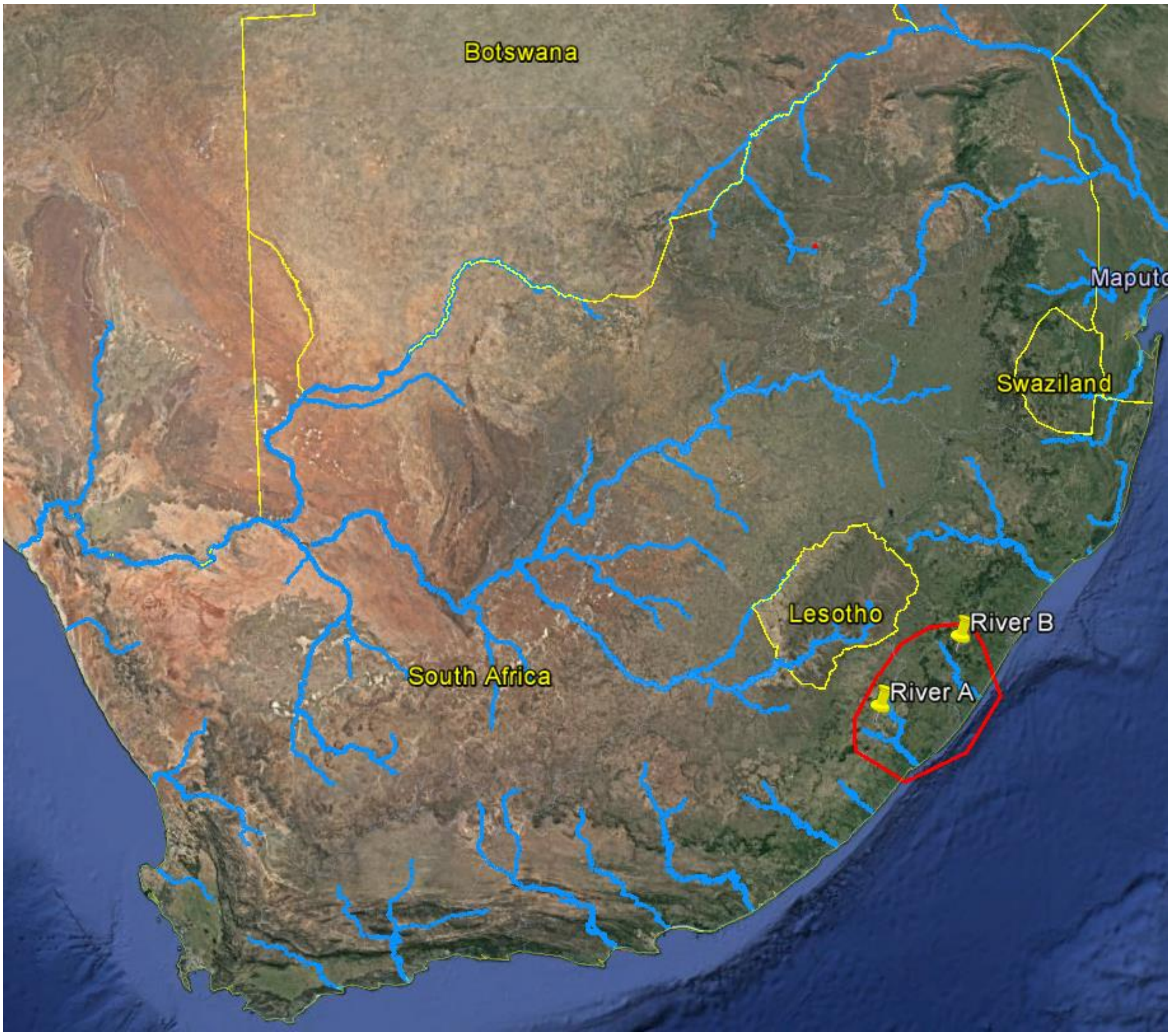


Figure 3.8 Main rivers in South Africa

The circled area in red contains two rivers (River A and River B) of interest as they are both closest to the Eastern Cape and Kwa-Zulu Natal border, which has a very high concentration of unelectrified villages as noted in Figure 3.2. River B was checked first, and it was noted that a suitable village within the size parameters could not be found. This left Area C, which is reviewed in more detail in Figure 3.9 below. From the diagram it is noted that a there are a fair amount of unelectrified areas in this region, thereby making it easier to select a village. KwanGqikiza village was selected as it was within the village size parameters and close to a station with useable river data.

KwanGqikiza is one of three sub-places that make up Nocona, which is located in the Port St Johns municipality within the Eastern Cape. The households of this village are fairly dispersed and close to the banks of the Mzimvubu river. Limited data was available on KwanGqikiza village as it was a sub-place of Ngcoya, however, any data that could be extracted is shown in section 3.2.4.

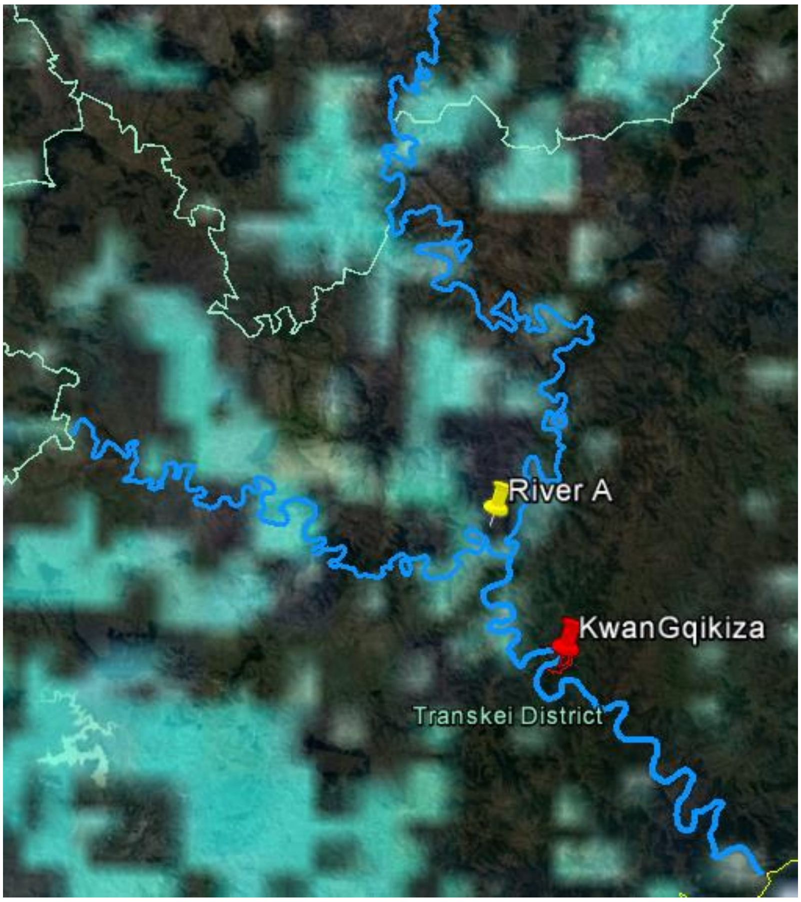


Figure 3.9 River A in relation to unelectrified areas

3.2.4 Village Comparison

One of the objectives of selecting the villages was to try and ensure that the villages were as similar as possible. The village size was the only parameter to be enforced strictly, with only villages between a 40 – 70 household bracket being selected. Other parameters such as population size, population density, etc. could not be enforced as there were already too many limitations with the amount of river/dam data available. The details of the different villages are given in Table 3.1 below. The village information was obtained from Stats South Africa Census 2011 data. [83]–[85].

A detailed review of the table identified De Grens as the biggest village in terms of area. It is generally quite flat and open with households sparsely located within the village. The population density is also the lowest with a value of 13 people/km^2. Furthermore, the number of households is the least.

Emntla in comparison is located at the base of a mountain, therefore parts of the village are on a low gradient slope. This village has the smallest area compared to the other two, with an extent of 0.69 km^2, therefore the households within the village are located in close proximity to one another. As a result, the population density is the highest at 246 people/km^2.

Table 3.1 Details of the three selected villages

	De Grens	Emntla	KwanGqikiza
Village area			
Location	25° 5'1.51"S, 27°53'29.41"E	31°45'4.87"S, 27°27'51.93"E	31°24'45.46"S, 29°17'28.90"E
Strongest renewable resource	Solar	Wind	Microhydro
Area (km²)	13.25	0.69	2.37
Number of households	44	53	66
Average household size	4	3.2	5.3
Formal dwelling (%)	95.5	18.9	
Total population	175	170	349
Population density (person/km²)	13	246	147
Male (%)	48.00	54.12	49.57
Female (%)	51.43	45.88	50.43
Electricity for lighting (%)	2.3	5.7	0
Primary cooking source	Wood	Wood	Wood
Primary lighting source	Candles	Candles	Candles
Primary heating source	Wood	Wood	Wood

KwanGqikiza is located on hilly terrain, and is the least flat as compared to the other two villages. The village has the largest resident population of 349 people however it ranks as the second largest in terms of area (2.37km2). As a result of having the highest population, KwanGqikiza also has the most households at 66, and a population density that is almost exactly half way between the other two villages at 147 people/km^2.

The microhydro sources for De Grens and Emntla were the Klipvoor dam and Lubisi Dam respectively, whilst the source for KwanGqikiza was the Mzimvubu river.

It is noted that even though the villages selected are slightly different in certain aspects, they are comparable in terms of the number of households in each village. This is the basis on which a comparison of the modelled systems between the different villages can be made, in order to determine how the resources in a given area will affect the technical and economic metrics of the systems implemented. The next step in the process is to determine the load for each village.

3.3 Load model

One of the key inputs into HOMER is the load demand. There are a number of different types of loads available namely electric, thermal and deferrable. The energy requirements of the villages were analysed in order to determine the load demand. The overall load of each village will be made up of the domestic load, commercial load and communal load.

3.3.1 Domestic Load

According to information extracted for the National Survey in 2011 by Stats SA, [83], [84], [86] the proportion of households in each village with the following appliances are shown in Figure 3.10 and Figure 3.11 below.

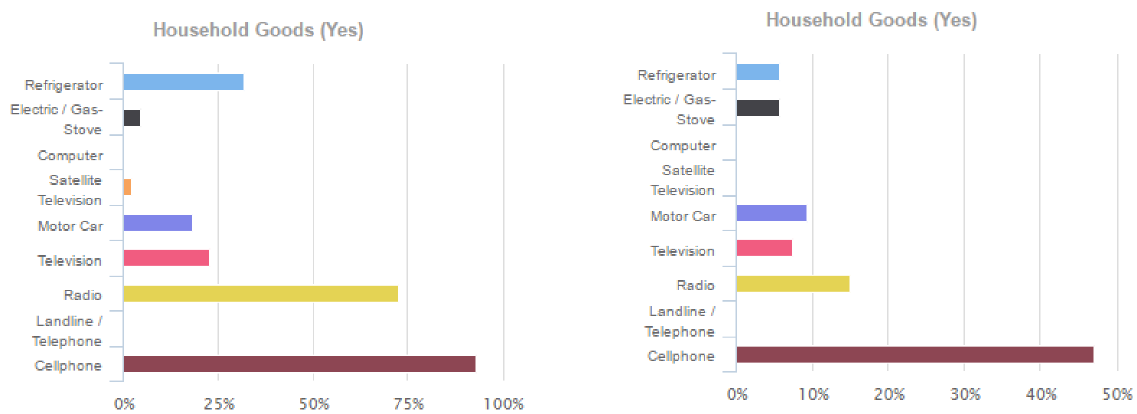


Figure 3.10 Households goods used in De Grens and Emntla [83], [84]

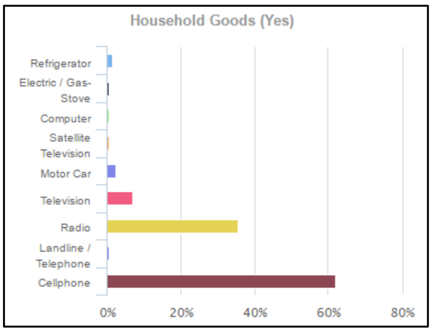


Figure 3.11 Households goods used in Ngcoya (refers to KwanGqikiza) [2] [86]

From the graphs it was clear that cell phones and radios were the predominant electrical appliances used in all three villages. The other appliances were not as popular due to the lack of electricity available.

In terms of energy sources, Table 3.1 shows that the primary cooking and heating source was wood, whilst the primary lighting source was candles for all the villages. This is typical for most villages as these are the cheapest energy sources that are available. It was also noted that the only form of electricity used, was for lighting in De Grens and Emntla, however only 2.3% and 5.7% of the village used electricity for this purpose. Reference [87] confirms that in most unelectrified villages, fuelwood and paraffin are the main sources of energy for cooking and heating. This is further confirmed by a number of authors discussing rural electrification in developing countries in general.

Reliance on the fuels such as fuelwood and paraffin poses the risk of fire as well as health hazards due to prolonged smoke inhalation. Reference [88] shows how the risk of burns and poisoning increases in 'energy poor' households. The paper notes that these risks are reduced at higher income levels where more energy sources are available, e.g. replacing paraffin with low pressure gas and candles with electric lighting.

Besides having essentials appliances to provide heat and light, it was noted in section 2.5.1, that just a basic system would not suffice for people in villages. This is especially the case for villages that are located close to other villages that are connected to the grid as noted in [1]. Therefore, systems provided should additionally cater for the minimum entertainment needs, such as TV and radio and not just provide illumination.

The above mentioned information was used to design a typical household load using appliances that would be considered useful by people living in these villages. The quantities of these appliances was based on the assumption that there were 4 people living in each household. A table of these appliances and the power generated by each is given in Table 3.2 below. The appliance ratings were obtained from [89].

Table 3.2 Appliances used in selected villages

Appliance	Quantity	Power Rating/W
Lights	4	15
Television	1	120
Radio	1	25
Fridge	1	100
Cell phone Charger	2	5
Small Stove	1	1500
Fan	2	60

[2] This data is assumed for KwanGqikiza as this village is a sub-place of Ngcoya

In order to input the load data in to HOMER, the hourly load data in kilowatts (kW), for every month is required for a 12 month period. As a result, a daily load profile based on the appliances in Table 3.2 needs to be created in order to be input into HOMER. The summer and winter, weekday and weekend profiles are shown Table 3.3 - Table 3.6 below.

Table 3.3 Hourly load demand for single household in summer - Weekday

Hour	Lights (W)	Television (W)	Radio (W)	Fridge (W)	Cell phone Charger (W)	Stove (W)	Fan (W)	Total (W)	Total (kW)
0:00 – 1:00	-	-	-	100	10	-	-	110	0.11
1:00 – 2:00	-	-	-	100	10	-	-	110	0.11
2:00 – 3:00	-	-	-	100	10	-	-	110	0.11
3:00 – 4:00	-	-	-	100	10	-	-	110	0.11
4:00 – 5:00	-	-	-	100	10	-	-	110	0.11
5:00 – 6:00	30	-	-	100	10	-	-	140	0.14
6:00 – 7:00	60	-	-	100	-	1,500	-	1,660	1.66
7:00 – 8:00	-	-	25	100	-	-	-	125	0.125
8:00 – 9:00	-	-	25	100	-	-	-	125	0.125
9:00 – 10:00	-	-	25	100	-	-	-	125	0.125
10:00 – 11:00	-	-	25	100	-	-	-	125	0.125
11:00 – 12:00	-	-	25	100	-	-	-	125	0.125
12:00 – 13:00	-	-	25	100	-	-	60	185	0.185
13:00 – 14:00	-	-	25	100	-	1,500	60	1,685	1.685
14:00 – 15:00	-	-	25	100	-	-	60	185	0.185
15:00 – 16:00	-	-	25	100	-	-	-	125	0.125
16:00 – 17:00	-	-	25	100	-	-	-	125	0.125
17:00 – 18:00	-	120	-	100	-	-	60	280	0.28
18:00 – 19:00	60	120	-	100	-	1,500	60	1,840	1.84
19:00 – 20:00	60	120	-	100	-	-	60	340	0.34
20:00 – 21:00	60	120	-	100	-	-	-	280	0.28
21:00 – 22:00	60	120	-	100	-	-	-	280	0.28
22:00 – 23:00	60	-	-	100	10	-	-	170	0.17
23:00 – 0:00	-	-	-	100	10	-	-	140	0.14
TOTAL	**420**	**600**	**250**	**1,900**	**30**	**4,500**	**360**	**8,060**	**8.06**

Table 3.4 Hourly load demand for single household in summer - Weekend

Hour	Lights (W)	Television (W)	Radio (W)	Fridge (W)	Cell phone Charger (W)	Stove (W)	Fan (W)	Total (W)	Total (kW)
0:00 – 1:00	-	-	-	100	10	-	-	110	0.11
1:00 – 2:00	-	-	-	100	10	-	-	110	0.11
2:00 – 3:00	-	-	-	100	10	-	-	110	0.11
3:00 – 4:00	-	-	-	100	10	-	-	110	0.11
4:00 – 5:00	-	-	-	100	10	-	-	110	0.11
5:00 – 6:00	-	-	-	100	10	-	-	110	0.11
6:00 – 7:00	60	-	-	100	-	1,500	-	1,660	1.66
7:00 – 8:00	-	-	25	100	-	-	-	125	0.125
8:00 – 9:00	-	-	25	100	-	-	-	125	0.125
9:00 – 10:00	-	-	25	100	-	-	-	125	0.125
10:00 – 11:00	-	120	25	100	-	-	-	245	0.245
11:00 – 12:00	-	120	25	100	-	-	60	305	0.305
12:00 – 13:00	-	120	25	100	-	-	60	305	0.305
13:00 – 14:00	-	120	25	100	-	1,500	60	1805	1.805
14:00 – 15:00	-	120	25	100	-	-	60	305	0.305
15:00 – 16:00	-	120	25	100	-	-	60	305	0.305
16:00 – 17:00	-	120	25	100	-	-	60	305	0.305
17:00 – 18:00	-	120	25	100	-	-	60	305	0.305
18:00 – 19:00	60	120	-	100	-	1,500	60	1,840	1.84
19:00 – 20:00	60	120	-	100	-	-	60	340	0.34
20:00 – 21:00	60	120	-	100	-	-	60	340	0.34
21:00 – 22:00	60	120	-	100	-	-	-	280	0.28
22:00 – 23:00	60	-	-	100	10	-	-	170	0.17
23:00 – 0:00	30	-	-	100	10	-	-	140	0.14
TOTAL	**390**	**1,440**	**275**	**1,800**	**20**	**4,500**	**600**	**9,025**	**9.03**

Table 3.5 Hourly load demand for single household in winter - Weekday

Hour	Lights (W)	Television (W)	Radio (W)	Fridge (W)	Cell phone Charger (W)	Stove (W)	Fan (W)	Total (W)	Total (kW)
0:00 – 1:00	-	-	-	100	10	-	-	110	0.11
1:00 – 2:00	-	-	-	100	10	-	-	110	0.11
2:00 – 3:00	-	-	-	100	10	-	-	110	0.11
3:00 – 4:00	-	-	-	100	10	-	-	110	0.11
4:00 – 5:00	-	-	-	100	10	-	-	110	0.11
5:00 – 6:00	30	-	-	100	10	-	-	140	0.14
6:00 – 7:00	60	-	-	100	-	1500	-	1,660	1.66
7:00 – 8:00	60	-	25	100	-	-	-	185	0.185
8:00 – 9:00	-	-	25	100	-	-	-	125	0.125
9:00 – 10:00	-	-	25	100	-	-	-	125	0.125
10:00 – 11:00	-	-	25	100	-	-	-	125	0.125
11:00 – 12:00	-	-	25	100	-	-	-	125	0.125
12:00 – 13:00	-	-	25	100	-	-	-	125	0.125
13:00 – 14:00	-	-	25	100	-	1500	-	1,625	1.625
14:00 – 15:00	-	-	25	100	-	-	-	125	0.125
15:00 – 16:00	-	-	25	100	-	-	-	125	0.125
16:00 – 17:00	-	-	25	100	-	-	-	125	0.125
17:00 – 18:00	60	120	-	100	-	-	-	280	0.28
18:00 – 19:00	60	120	-	100	-	1500	-	1,780	1.78
19:00 – 20:00	60	120	-	100	-	-	-	280	0.28
20:00 – 21:00	60	120	-	100	-	-	-	280	0.28
21:00 – 22:00	60	120	-	100	-	-	-	280	0.28
22:00 – 23:00	60	-	-	100	10	-	-	170	0.17
23:00 – 0:00	30	-	-	100	10	-	-	140	0.14
TOTAL	**540**	**600**	**250**	**1,900**	**30**	**4,500**	**0**	**7,820**	**8.00**

Table 3.6 Hourly load demand for single household in winter - Weekend

Hour	Lights (W)	Television (W)	Radio (W)	Fridge (W)	Cell phone Charger (W)	Stove (W)	Fan (W)	Total (W)	Total (kW)
0:00 – 1:00	-	-	-	100	10	-	-	110	0.11
1:00 – 2:00	-	-	-	100	10	-	-	110	0.11
2:00 – 3:00	-	-	-	100	10	-	-	110	0.11
3:00 – 4:00	-	-	-	100	10	-	-	110	0.11
4:00 – 5:00	-	-	-	100	10	-	-	110	0.11
5:00 – 6:00	-	-	-	100	10	-	-	110	0.11
6:00 – 7:00	30	-	-	100	-	1500	-	1,630	1.63
7:00 – 8:00	60	-	25	100	-	-	-	185	0.185
8:00 – 9:00	-	-	25	100	-	-	-	125	0.125
9:00 – 10:00	-	-	25	100	-	-	-	125	0.125
10:00 – 11:00	-	-	25	100	-	-	-	125	0.125
11:00 – 12:00	-	120	25	100	-	-	-	245	0.245
12:00 – 13:00	-	120	25	100	-	-	-	245	0.245
13:00 – 14:00	-	120	25	100	-	1500	-	1,745	1.745
14:00 – 15:00	-	120	25	100	-	-	-	245	0.245
15:00 – 16:00	-	120	25	100	-	-	-	245	0.245
16:00 – 17:00	-	120	25	100	-	-	-	245	0.245
17:00 – 18:00	60	120	-	100	-	-	-	280	0.28
18:00 – 19:00	60	120	-	100	-	1500	-	1,780	1.78
19:00 – 20:00	60	120	-	100	-	-	-	280	0.28
20:00 – 21:00	60	120	-	100	-	-	-	280	0.28
21:00 – 22:00	60	120	-	100	-	-	-	280	0.28
22:00 – 23:00	60	-	-	100	10	-	-	170	8.28
23:00 – 0:00	30	-	-	100	10	-	-	140	0.14
TOTAL	**480**	**1,320**	**250**	**1,800**	**20**	**4,500**	**0**	**8,370**	**8.37**

The weather plays a major role in terms of energy demand and consumption in domestic households. As a result, the load demand was split into a Winter load and Summer load. The Winter load occurred during the typically colder months in South Africa from April to August (5 months), whilst the Summer load occurred during the rest of the year from September to March (7 months). The loads for Autumn and Spring were assumed to be the same as the Winter and Summer loads, respectively. The primary difference between the two loads was the inclusion of a fan in the Summer load profile, where more energy was required to operate this device. Additionally, due to the sun setting earlier and rising later in Winter, it was noted that the lights were switched on earlier during Winter.

HOMER provides the user with the option to model the hourly loads during the weekdays separately to loads during the week. This provides improved accuracy from a load modelling perspective. It was assumed that household members were likely to be at their homes over the weekends, resulting in increased usage of the TV and radio during this period. This leads to an increased load as compared to a weekday. This was the main difference between these two loads.

3.3.2 Communal and Commercial Loads

It was noted in [1] that microgrid systems allow for the extension of electricity to other activities such as irrigation, workshop tools, schools, etc. Furthermore, it was noted in [13] how the provision of electricity can be useful in empowering the population and energising devices such as workshop machinery, that would facilitate improvements in the livelihood of people living in these villages. This will additionally allow them to have an income that will allow them to pay for electricity as well as support themselves.

The communal load consists of any load that will be beneficial to the community as a whole. The only communal load that will be modelled for this work for each village is a school. Even though schools are not directly linked to economic income, they develop human capital, thereby alleviating the village of poverty and providing people with the skills to support themselves.

The school load consisted of mainly basic appliances, the most important being lighting for classrooms as well as for security at night. The load is categorised into weekday and weekend load, in the same way as the household load in the previous section. The main difference is that energy (in the school) was used only for security lights in the evening and the fridge.

Table 3.7 Appliances used in the school

Appliance	Quantity	Power Rating/W
Lights	16	30
Radio	2	25
Fridge	1	100
Cell phone charging	5	5
Television	1	120

The weekday and weekend hourly load demand of the school during school term is shown in the Table 3.8 and Table 3.9**Error! Reference source not found.** below.

Table 3.8 Hourly load demand for school - Weekday

Hour	Lights (W)	Television (W)	Radio (W)	Fridge (W)	Cell phone Charger (W)	Total (W)	Total (kW)
0:00 – 1:00	120	-	-	100	-	220	0.22
1:00 – 2:00	120	-	-	100	-	220	0.22
2:00 – 3:00	120	-	-	100	-	220	0.22
3:00 – 4:00	120	-	-	100	-	220	0.22
4:00 – 5:00	120	-	-	100	-	220	0.22
5:00 – 6:00	120	-	-	100	-	220	0.22
6:00 – 7:00	120	-	-	100	-	220	0.22
7:00 – 8:00	300	120	50	100	-	570	0.57
8:00 – 9:00	300	-	50	100	-	450	0.45
9:00 – 10:00	300	-	50	100	-	450	0.45
10:00 – 11:00	300	-	50	100	-	450	0.45
11:00 – 12:00	300	120	50	100	-	570	0.57
12:00 – 13:00	300	120	50	100	-	570	0.57
13:00 – 14:00	300	120	50	100	-	570	0.57
14:00 – 15:00	300	-	50	100	-	450	0.45
15:00 – 16:00	300	-	50	100	25	475	0.475
16:00 – 17:00	300	-	50	100	25	475	0.475
17:00 – 18:00	300	-	50	100	25	475	0.475
18:00 – 19:00	120	-	50	100	25	295	0.295
19:00 – 20:00	120	-	-	100	-	220	0.22
20:00 – 21:00	120	-	-	100	-	220	0.22
21:00 – 22:00	120	-	-	100	-	220	0.22
22:00 – 23:00	120	-	-	100	-	220	0.22
23:00 – 0:00	120	-	-	100	-	220	0.22
TOTAL	**4,860**	**2,400**	**600**	**100**	**480**	**8,440**	**8.44**

Table 3.9 Hourly load demand for school - Weekend

Hour	Lights (W)	Television (W)	Radio (W)	Fridge (W)	Cell phone Charger (W)	Total (W)	Total (kW)
0:00 – 1:00	120	-	-	100	-	220	0.22
1:00 – 2:00	120	-	-	100	-	220	0.22
2:00 – 3:00	120	-	-	100	-	220	0.22
3:00 – 4:00	120	-	-	100	-	220	0.22
4:00 – 5:00	120	-	-	100	-	220	0.22
5:00 – 6:00	120	-	-	100	-	220	0.22
6:00 – 7:00	120	-	-	100	-	220	0.22
7:00 – 8:00	-	-	-	100	-	100	0.1
8:00 – 9:00	-	-	-	100	-	100	0.1
9:00 – 10:00	-	-	-	100	-	100	0.1
10:00 – 11:00	-	-	-	100	-	100	0.1
11:00 – 12:00	-	-	-	100	-	100	0.1
12:00 – 13:00	-	-	-	100	-	100	0.1
13:00 – 14:00	-	-	-	100	-	100	0.1
14:00 – 15:00	-	-	-	100	-	100	0.1
15:00 – 16:00	-	-	-	100	-	100	0.1
16:00 – 17:00	-	-	-	100	-	100	0.1
17:00 – 18:00	-	-	-	100	-	100	0.1
18:00 – 19:00	-	-	-	100	-	100	0.1
19:00 – 20:00	120	-	-	100	-	220	0.22

20:00 – 21:00	120	-	-	100	-	220	0.22
21:00 – 22:00	120	-	-	100	-	220	0.22
22:00 – 23:00	120	-	-	100	-	220	0.22
23:00 – 0:00	120	-	-	100	-	220	0.22
TOTAL	**1,440**	**2,400**	**0**	**0**	**0**	**3,840**	**3.84**

The commercial load in each village consists of a shop and a workshop. The shop was considered to be small and supplied essential goods and groceries. The main power consuming appliance was the double door fridges. The second commercial load consisted of a workshop with metal work and carpentry tools. The appliances used in this workshop were obtained from [13]. This load was anticipated to promote economic activities such as eco-tourism and forestry. The appliances used in the shop and the workshop are shown in Table 3.10 below.

Table 3.10 Appliances used in the commercial load

Appliance	Quantity	Power Rating/W
Shop		
Lights	4	23
Double door display fridge	2	780
Radio	1	25
Electric fan	1	60
Workshop		
Lights	4	30
Welding set	2	1,500
Grinder set	2	800
Compressor	1	1,500
Drilling machine	2	800
Electric saw	1	3,000
Planner	1	3,000
Lathe	1	1,500

The weekday and weekend hourly load demands were modelled for both the shop and the workshop and is shown in Table 3.11, Table 3.12, Table 3.13 and Table 3.14 below.

Additionally, a water pump, rated at 3,000 W, is included as a deferrable load as is the case in Lucingweni village in [13]. A deferrable load is a load that must be met within a certain time period. This is useful in times where the generation is in excess. The average load is anticipated to be 6 kWh/day which is one quarter of that used in reference [13]. The reason for this is that the selected villages are approximately a quarter of the size of Lucingweni. The water pump will help with irrigation or as a method of collecting water for use by people living in the village; therefore, it can be classed as either a communal or commercial load depending on its use.

Table 3.11 Hourly load demand for shop - Weekday

Hour	Lights (W)	Double door fridge (W)	Radio (W)	Fan (W)	Total (W)	Total (kW)
0:00 – 1:00	46	1,560	-	-	1,606	1.606
1:00 – 2:00	46	1,560	-	-	1,606	1.606
2:00 – 3:00	46	1,560	-	-	1,606	1.606
3:00 – 4:00	46	1,560	-	-	1,606	1.606
4:00 – 5:00	46	1,560	-	-	1,606	1.606
5:00 – 6:00	46	1,560	-	-	1,606	1.606
6:00 – 7:00	46	1,560	-	-	1,606	1.606
7:00 – 8:00	46	1,560	-	-	1,606	1.606
8:00 – 9:00	92	1,560	25	-	1,677	1.677
9:00 – 10:00	92	1,560	25	-	1,677	1.677
10:00 – 11:00	92	1,560	25	60	1,737	1.737
11:00 – 12:00	92	1,560	25	60	1,737	1.737
12:00 – 13:00	92	1,560	25	60	1,737	1.737
13:00 – 14:00	92	1,560	25	60	1,737	1.737
14:00 – 15:00	92	1,560	25	60	1,737	1.737
15:00 – 16:00	92	1,560	25	60	1,737	1.737
16:00 – 17:00	92	1,560	25	60	1,737	1.737
17:00 – 18:00	46	1,560	25	-	1,631	1.631
18:00 – 19:00	46	1,560	25	-	1,631	1.631
19:00 – 20:00	46	1,560	-	-	1,606	1.606
20:00 – 21:00	46	1,560	-	-	1,606	1.606
21:00 – 22:00	46	1,560	-	-	1,606	1.606
22:00 – 23:00	46	1,560	-	-	1,606	1.606
23:00 – 0:00	46	1,560	-	-	1,606	1.606
TOTAL	**1,518**	**37,440**	**275**	**420**	**39,653**	**39.65**

Table 3.12 Shop hourly load demand – Weekend

Hour	Lights (W)	Double door fridge (W)	Radio (W)	Fan (W)	Total (W)	Total (kW)
0:00 – 1:00	46	1,560	-	-	1,606	1.606
1:00 – 2:00	46	1,560	-	-	1,606	1.606
2:00 – 3:00	46	1,560	-	-	1,606	1.606
3:00 – 4:00	46	1,560	-	-	1,606	1.606
4:00 – 5:00	46	1,560	-	-	1,606	1.606
5:00 – 6:00	46	1,560	-	-	1,606	1.606
6:00 – 7:00	46	1,560	-	-	1,606	1.606
7:00 – 8:00	46	1,560	-	-	1,606	1.606
8:00 – 9:00	92	1,560	25	60	1,737	1.737
9:00 – 10:00	92	1,560	25	60	1,737	1.737
10:00 – 11:00	46	1,560	-	-	1,606	1.606
11:00 – 12:00	46	1,560	-	-	1,606	1.606
12:00 – 13:00	46	1,560	-	-	1,606	1.606
13:00 – 14:00	46	1,560	-	-	1,606	1.606
14:00 – 15:00	46	1,560	-	-	1,606	1.606
15:00 – 16:00	46	1,560	-	-	1,606	1.606
16:00 – 17:00	46	1,560	-	-	1,606	1.606
17:00 – 18:00	46	1,560	-	-	1,606	1.606
18:00 – 19:00	46	1,560	-	-	1,606	1.606
19:00 – 20:00	46	1,560	-	-	1,606	1.606
20:00 – 21:00	46	1,560	-	-	1,606	1.606
21:00 – 22:00	46	1,560	-	-	1,606	1.606
22:00 – 23:00	46	1,560	-	-	1,606	1.606
23:00 – 0:00	46	1,560	-	-	1,606	1.606
TOTAL	**1,196**	**3,7440**	**50**	**120**	**38,806**	**38.806**

Table 3.13 Workshop hourly load demand - Weekday

Hour	Lights (W)	Welding Set (W)	Grinder Set (W)	Compressor (W)	Drilling machine (W)	Electric Saw (W)	Planner (W)	Lathe (W)	Total (W)	Total (kW)
0:00 – 1:00	60	-	-	-	-	-	-	-	60	0.06
1:00 – 2:00	60	-	-	-	-	-	-	-	60	0.06
2:00 – 3:00	60	-	-	-	-	-	-	-	60	0.06
3:00 – 4:00	60	-	-	-	-	-	-	-	60	0.06
4:00 – 5:00	60	-	-	-	-	-	-	-	60	0.06
5:00 – 6:00	60	-	-	-	-	-	-	-	60	0.06
6:00 – 7:00	60	-	-	-	-	-	-	-	60	0.06
7:00 – 8:00	60	-	-	-	-	-	-	-	60	0.06
8:00 – 9:00	120	3,000	-	1,500	800	3,000	3,000	-	11,420	11.42
9:00 – 10:00	120	3,000	1,600	1,500	1,600	3,000	3,000	1,500	15,320	15.32
10:00 – 11:00	120	3,000	1,600	1,500	800	-	-	1,500	8,520	8.52
11:00 – 12:00	120	-	1,600	1,500	-	3,000	-	-	6,220	6.22
12:00 – 13:00	120	3,000	-	1,500	800	3,000	3,000	1,500	12,920	12.92
13:00 – 14:00	120	-	-	-	-	-	-	-	120	0.12
14:00 – 15:00	120	3,000	1,600	1,500	1,600	3,000	3,000	1,500	15,320	15.32
15:00 – 16:00	120	3,000	1,600	1,500	800	3,000	3,000	-	13,020	13.02
16:00 – 17:00	120	-	1,600	1,500	-	-	3,000	1,500	7,720	7.72
17:00 – 18:00	60	-	-	-	-	-	-	-	60	0.06
18:00 – 19:00	60	-	-	-	-	-	-	-	60	0.06
19:00 – 20:00	60	-	-	-	-	-	-	-	60	0.06
20:00 – 21:00	60	-	-	-	-	-	-	-	60	0.06
21:00 – 22:00	60	-	-	-	-	-	-	-	60	0.06
22:00 – 23:00	60	-	-	-	-	-	-	-	60	0.06
23:00 – 0:00	60	-	-	-	-	-	-	-	60	0.06
TOTAL	**1,980**	**18,000**	**9,600**	**12,000**	**6,400**	**18,000**	**18,000**	**7,500**	**91,480**	**91.48**

Table 3.14 Workshop hourly load demand - Weekend

Hour	Lights (W)	Welding Set (W)	Grinder Set (W)	Compressor (W)	Drilling machine (W)	Electric Saw (W)	Planner (W)	Lathe (W)	Total (W)	Total (kW)
0:00 – 1:00	60	-	-	-	-	-	-	-	60	0.06
1:00 – 2:00	60	-	-	-	-	-	-	-	60	0.06
2:00 – 3:00	60	-	-	-	-	-	-	-	60	0.06
3:00 – 4:00	60	-	-	-	-	-	-	-	60	0.06
4:00 – 5:00	60	-	-	-	-	-	-	-	60	0.06
5:00 – 6:00	60	-	-	-	-	-	-	-	60	0.06
6:00 – 7:00	60	-	-	-	-	-	-	-	60	0.06
7:00 – 8:00	60	-	-	-	-	-	-	-	60	0.06
8:00 – 9:00	60	-	-	-	-	-	-	-	60	0.06
9:00 – 10:00	60	-	-	-	-	-	-	-	60	0.06
10:00 – 11:00	60	-	-	-	-	-	-	-	60	0.06
11:00 – 12:00	60	-	-	-	-	-	-	-	60	0.06
12:00 – 13:00	60	-	-	-	-	-	-	-	60	0.06
13:00 – 14:00	60	-	-	-	-	-	-	-	60	0.06
14:00 – 15:00	60	-	-	-	-	-	-	-	60	0.06
15:00 – 16:00	60	-	-	-	-	-	-	-	60	0.06
16:00 – 17:00	60	-	-	-	-	-	-	-	60	0.06
17:00 – 18:00	60	-	-	-	-	-	-	-	60	0.06
18:00 – 19:00	60	-	-	-	-	-	-	-	60	0.06
19:00 – 20:00	60	-	-	-	-	-	-	-	60	0.06
20:00 – 21:00	60	-	-	-	-	-	-	-	60	0.06
21:00 – 22:00	60	-	-	-	-	-	-	-	60	0.06
22:00 – 23:00	60	-	-	-	-	-	-	-	60	0.06
23:00 – 0:00	60	-	-	-	-	-	-	-	60	0.06
TOTAL	**1440**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1,440**	**1.44**

Table 3.15 Combined village loads (kW)

Hour	De Grens (kW)				Emntla (kW)				KwanGqikiza (kW)			
	Summer		Winter		Summer		Winter		Summer		Winter	
	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
0:00 – 1:00	6.73	6.73	6.73	6.73	7.72	7.72	7.72	7.72	9.146	9.15	9.15	9.15
1:00 – 2:00	6.73	6.73	6.73	6.73	7.72	7.72	7.72	7.72	9.15	9.15	9.15	9.15
2:00 – 3:00	6.73	6.73	6.73	6.73	7.72	7.72	7.72	7.72	9.15	9.15	9.15	9.15
3:00 – 4:00	6.73	6.73	6.73	6.73	7.72	7.72	7.72	7.72	9.15	9.15	9.15	9.15
4:00 – 5:00	6.73	6.73	6.73	6.73	7.72	7.72	7.72	7.72	9.15	9.15	9.15	9.15
5:00 – 6:00	8.05	6.73	8.05	6.73	9.31	7.72	9.31	7.72	11.13	9.15	11.13	9.15
6:00 – 7:00	74.93	74.93	74.93	73.61	89.87	89.87	89.87	88.28	111.45	111.45	111.45	109.47
7:00 – 8:00	7.74	7.27	10.38	9.91	8.86	8.39	12.04	11.57	10.49	10.02	14.45	13.98
8:00 – 9:00	19.05	7.40	19.05	7.40	20.17	8.52	20.17	8.52	21.80	10.15	21.80	10.15
9:00 – 10:00	22.95	7.40	22.95	7.40	24.07	8.52	24.07	8.52	25.70	10.15	25.70	10.15
10:00 – 11:00	16.21	12.55	16.21	7.27	17.33	14.75	17.33	8.39	18.96	17.94	18.96	10.02
11:00 – 12:00	14.03	15.19	14.03	12.55	15.15	17.93	15.15	14.75	16.78	21.90	16.78	17.94
12:00 – 13:00	23.37	15.19	20.73	12.55	25.03	17.93	21.85	14.75	27.44	21.90	23.48	17.94
13:00 – 14:00	76.57	81.19	73.93	78.55	91.73	97.43	88.55	94.25	113.64	120.90	109.68	116.94
14:00 – 15:00	25.65	15.19	23.01	12.55	27.31	17.93	24.13	14.75	29.72	21.90	25.76	17.94
15:00 – 16:00	20.73	15.19	20.73	12.55	21.86	17.93	21.86	14.75	23.48	21.90	23.48	17.94
16:00 – 17:00	15.43	15.19	15.43	12.55	16.56	17.93	16.56	14.75	18.18	21.90	18.18	17.94
17:00 – 18:00	14.49	15.19	14.49	14.09	17.01	17.93	17.01	16.61	20.65	21.90	20.65	20.25
18:00 – 19:00	82.95	82.73	80.31	80.09	99.51	99.29	96.33	96.11	123.43	123.21	119.47	119.25
19:00 – 20:00	16.85	16.85	14.21	14.21	19.91	19.91	16.73	16.73	24.33	24.33	20.37	20.37
20:00 – 21:00	14.21	16.85	14.21	14.21	16.73	19.91	16.73	16.73	20.37	24.33	20.37	20.37
21:00 – 22:00	14.21	14.21	14.21	14.21	16.73	16.73	16.73	16.73	20.37	20.37	20.37	20.37
22:00 – 23:00	9.37	9.37	9.37	9.37	10.90	10.90	10.90	10.90	13.11	13.11	13.11	13.11
23:00 – 0:00	8.05	8.05	8.05	8.05	9.31	9.31	9.31	9.31	11.13	11.13	11.13	11.13
TOTAL	**518.41**	**470.23**	**507.85**	**441.41**	**595.90**	**557.39**	**583.18**	**522.68**	**707.833**	**683.30**	**691.99**	**640.07**

3.3.3 Village Loads

All the loads for each village were combined to give the final load profile for each village. This was calculated by multiplying the household profile by the number of households in each village. This gave the total load that was required by the all households of each village. After calculating the total household loads for each village, the communal and commercial loads were added to give the total hourly demand of each village. The hourly load demands for each village are shown in Table 3.15 above.

From the load data, it is noted that KwanGqikiza had the highest load, since it had the highest number of households. The peak loads in a given hour for De Grens, Emntla and KwanGqikiza were 82.95 kW, 99.51 kW and 123.43 kW respectively. The values from Table 3.15 were entered into HOMER and the following daily load profiles for each village were shown on HOMER.

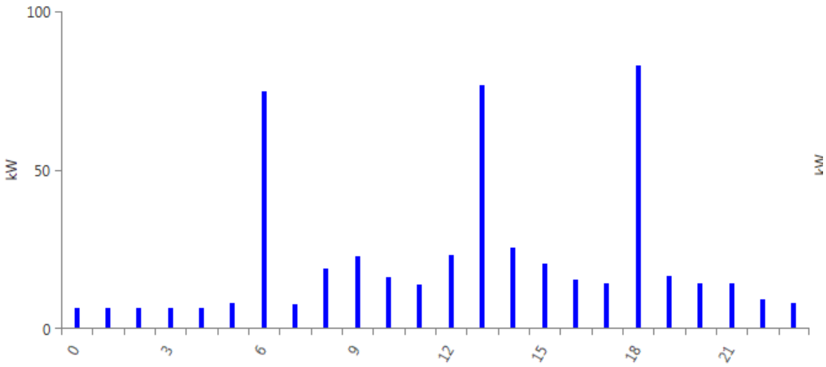


Figure 3.12 Daily load profile De Grens village

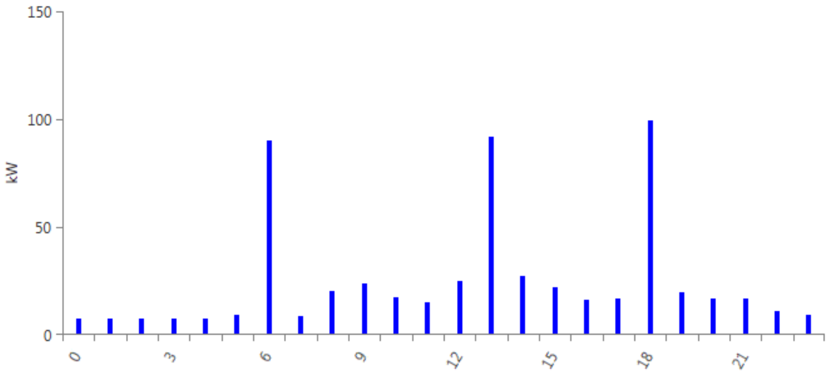


Figure 3.13 Daily load profile Emntla village

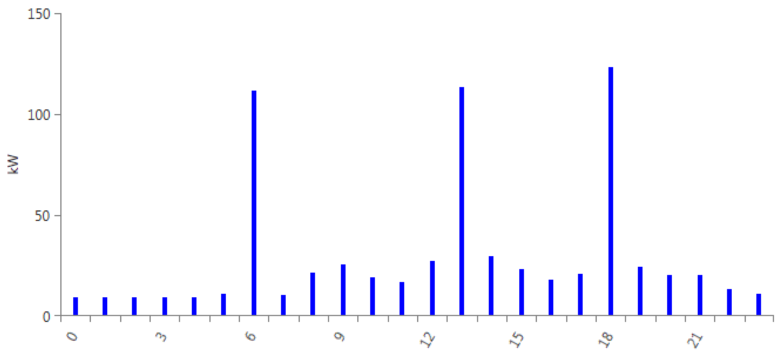


Figure 3.14 Daily load profile KwanGqikiza village

Figures 3.12, 3.13 and 3.14 indicate that all the villages have a similar load profile. The only difference is the magnitude of the loads due to the number of households per village. Table 3.16 below provides the load details as extracted from HOMER based on the input data for a year.

Table 3.16 Village load details from HOMER

	De Grens		Emntla		KwanGqikiza	
	Baseline	Scaled	Baseline	Scaled	Baseline	Scaled
Average energy (kWh/day)	498.01	622.51	576.89	721.11	690.91	863.64
Average power (kW)	20.75	25.94	24.04	30.05	28.79	35.99
Peak power (kW)	140.56	175.7	168.62	210.78	209.17	261.46
Load Factor	0.15	0.15	0.14	0.14	0.14	0.14

HOMER allows the user to enter a scaled annual average value, which changes all the other parameters. The 'Scaled' columns are therefore user defined with the default being the same as the baseline values. For these simulations, a 25% safety factor is entered as the scaled value as per good design practice. This safety factor is necessary in order to provide room for future load growth.

HOMER also allows the user to add random variability to the load by changing the day to day factor and the time step factor. These factors are necessary in order to make the load more realistic, as the load size and shape will not be constant every day. The day to day factor scales the load up and down the y-axis, meaning that it adds some variability to the magnitude of the load. The time step factor changes the values along the x-axis without changing the magnitude. These factors cannot be made too high as this will significantly change the load. These variables were kept at their default values of 15% for the day to day factor and 20% for the time step factor. [81]

The load for the 3 villages has been modelled and input into HOMER. The next critical step in simulating these renewable systems was to determine the renewable resources available in each village in a format that can be input into HOMER.

3.4 Renewable Resources

The resources of interest were solar, wind and microhydro. The resource levels of these three technologies had to be determined in each village in order to simulate each respective system to compare with one another. The method used to attain this information is explained in the following subsections.

3.4.1 Global Horizontal Irradiation

HOMER uses the GHI as stated in section 2.2.1 in order to simulate a PV system. The data can either be entered as monthly averages of the daily radiation in kWh/m^2/day of which HOMER will synthesize hourly data or imported hourly (or minute) data from a time series data file. For the purposes of this dissertation the monthly averages will be entered.

The monthly averages can be entered by either downloading the data from the HOMER website or entering the values manually. Data download from the HOMER website was initially attempted; however, no data was available for any of the selected villages. As a result, the data had to be entered manually. In order to do so this information was obtained from a meteorological database providing satellite derived irradiation values.

There are many meteorological databases that offer solar irradiation data in the format required such as SolarGIS, Meteonorm, HelioClim, etc. These sources output solar irradiation in different formats, with monthly and hourly being the most common. Additionally, these databases have differing levels of accuracy depending on how they capture the solar irradiation, as well as the length of the time period they have data for. Most of these databases however, required a subscription fee to be paid or the required data to be purchased. Only information attainable for free was considered; hence NASA-SSE (Surface meteorology and Solar Energy) database was selected as the data source.

NASA-SSE data holds monthly satellite data for a 1° x 1° grid of the world for a 25-year period from 1983 – 2005. The only inputs required are the co-ordinates of the location, which when entered, generate a table of data. An example of the data provided for De Grens is shown in Figure 3.15 below. [90].

ATMOSPHERIC SCIENCE DATA CENTER

NASA Surface meteorology and Solar Energy: RETScreen Data

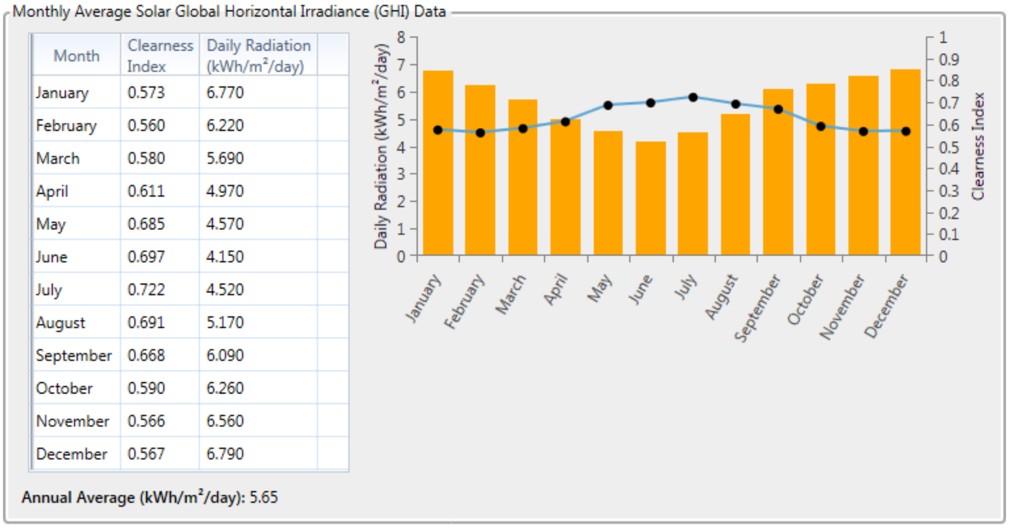
Latitude -25.084 / Longitude 27.892 was chosen.

	Unit	Climate data location
Latitude	°N	-25.084
Longitude	°E	27.892
Elevation	m	1264
Heating design temperature	°C	6.09
Cooling design temperature	°C	29.78
Earth temperature amplitude	°C	16.93
Frost days at site	day	0

Month	Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
	°C	%	$kWh/m^2/d$	kPa	m/s	°C	°C-d	°C-d
January	23.1	55.9%	6.77	87.5	2.9	25.8	0	407
February	23.0	54.7%	6.22	87.5	2.8	25.6	0	367
March	21.9	53.6%	5.69	87.7	2.7	24.3	0	371
April	19.4	48.8%	4.97	87.9	2.8	21.9	10	285
May	15.9	44.6%	4.57	88.0	2.9	17.8	64	192
June	12.3	46.0%	4.15	88.2	3.1	13.7	162	79
July	12.2	43.6%	4.52	88.2	3.2	13.8	173	79
August	15.5	39.2%	5.17	88.1	3.7	18.0	82	172
September	19.5	37.5%	6.09	87.9	4.0	23.1	19	282
October	21.4	46.0%	6.26	87.8	3.9	25.2	7	349
November	21.8	53.2%	6.56	87.6	3.5	25.1	3	352
December	22.1	59.0%	6.79	87.5	3.1	24.8	1	377
Annual	19.0	48.5%	5.65	87.8	3.2	21.6	521	3312
Measured at (m)					10.0	0.0		

Figure 3.15 De Grens meteorological data provided by NASA-SSE

The daily solar horizontal irradiation column was manually input into HOMER for each village. An example of the HOMER solar irradiation input for De Grens is shown in Figure 3.16 below.


Monthly Average Solar Global Horizontal Irradiance (GHI) Data

Month	Clearness Index	Daily Radiation (kWh/m²/day)
January	0.573	6.770
February	0.560	6.220
March	0.580	5.690
April	0.611	4.970
May	0.685	4.570
June	0.697	4.150
July	0.722	4.520
August	0.691	5.170
September	0.668	6.090
October	0.590	6.260
November	0.566	6.560
December	0.567	6.790

Annual Average (kWh/m²/day): 5.65

Figure 3.16 GHI values input into HOMER for De Grens

3.4.2 Wind Speed

The following step was taken to enter the wind resource values for each village. HOMER requires that the average monthly wind speed in m/s is input in order to simulate a wind system. Much like for the solar GHI inputs, the required data could either be entered manually or downloaded from the HOMER website. The data was not available on the HOMER website; therefore, it had to be entered manually. Additionally, the following parameters were necessary in order to synthesize the wind profile for each village:

- Weibull factor (k);
- 1 hour autocorrelation factor
- Diurnal pattern strength
- Hours of peak wind speed

These are explained in more detail below.

3.4.2.1 Wind parameters

Weibull factor

The Weibull factor (k) reflects the shape of the Weibull distribution, with higher values corresponding to a higher distribution. The Weibull distribution is used to characterise the variation in wind speeds. The Weibull distribution is given by the probability distribution function and the cumulative distribution function given by Equation 3.2 and Equation 3.3 respectively. [81]

$$f(U) = \frac{k}{c}\left(\frac{U}{c}\right)^{k-1} * exp\left[-\left(\frac{U}{c}\right)^{k}\right] \quad (3.2)$$

$$f(U) = 1 - exp\left[-\left(\frac{U}{c}\right)^{k}\right] \quad (3.3)$$

where,

U - wind speed (m/s)
c - Weibull c factor
k – Weibull k factor

The two Weibull factors are related to the long-term average wind speed by the following equation.

$$\bar{U} = c\Gamma\left(\frac{1}{k} + 1\right) \tag{3.4}$$

Where,

$\bar{U}$ – average wind speed (m/s)
Γ – gamma function

The variation in Weibull distribution due to different Weibull factors is shown in Figure 3.17 below.

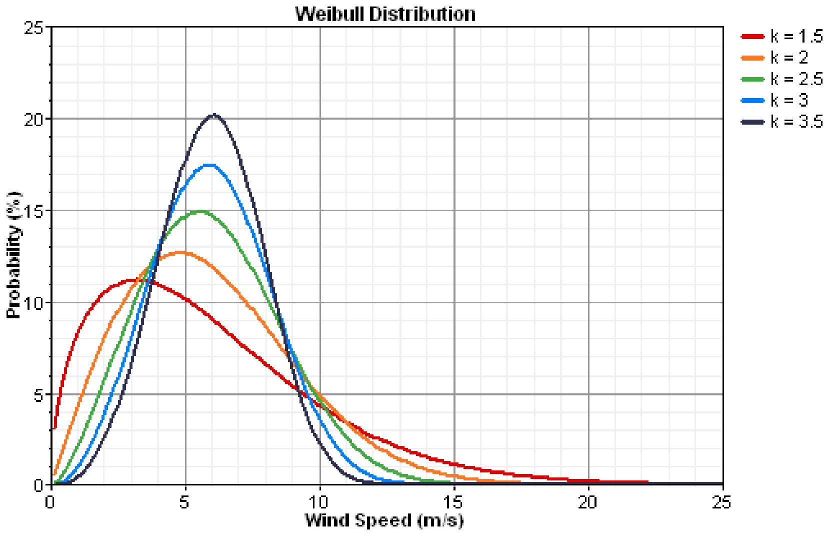


Figure 3.17 Weibull distribution variation due to different Weibull factors [80]

1 hour autocorrelation factor

The autocorrelation factor determines how much of an effect the wind speed in one time step, affects the wind speed in another time step. A high autocorrelation factor means that the wind speed in a given time step depends greatly on the wind speed in the previous step. The auto correlation co-efficient is given by the following equation. [81]

$$r_k = \frac{\sum_{i=1}^{n-k}(z_i-\bar{z})(z_{i+k}-\bar{z})}{\sum_{i=1}^{n}(z_i-\bar{z})^2} \tag{3.5}$$

where,

$z_1, z_2, z_3, \ldots, z_n$ is the time series
r_k – autocorrelation co-efficient
k – separation between two time units

The one hour autocorrelation co-efficient is the auto correlation co-efficient at a lag of one hour simplifying the above equation to the following:

$$r_k = {r_1}^k$$

where r_1 is the correlation coefficient for a lag of one time step [81].

This factor lies typically in the range of 0.80 – 0.95 depending on the complexity of the topography. Areas surrounded by a lot of physical features, such as mountains and hills, tend to have a lower topography (0.7 – 0.8), whereas those not surrounded by physical features, e.g. in open plain, tend to have a higher value (0.9 – 0.97). [81]

Since De Grens is located in an open area, with limited physical features surrounding the village, it was determined that the 1-hour correlation co-efficient would be 0.75. Emntla and KwanGqikiza are located in a hilly area, therefore the 1-hour correlation co-efficient for these two villages was determined to be 0.9.

Diurnal Pattern Strength

The diurnal pattern strength is a measure of how the wind speed is dependent on the time of day. HOMER assumes a co-sinusoidal diurnal pattern as given by the following equation [81]:

$$\boldsymbol{U_i} = \overline{\boldsymbol{U}} \left\{ \mathbf{1} + \boldsymbol{\delta} \cos \left[\left(\frac{\mathbf{2}\boldsymbol{\pi}}{\mathbf{24}} \right) (\boldsymbol{i} - \emptyset) \right] \right\} \text{ for i = 1,2,...,24} \quad \textbf{(3.6)}$$

where,

U_i – the mean wind speed in hour i (m/s)
U – overall mean wind speed (m/s)
δ – diurnal pattern strength (a number between 0 and 1)
Ø - hour of peak wind speed (integer between 1 and 24)

The diurnal pattern strength varies between 0 and 1; however according to HOMER, the typical range of this value is between 0 and 0.4. [81]

Hour of Peak Wind Speed

This is simply the hour of day when the wind speed is at its highest. The typical range is dependent on the location.

3.4.2.2 Data Collection

In order to carry out this task, Windographer was used to download and process the raw wind speed data.

Windographer is a program used for analysing wind resource data by importing raw data files and displaying the data in different ways such that the data can be effectively analysed. Most data sources, whether measured by met tower, SoDAR or LiDAR can be processed by Windographer. [91]

The first step in using Windographer, was to download the raw data. This was done by using the Data Downloader located in the Tools menu. This tool allows the user to download long term meteorological data. MERRA and MERRA-2 were the only two data source options. [91] MERRA-2 is an updated version of MERRA (Modern-Era Retrospective analysis for Research and Applications), which is a reanalysis of dataset by NASA using Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5). [92] Reanalysis is a scientific method of developing a record of weather and climate data using observation all over the world and a numerical prediction model. [93] One of the outputs of MERRA-2 includes long term wind estimates, making it ideal for wind resource assessment.

Once the Data Downloader is selected, the co-ordinates of the location for which the data was required was entered. The following window was opened on entering the co-ordinates for Emntla, the wind village.

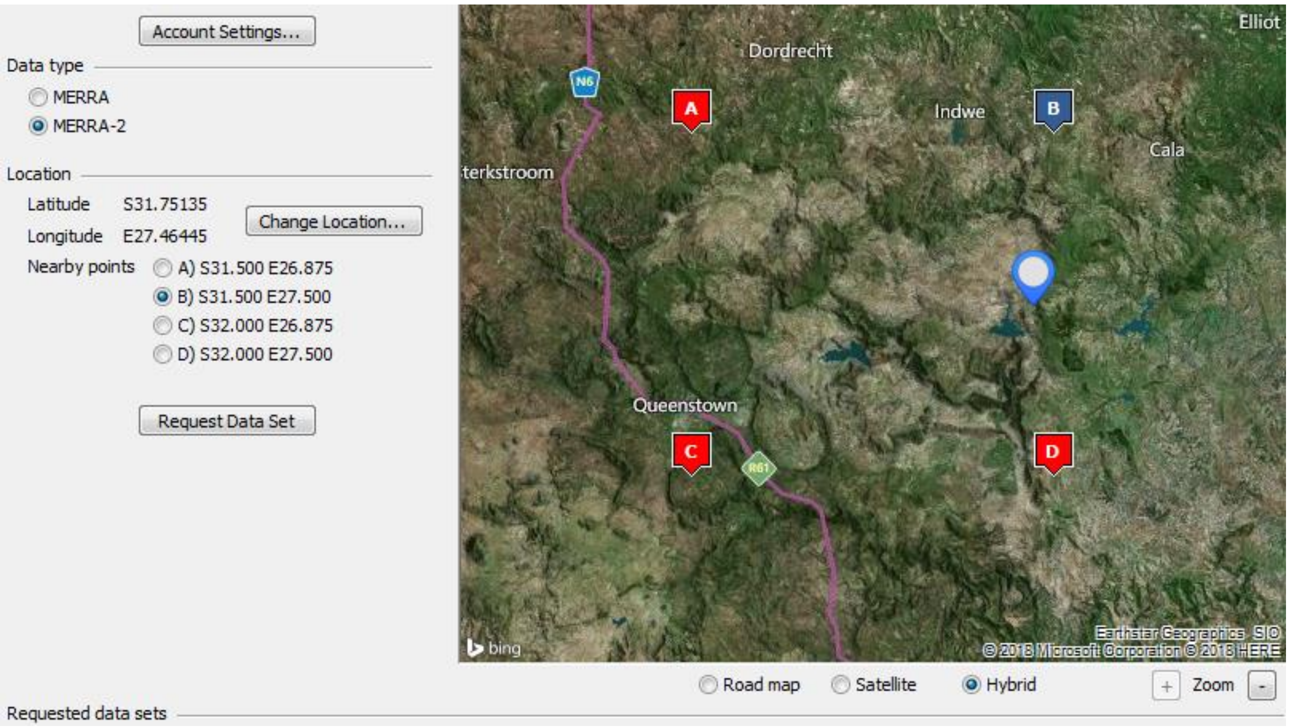


Figure 3.18 Downloading raw wind data for Emntla

The wind data was only available for certain locations and not necessarily, the exact site location. Therefore, once the co-ordinates were entered, the four closest areas with available wind data was given as shown in Figure 3.18 above. The wind data sites were labelled as A, B, C and D on the map, with their coordinates under the location on the left of the window. The closest data site to the village was data site B (highlighted in blue in Figure 3.18), therefore it was selected and the data was downloaded. The data downloaded provided the wind speed in an hourly format from January 1979. The wind speed was measured at a height of 50m above ground level.

The downloaded data was then imported into Windographer. Once imported, different information relating to the data could be processed and analysed. The Summary tab for the Emntla data set is shown in Figure 3.19 below.

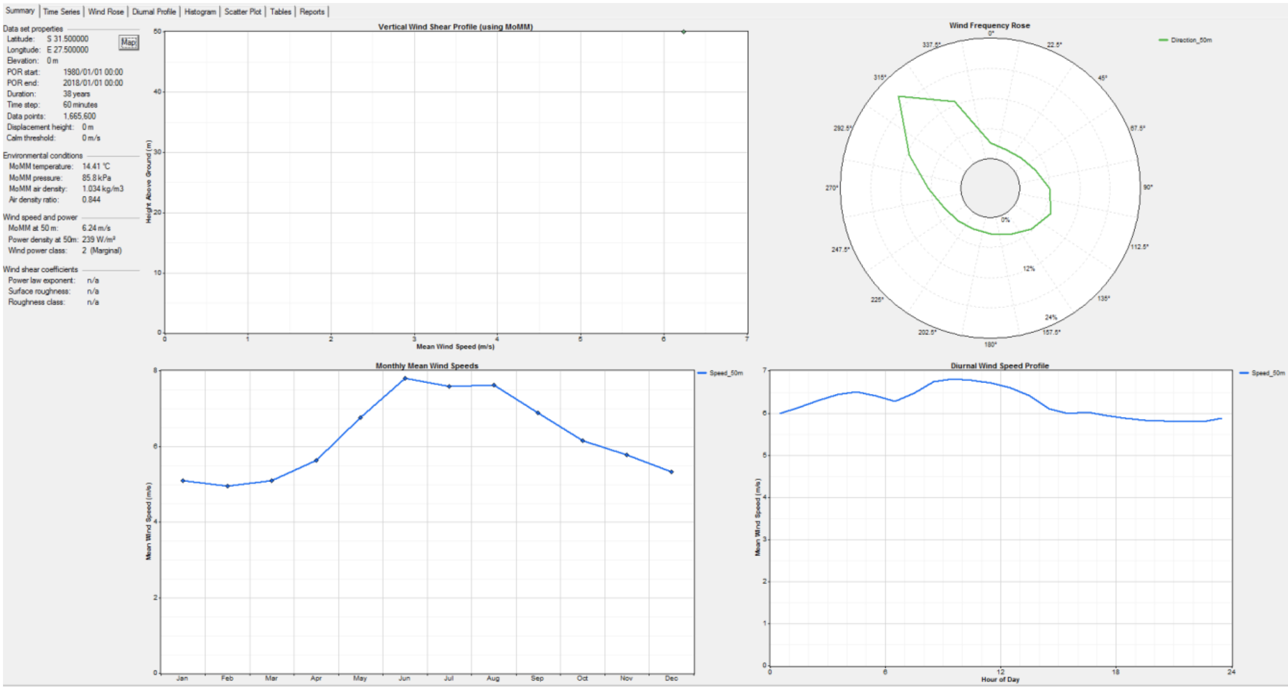
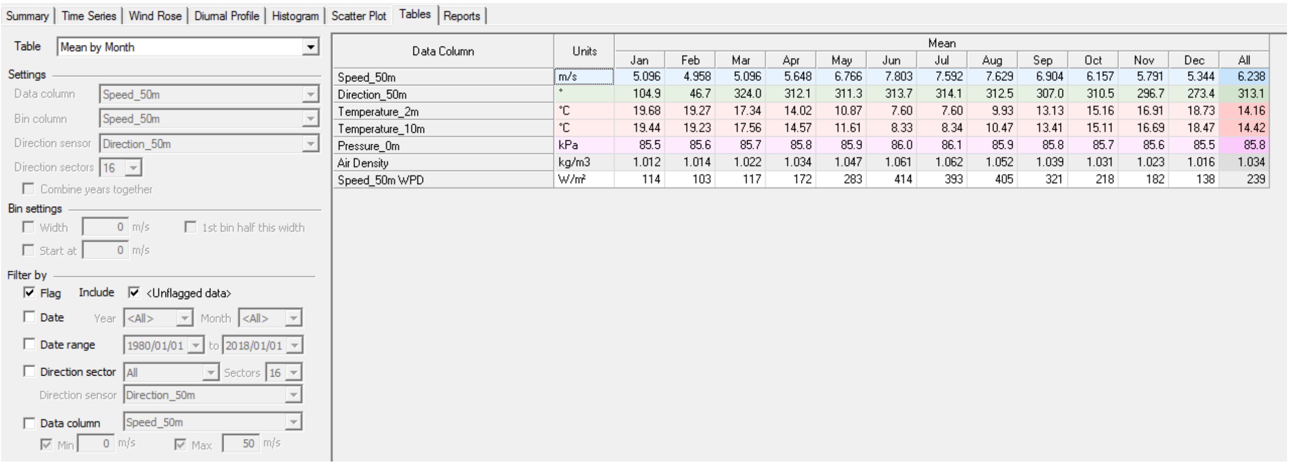


Figure 3.19 Summary tab of imported wind speed data for Emntla

Besides the Summary tab, there were seven additional tabs of useable data. In order to obtain the monthly average wind speeds, the Tables tab was used and the 'Mean by Month' table option was selected as shown in Figure 3.19 below.



Data Column	Units	Mean												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
Speed_50m	m/s	5.096	4.958	5.096	5.648	6.766	7.803	7.592	7.629	6.904	6.157	5.791	5.344	6.238
Direction_50m	°	104.9	46.7	324.0	312.1	311.3	313.7	314.1	312.5	307.0	310.5	296.7	273.4	313.1
Temperature_2m	°C	19.68	19.27	17.34	14.02	10.87	7.60	7.60	9.93	13.13	15.16	16.91	18.73	14.16
Temperature_10m	°C	19.44	19.23	17.56	14.57	11.61	8.33	8.34	10.47	13.41	15.11	16.69	18.47	14.42
Pressure_0m	kPa	85.5	85.6	85.7	85.8	85.9	86.0	86.1	85.9	85.8	85.7	85.6	85.5	85.8
Air Density	kg/m3	1.012	1.014	1.022	1.034	1.047	1.061	1.062	1.052	1.039	1.031	1.023	1.016	1.034
Speed_50m WPD	W/m²	114	103	117	172	283	414	393	405	321	218	182	138	239

Figure 3.20 Extracting mean monthly wind speed for Emntla

The Histogram tab was selected to determine the Weibull factor. This tab provided a probability distribution of the wind speeds for the given data set. The Weibull factor was given underneath the curve and was found to be 2.03. An example of this is shown for Emntla in Figure 3.21 below.

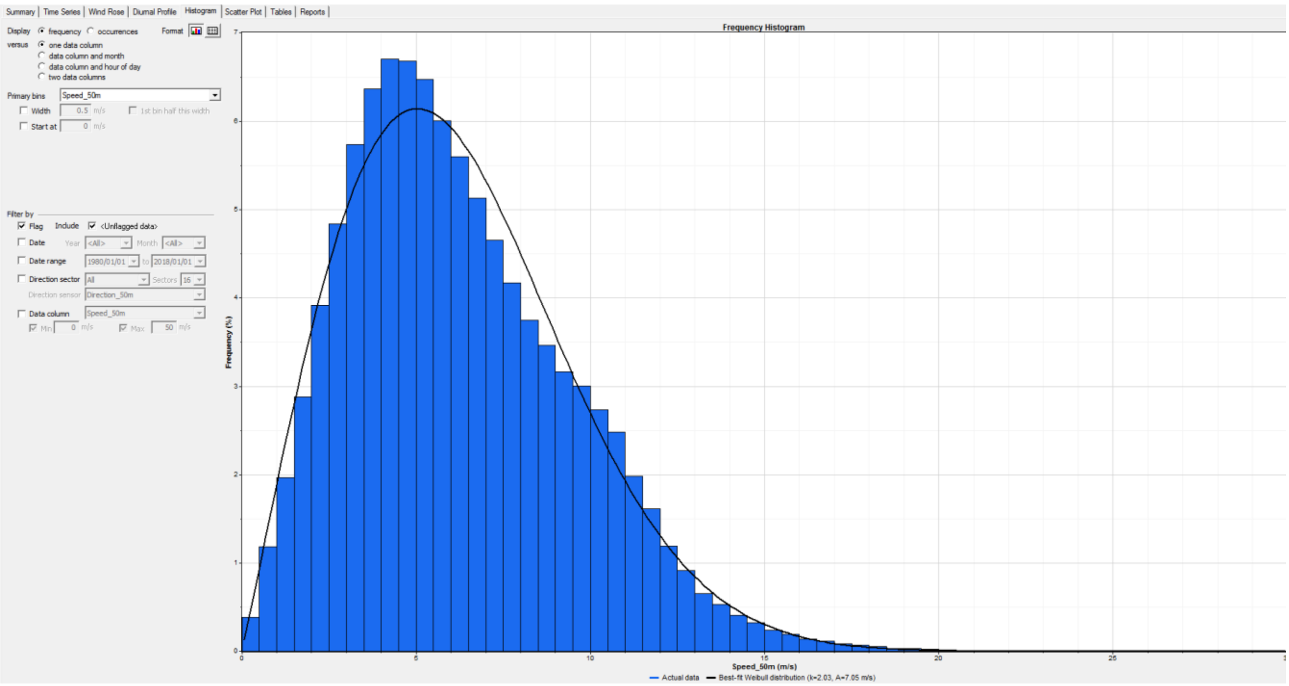
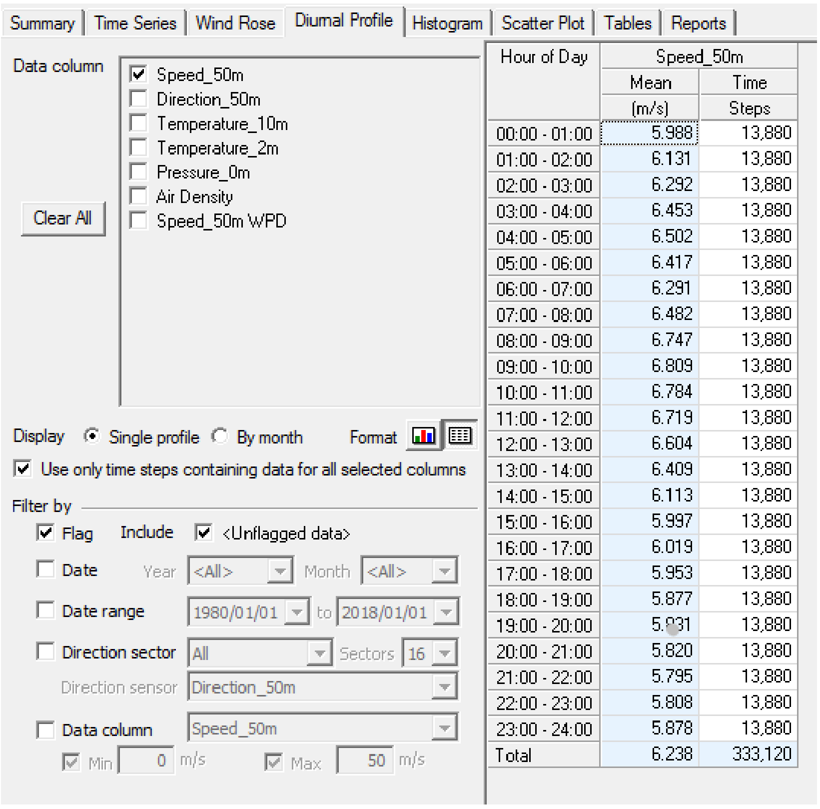


Figure 3.21 Probability distribution of wind speeds for Emntla

The hour of peak wind speed was determined from the Diurnal profile tab which showed mean wind speeds on an hourly basis. The diurnal profile for Emntla is shown in Figure 3.22 below as an example.



Hour of Day	Speed_50m Mean (m/s)	Speed_50m Time Steps
00:00 - 01:00	5.988	13,880
01:00 - 02:00	6.131	13,880
02:00 - 03:00	6.292	13,880
03:00 - 04:00	6.453	13,880
04:00 - 05:00	6.502	13,880
05:00 - 06:00	6.417	13,880
06:00 - 07:00	6.291	13,880
07:00 - 08:00	6.482	13,880
08:00 - 09:00	6.747	13,880
09:00 - 10:00	6.809	13,880
10:00 - 11:00	6.784	13,880
11:00 - 12:00	6.719	13,880
12:00 - 13:00	6.604	13,880
13:00 - 14:00	6.409	13,880
14:00 - 15:00	6.113	13,880
15:00 - 16:00	5.997	13,880
16:00 - 17:00	6.019	13,880
17:00 - 18:00	5.953	13,880
18:00 - 19:00	5.877	13,880
19:00 - 20:00	5.931	13,880
20:00 - 21:00	5.820	13,880
21:00 - 22:00	5.795	13,880
22:00 - 23:00	5.808	13,880
23:00 - 24:00	5.878	13,880
Total	6.238	333,120

Figure 3.22 Diurnal profile of wind speed data for Emntla

From Figure 3.22 above, it is clear that the highest wind speeds for Emntla occurs between 09:00 and 10:00.

These hourly mean values were also used to determine the diurnal pattern strength using the procedure noted in [94]. The procedure noted that the diurnal pattern could be estimated by plotting a bar graph of the measured hourly values and comparing this with the graphs obtained using Equation 3.6, whilst varying the diurnal pattern strength (δ) between 0.1 and 0.4. This procedure is shown for Emntla as noted in Figure 3.23 - Figure 3.26 below.

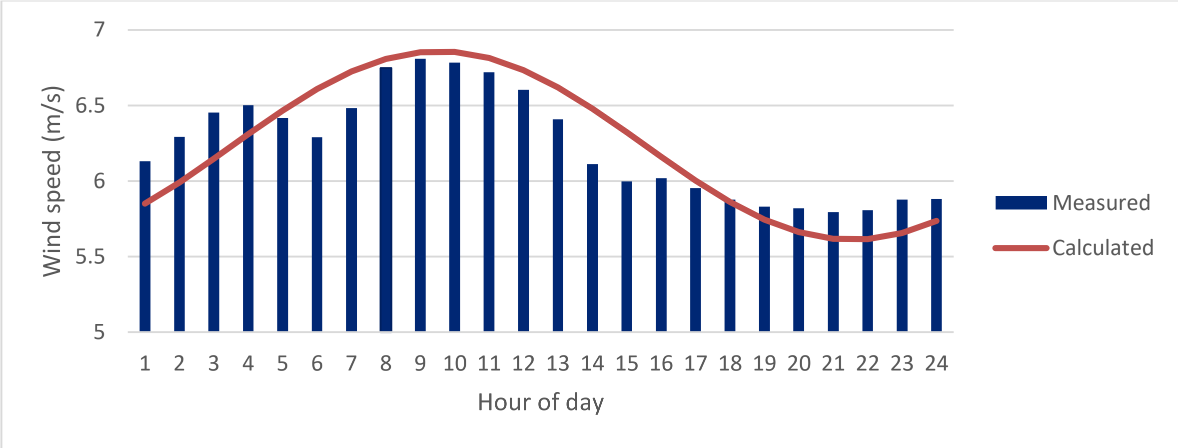


Figure 3.23 Measured vs calculated when diurnal pattern strength is 0.1

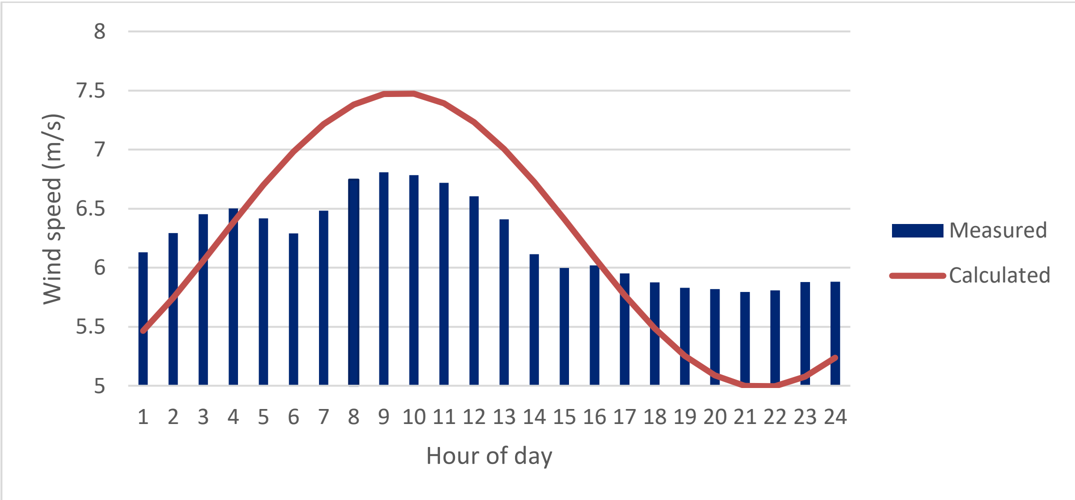


Figure 3.24 Measured vs calculated when diurnal pattern strength is 0.2

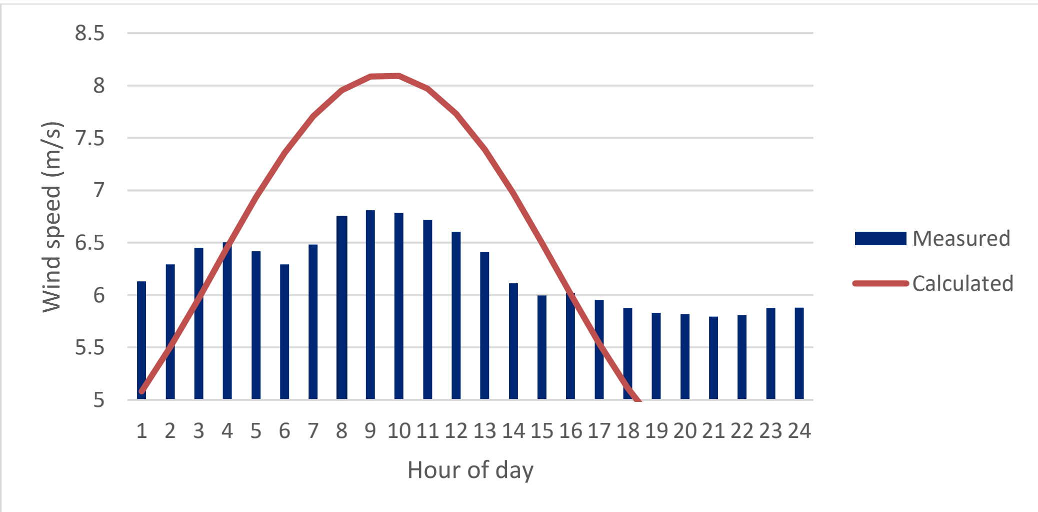


Figure 3.25 Measured vs calculated when diurnal pattern strength is 0.3

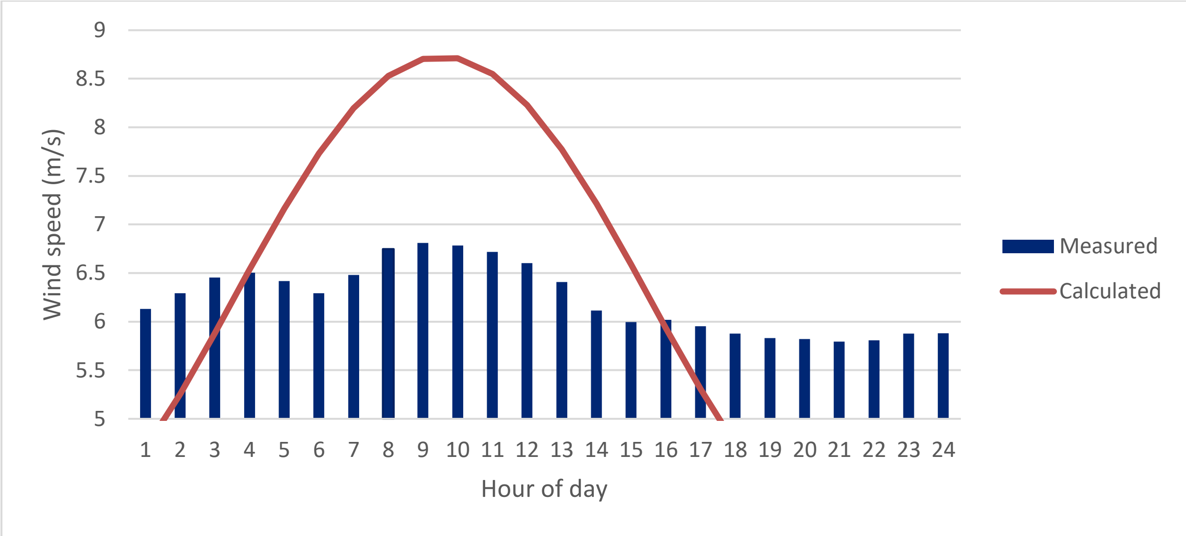


Figure 3.26 Measured vs calculated when diurnal pattern strength is 0.4

Comparing the Figure 3.23 - Figure 3.26, it was noted that the graph resulting from a diurnal pattern strength of 0.1 came closest to matching the measured values at Emntla.

The above mentioned procedures were carried out for all the villages in order to determine the unknown variables. A summary of the parameters for each village are given in Table 3.17 below. An example of the wind speed entered in to HOMER for Emntla village is shown in Figure 3.27.

Table 3.17 Wind synthesis parameters

	De Grens	Emntla	KwanGqikiza
Weibull Factor	2.05	2.03	2.35
One-hour autocorrelation co-efficient	0.75	0.90	0.90
Diurnal pattern strength	0.2	0.1	0.1
Hour of peak wind speed	21:00	09:00	14:00

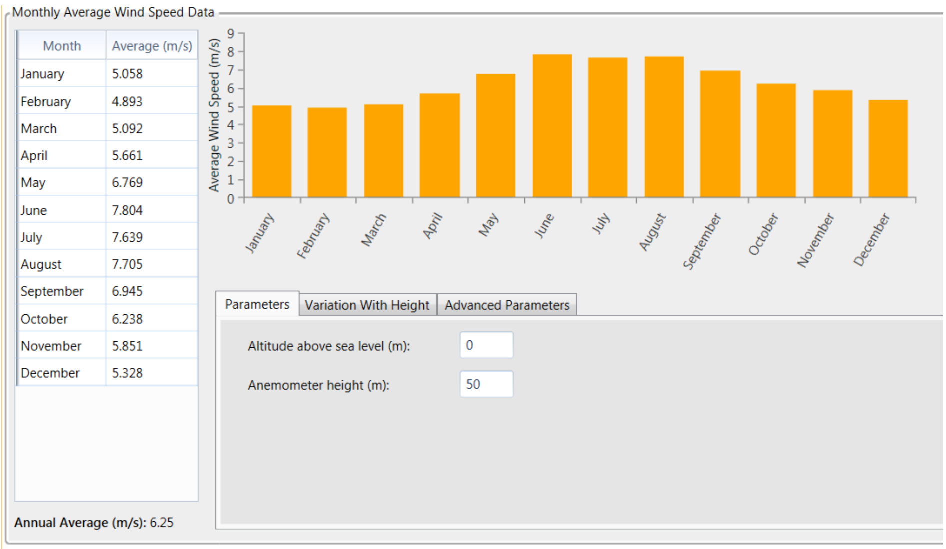


Figure 3.27 **Wind speed input in HOMER**

3.4.3 Stream Flow for microhydro

It was noted in section 2.2.3 that South Africa had promising small scale hydro potential. In order to simulate a microhydro system, HOMER requires monthly flow rate data (in L/s) for a year to be input. This data was freely available in the public domain through the DWAS website. [82]

The DWAS is tasked with being custodian of South Africa's water resources, with their main responsibility being creating and implementing policies within this sector. Part of carrying out this objective is knowing the state of the country's hydrological assets. In order to carry this out the DWAS opened the Resource Quality Information Services (RQIS) directorate.

RQS developed the Water Management system (WMS), an integrated computer system that provided water resource and monitoring information in South Africa. Some of the information provided included chemical water quality, hydrological data, ecosystem data, etc. The hydrological data was collected from approximately 3000 gauging stations on rivers and dams throughout the country. Additionally, the different river systems and their tributaries were mapped. This system and its data was accessible using Google Earth. For the purposes of this dissertation the hydrology data from gauging stations was used to determine the flow rates. [82]

The Google Earth files containing all the data were downloaded from [82]. The files were opened in Google Earth in order to determine the dam/river source closed to the selected village. Furthermore, each source had to have useable flow data in order to be input into HOMER. The measuring station for each village is shown on Google Earth in Figure 3.28 - Figure 3.30 below.

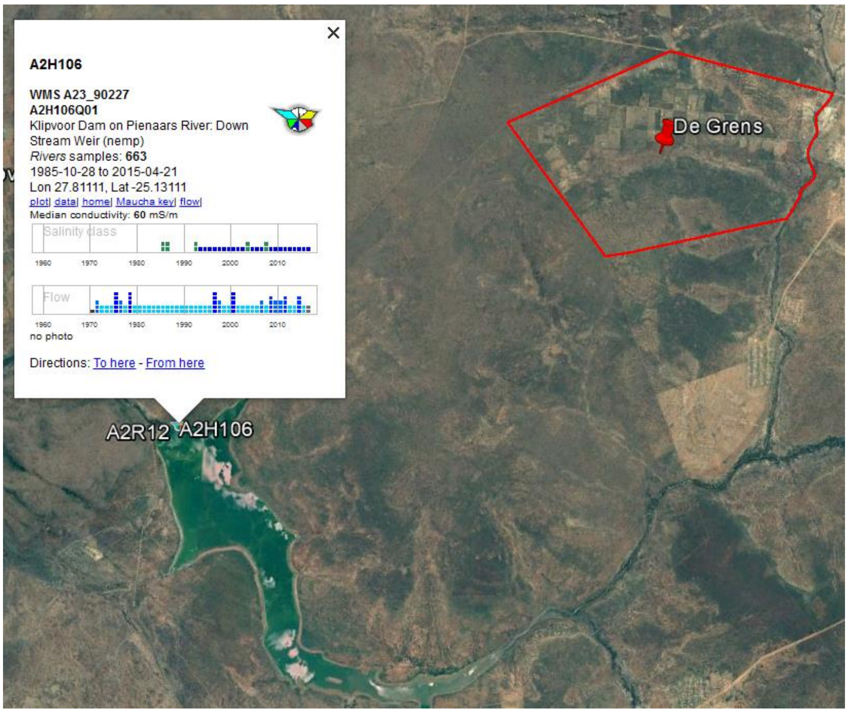


Figure 3.28 Gauge station closest to De Grens

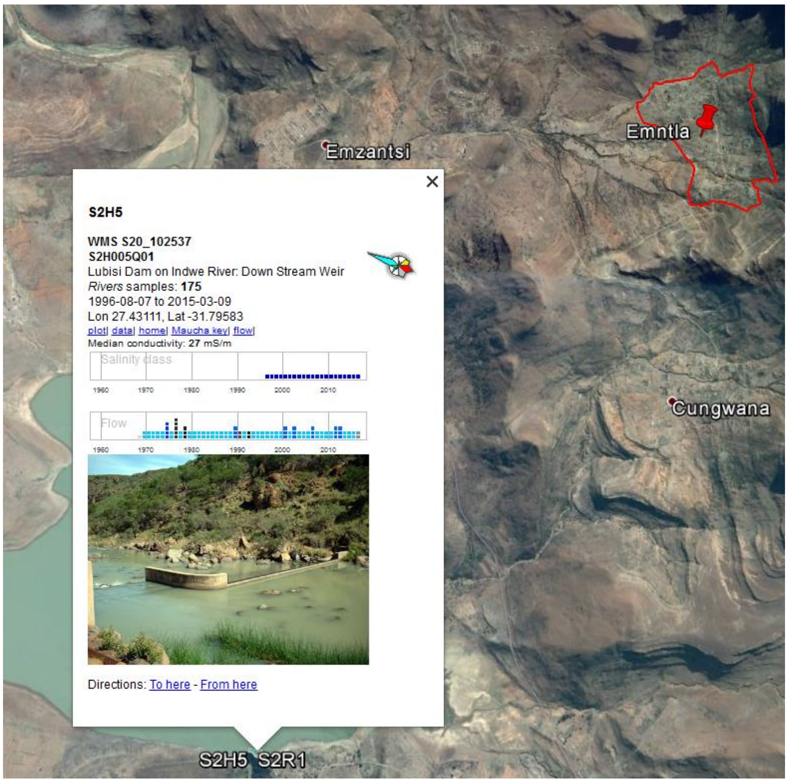


Figure 3.29 Gauge station closest to Emntla

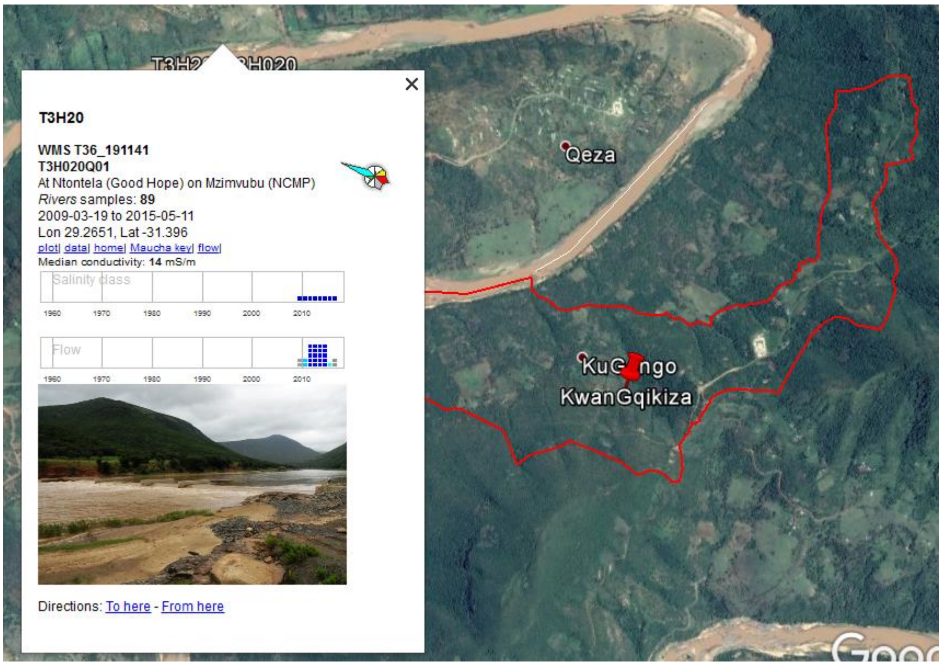


Figure 3.30 Gauge station closest to KwanGqikiza

The closest station to De Grens village is station A2H106 on the Klipvoor Dam. For Emntla, station S2H5 on Lubisi dam is the closest. KwanGqikiza was slightly different as there were no dams situated close to the village, and the T3H20 was the closest station, located on the Mzimvubu river. This station was used as the source even though there was no dam as a run off river system could be implemented for this village, which is a form of microhydro generation as noted in section 2.3.3.2. It was from these stations, that the microhydro data could be selected.

When the station was selected, the flow data could be accessed if available. Some of the stations were built from as early as 1950, meaning they had over 60 years' worth of flow data. However, this was not the case for all the stations. Once the flow option was selected, the raw daily average flow rate was provided as the in m^3/s. The amount of data supplied depended on when the gauge station was built.

In some cases, data was not available throughout the full period from when the gauge station was first built. Furthermore, the data provided was in a daily rate format instead of a monthly rate format. Therefore, in order to extract the data in the correct format, the raw data provided had to be processed. Pivot tables in Microsoft Excel were used to carry out this task. Once the data was placed in the pivot table, the monthly average flow rate for every year since the station was built could be determined. An example of the flow rate pivot table for KwanGqikza is shown in Table 3.18. The last column of the pivot table gives the monthly average flow rate for every year. These values were converted to L/s by multiplying by 1,000, and the results were entered into HOMER.

Table 3.18 Pivot table of flow rate data from Mzimvubu river (KwanGqikiza village)

Average of D AVG F/R	Column Labels								
Row Labels	2009	2010	2011	2012	2013	2014	2015	2016	Grand Total
1		108.6566774	367.2431935	131.1323226	157.4560645	271.4550323	154.4313548	48.17793548	176.9360829
2		100.4636071	214.3769286	124.4707931	158.6690357	389.1167857	114.1877857	81.94468966	168.367904
3		54.11216129	201.333129	78.50019355	134.5493871	263.1095806	55.09774194	72.95116129	122.8076221
4		33.16616667	111.6269	109.1688	308.2177667	49.6002	46.7089	24.55973333	97.57835238
5		13.18722581	55.71780645	22.94067742	92.75041935	22.54429032	13.04693548	11.20712903	33.05635484
6		11.22886667	59.81463333	16.85616667	40.24	12.51986667	7.6808	5.904333333	22.03495238
7		8.027580645	49.26403226	19.14787097	25.31867742	10.46709677	10.28129032		20.41775806
8		5.012	61.25770968	108.56	15.80658065	8.737774194	8.084451613		34.57641935
9	6.65	2.801233333	25.98293333	63.49473333	12.0286	5.475533333	5.7127		17.44939048
10	66.69425806	7.71716129	31.33719355	107.3980323	19.36351613	9.826677419	5.556032258		35.41326728
11	81.00726667	51.4689	17.20416667	139.2937333	34.9719	31.22733333	5.102933333		51.46803333
12	51.40329032	115.4491935	104.274	261.0466129	219.2742258	106.4433226	5.102612903		123.2847512
Grand Total	**51.56345902**	**42.32865205**	**108.0127452**	**98.53703005**	**101.1138795**	**96.79467123**	**35.48775616**	**40.61945604**	**76.07707335**

This process was followed for the other two remaining villages. An example of the river flow entered into HOMER for KwanGqikiza is shown in Figure **3.31**. A comparison of the different flow rates in each village is given in Section 4.2.3.

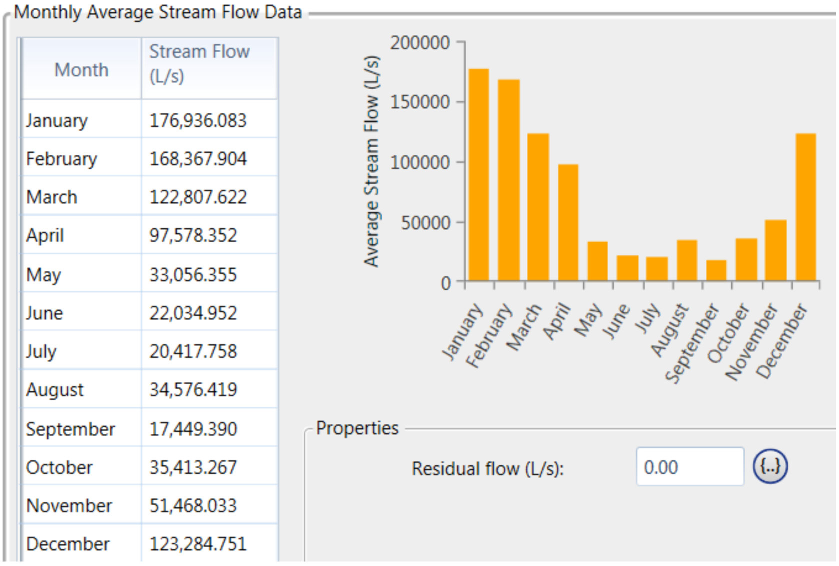


Figure 3.31 **HOMER river flow inputs for KwanGqikiza**

3.5 HOMER Simulation

The previous sections focussed on the load development and the resource assessment of the three selected villages. These were both key components, necessary for the simulations to be carried out successfully on HOMER. The final step of the modelling process was to create the microgrid systems for each village. The procedure followed to carry this out is covered in more detail in the sections to follow.

3.5.1 HOMER System Inputs

Certain system inputs, on HOMER will be common to all the simulated systems irrelevant of the village and the type of renewable resource used, for example the lifetime of the systems. These inputs were found under the Project tab on HOMER. Some inputs were not applicable to the systems modelled; as a result, they were left at their default values. The time step selected for each simulation was 60 minutes, meaning that there were 8760 time steps in a year. The 'Economics' inputs for all the simulated systems are shown in Figure 3.32 below.

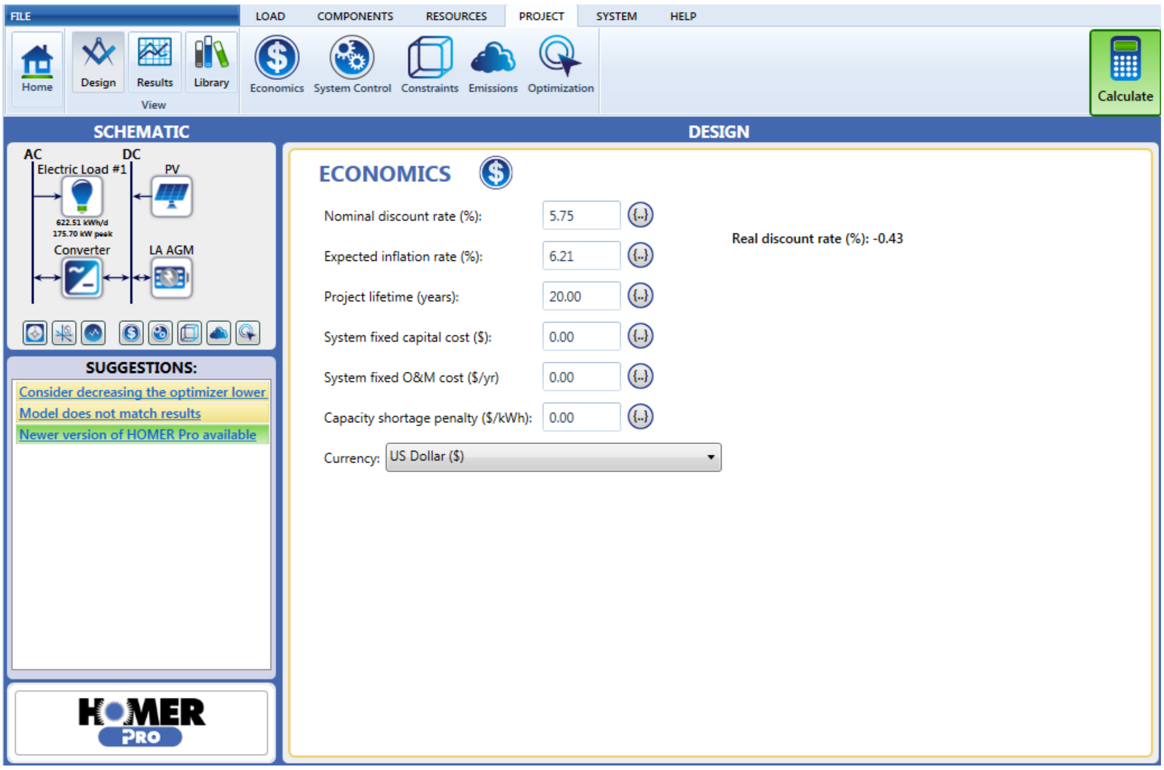


Figure 3.32 Economic inputs for all simulated systems

The nominal discount rate is the rate at which money is borrowed whilst the expected inflation rate is the expected inflation rate over the project lifetime. These two inputs are used to determine the real discount rate which is used to convert between one-time costs and annualised costs. The real discount rate is given by the following formula [81]:

$$i = \frac{i' - f}{1 + f} \qquad (3.7)$$

where,

i – real discount rate

i' – nominal discount rate (5.75%)

f – expected inflation rate (6.25%)

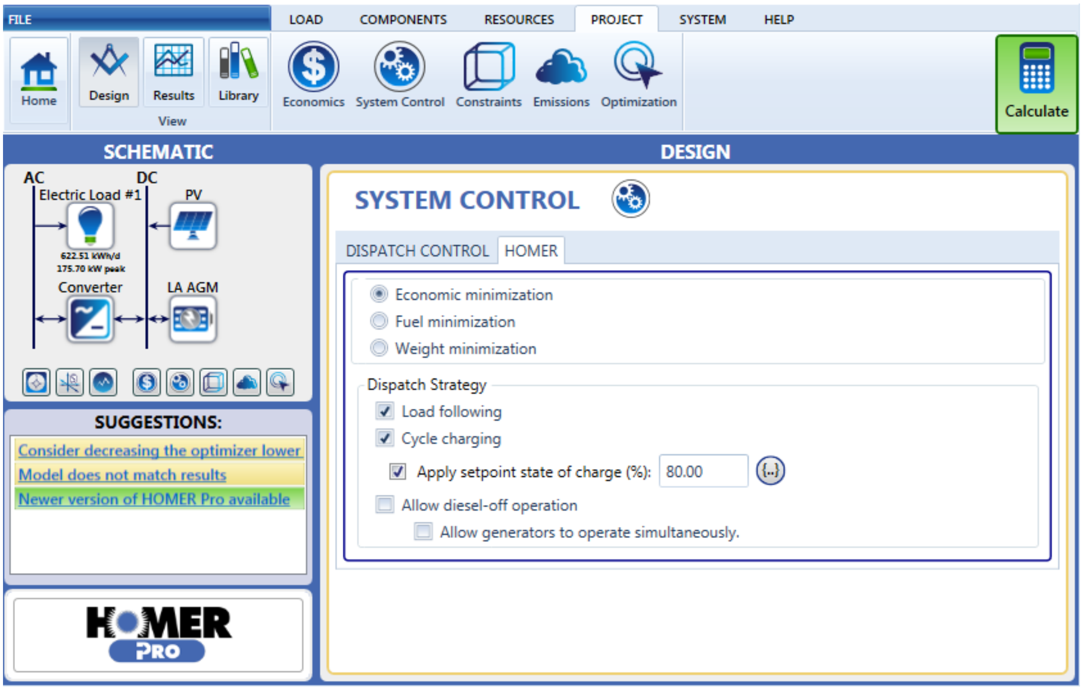


Figure 3.33 System control inputs

The 'System Control' tab allows the user to modify how HOMER carries out the simulations. The settings selected are shown in Figure 3.33 above. The system is set to minimise economic costs. The dispatch strategy, which is defined as the set of rules that govern the operation of the generator and the battery bank were also selected. Both the load following and cycle charging options were selected, meaning that HOMER would run the simulations under both strategies and select the optimal one. In the load following strategy, the generator will follow the load, producing power to meet the demand. In cyclic charging the generator operates at full capacity, charging the batteries with any surplus energy. [81]] We would expect the cyclic charging methodology to be implemented over the load following methodology as surplus energy will be expected and all systems will have a battery bank that can be charged by the extra energy. A set point of 80% is applied under cycle charging so that the batteries are only charged to that level, thereby maintaining their lifetime.

The other system inputs were either left at default values as they were not applicable to the systems being modelled. e.g. system inputs related to grid connection. The modelled systems and the selected components are covered in more detail in the following sections.

3.5.2 PV-Battery Systems

The PV-battery systems for all three villages have the same components in order for fair comparison to be made between the three systems. The block diagram representation of all three systems are shown in Figure 3. below. Each individual component will be analysed in more detail in the following sections.

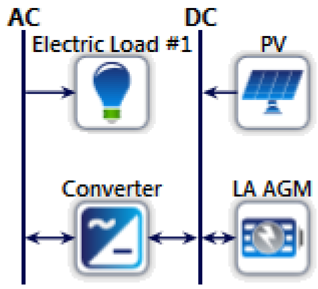


Figure 3.34 PV-battery systems for all three villages

3.5.2.1 PV module

In order to select the PV module for the system, various models and their prices were compared from different trading sites online. The three systems were implemented in South Africa, therefore South African online trading websites were given top priority for finding the components and their related price as this would give a more accurate LCOE and NPC and would be more applicable to the South African context. Prices in South African Rand were converted to United States dollars (USD), in order to make them comparable to other microgrid systems modelled in the literature. The exchange rate used as of July 2017, when the prices were collected was as follows:

1 USD = R14.18

The PV-battery system in Figure 3. only models the primary components of the system. Models for the components of the system such as wiring, mounting structure, etc. were not included in HOMER. Therefore, the cost of these items was added to the cost of the module. A list of modules and their prices are shown in the table below.

Table 3.19 Various modules and their prices

Manufacturer	Model	Size/(W)	Efficiency/(%)	Price/Panel	Price/($/W) incl. tax	Reference
ReneSola	Virtuous II	260	16	239.84	0.92	[95]
Canadian Solar	DYMOND CS6X-315	315	16.14	248.85	0.79	Homer Pro
Hanhwa	Q.Pro-G3-260	260	15.6	226.20	0.87	[96]
Astronergy	CHSM6601P	260	15.8	252.68	0.97	[95]
SDDirect	Enersol 255	255	15.7	215.59	0.85	[95]
Trina Solar	TSM-310 PD14	310	16	274.12	0.88	[95]
Renewsys	Deserv 300	300	15.74	260.51	0.87	[95]
SDDirect	Enersol 255	300	15.5	188.02	0.63	[97]
Renesola	Virtus II	305	15.7	197.39	0.65	[98]
Average					**0.83**	

From Table 3.19, it is noted that the average price of the modules per watt was roughly $0.83/W. The module with the price closest to the average was selected as the module for the PV systems. In this case the Enersol 255 module, manufactured by SDDirect was selected at a price of $0.85/W. The same procedure was followed for the mounting structure as shown in Table 3.20 below.

Table 3.20 Various mounting structures and their prices

Manufacturer	Model	Price/($/W)	Price/($/W) incl. tax	Reference
Empery Solar	EPR-GM-AL	0.09	0.11	[99]
ZY	-	0.08	0.10	[99]
Haining Chuangyuan Solar Energy	-	0.10	0.13	[99]
Valsa	Tensile Cable Flat Ground	0.10	0.13	[99]
UIS Solar	-	0.09	0.11	[99]
Average			**0.12**	

The price of mounting structures in South Africa could not be found, therefore prices from other international websites were used. According to the South African Revenue Authority, goods that are imported into South Africa incur 10% import duty tax. Furthermore, 14% Value Added Tax (VAT) is also incurred. [100] As a result, the price of the mounting structure, including tax was determined considering these factors. The average price including tax was found to be $0.12/W, with the closest mounting structure to this being the structure manufactured by Haining Chuangyuan Solar Energy at a cost of $0.13/W.

According to [101], a report by the South African Photovoltaic Industry Association (SAPVIA) the balance of system (BOS) price was found to be 10% of the PV system cost. Balance of system components consist mainly of wiring but also includes any other small components making up the full PV system. The report also estimated the design and installation costs to be 15% of the PV system costs including preliminary and general equipment such as cranes, forklifts, etc. These costs were combined with the other components that were included with the modules as shown in Table 3.21 below to give the total capital cost of the module.

Table 3.21 Capital cost of module

Component	Price/($/W)	Reference
Module	0.85	-
Mounting structure	0.13	-
Balance of System	0.40	[101]
Design and Installation	0.60	[101]
Total Capital Cost	**1.98**	

The capital costs as well as the technical details of the module obtained from the datasheet were entered into HOMER as shown in the Figure 3.35 below. The module datasheet is also found in Appendix A.

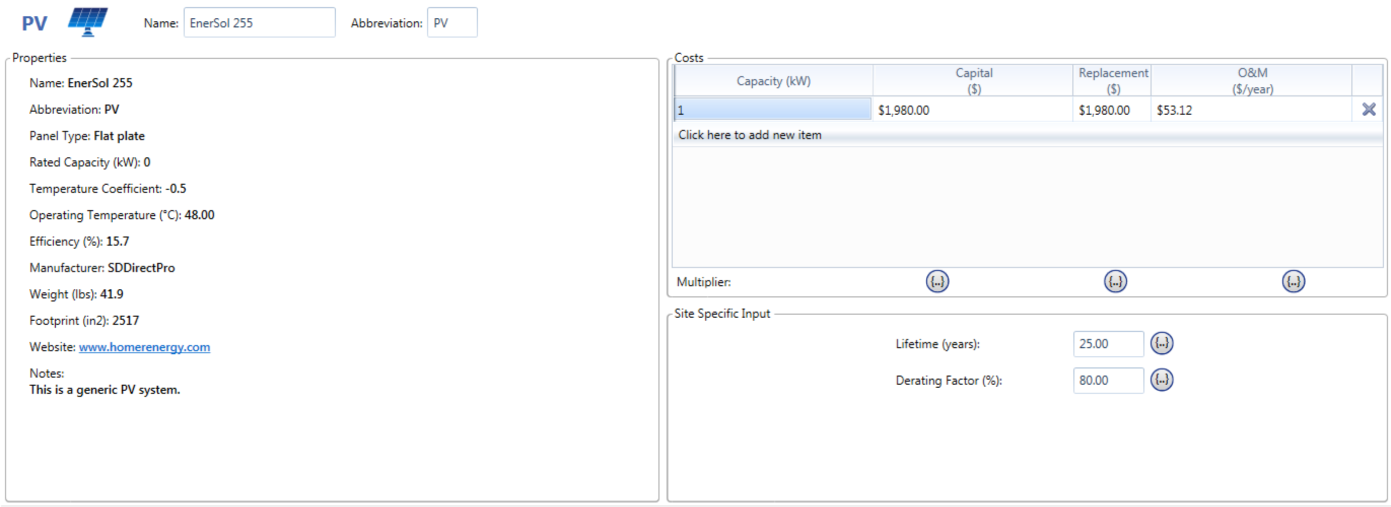


Figure 3.35 PV module inputs for HOMER

The lifetime of the module was 25 years in line with the warranty period. The de-rating factor accounts for real time losses related to PV systems such as soiling, wiring losses, shading, etc. [81] Temperature effects were also considered with the temperature characteristics from the module datasheet being entered into HOMER. The Operations and Maintenance (O&M) cost, obtained from [102], was found to be $53.12/kW per year[3] for a ground mount solar PV plant. The O&M work would typically consist of cleaning the modules, maintaining vegetation, and maintaining the structure, electrical components and buildings on site. The replacement cost was assumed to be the same as the capital cost as a more conservative approach. This will not have an impact on the simulations as the PV module life is longer the plant lifetime, therefore the modules will not be replaced. The next step was to enter the inverter inputs.

3.5.2.2 Inverter

The inverter is essential in this system in order to convert the DC power to useable AC power. There are no AC generation sources for the three types of different systems, therefore an inverter is considered sufficient as electricity will only need to be converted from DC to AC. The same procedure was followed, as in Section 3.5.2.1, to select the inverter, with the first step being finding the price of different inverters as shown in Table 3.22 below.

Table 3.22 Various inverters and their prices

Manufacturer	Model	Size/(W)	Price/($/W) incl. tax	Reference
SMA	Sunny Tripower 25000TL	25,000	0.23	[95]
SMA	Sunny Tripower 20000TL	20,000	0.27	[95]
Chint Power	SCA 3 phase 25kW	25,000	0.22	[95]
MLT drives	Karoo 70KVA	70,000	0.34	[103]
Fronius	Eco 27kW	27,000	0.17	[104]
SMA	Sunny Tripower 20000 TL	20,000	0.23	[104]
Average			**0.24**	

From Table 3.25 it is noted that the average price of the inverters per watt was found to be $0.24/W. The inverter with the price closest to the average was selected for the PV systems. In this case the Sunny Tripower 25000TL converter, manufactured by SMA was selected at a price of $0.23/W.

[3] This was found using an exchange rate of 1USD = R7.56, as of July 2010 when the report was written, from the following website: http://www.xe.com/currencytables/?from=ZAR&date=2010-07-15

Also included under the inverter is the charge controller which according to [101], costs approximately 3.5% of the total PV system price, which is equal to $0.14/W. The total capital cost of the converter as a result, was found to be $0.37/W.

The technical details were entered into HOMER, based on information from the datasheet provided in Appendix A. Additionally, the capital, replacement and O&M cost were also entered as shown in Figure 3.36 below. Even though the prices of inverters are likely to fall with time, the capital and replacement cost are assumed to be the same for these simulations as a more conservative approach. The O&M cost was $0/kW per year as this cost was already covered under the O&M cost of the module. The Rectifier Inputs were kept as default values, as power generated would only need to be converted from DC to AC and not vice versa, therefore a rectifier would not be necessary. The efficiency of the inverter was 98.30% as per the technical datasheet. The life time of the inverters is 10 years. [105]

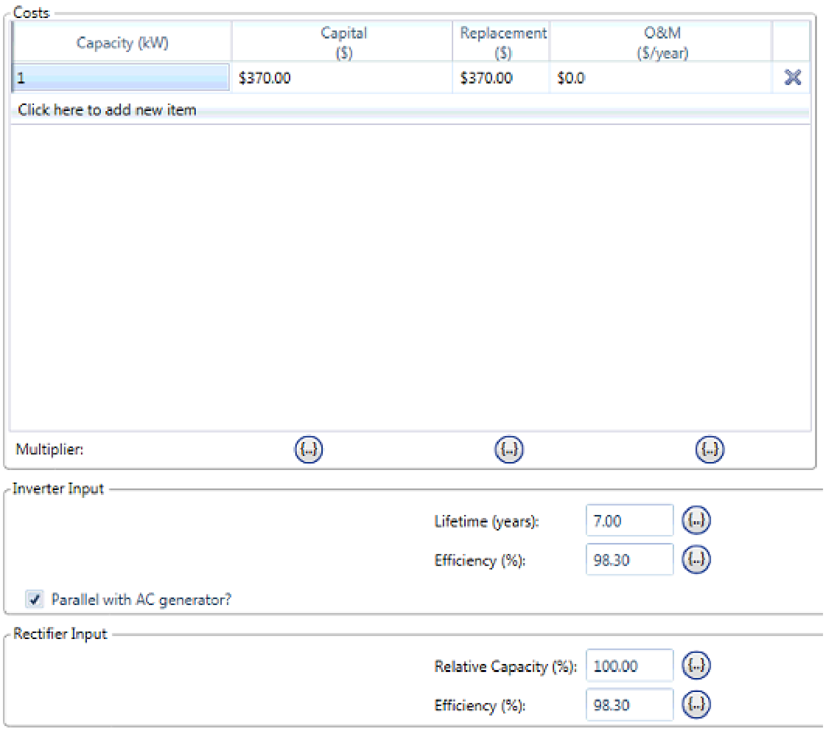


Figure 3.36 Inverter inputs entered into HOMER

3.5.2.3 Battery

The battery is a critical component of this system because it provides storage when the PV modules cannot supply enough power to the load. Any excess power is also used to charge the batteries. The battery was selected following the same procedure used to select the module and inverter. Table 3.23 lists the prices for different batteries.

Table 3.23 Various batteries and their prices

Manufacturer	Model	Voltage/(V)	Size/(Ah)	Price ($/unit)	Price/($/Ah) incl tax	Reference
Deltec	BD125ON	12	102	140.20	1.37	[95]
Maximus	Maintenance free SLA	12	105	129.69	1.24	[95]
Trojan	T1275	12	150	298.38	1.99	[95]
SonX	RA12	12	200	352.75	1.76	[95]

SDDirectPro	AGM G+	12	200	331.45	1.66	[97]
Excis	LA Deep cycle	12	230	238.36	1.04	[97]
Trojan	T1275	12	150	319.25	2.12	[103]
Trojan	L16HC	12	420	495.06	1.17	[103]
AGM	Deep cycle	12	150	255.36	1.70	[97]
Average					**1.56**	

The AGM G+ deep cycle battery manufactured by SDDirectPro was selected for the system. The battery is made of an AGM separator with a gel electrolyte according to the datasheet which is provided in Appendix A. The 12V battery, has an expected design life of 10 years. The lifetime of the battery is dependent on not just time (design life of battery), but also throughput, which assumes that the battery will need replacement after a certain fixed amount of energy cycles. These two variables, time and throughput, can be modelled separately or together in HOMER to determine the storage bank lifetime, as shown in Figure 3.37 below.

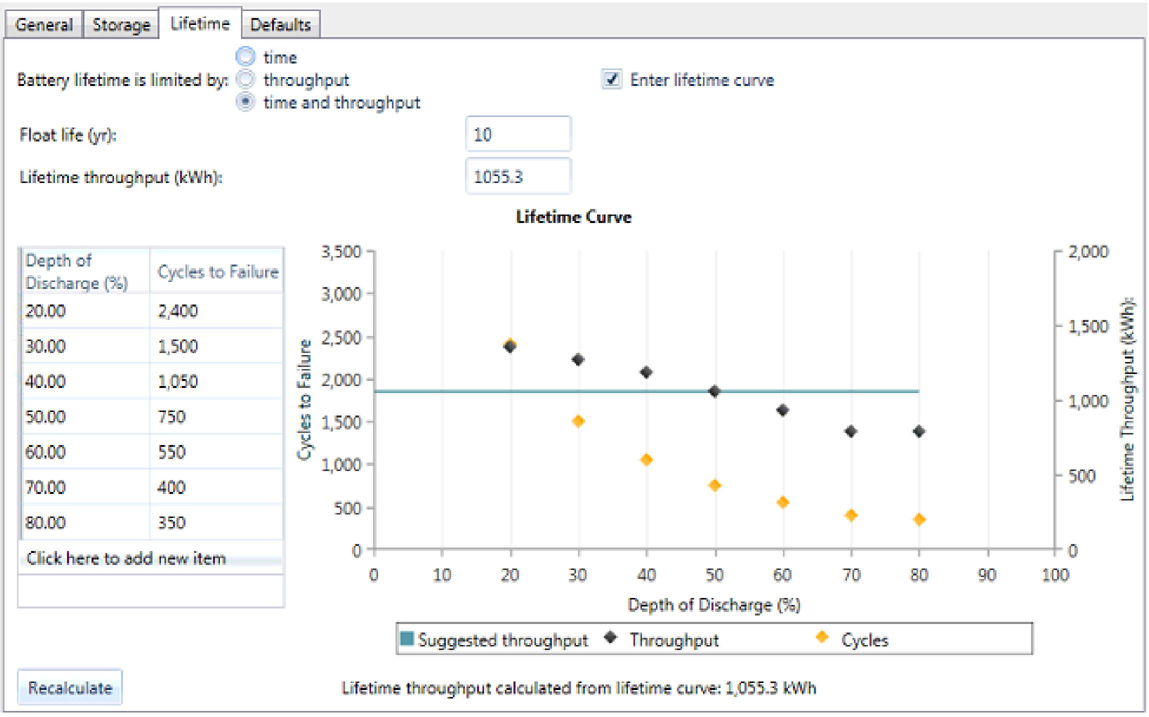


Figure 3.37 Battery lifetime parameters

From Figure 3.38 it was noted that the 'time and throughput' option was selected. The float life was selected as 10 years, in line with battery expected design life. The lifetime throughput was calculated using the lifetime curve. The input values of this curve were obtained from the battery datasheet (provided in Appendix A). Based on the information entered, the battery throughput was found to be 1,055.3 kWh as denoted by the blue line on the graph. The storage battery life time was calculated using the following formula [81].

$$\mathbf{R_{batt} = MIN \left\{ \frac{N_{batt} * Q_{lifetime}}{Q_{thrpt}}, R_{batt,f} \right\}} \qquad \textbf{Equation 3.8}$$

where,

R_{batt} – storage bank lifetime (yr)
N_{batt} – number of batteries in storage bank
$Q_{lifetime}$ – lifetime throughput of a single storage (kWh)
Q_{thrpt} – annual storage throughput (kW/yr)

$R_{batt,f}$ – storage float life (yr)

The nominal battery capacity was also found by plotting the capacity curve using information from the datasheet. The curve was used to determine the maximum capacity, of which HOMER automatically set this to be the nominal battery capacity. The value was found to be 235.41 Ah as shown in Figure 3.38 below.

Figure 3.38 Battery capacity curve inputs

A summary of the details entered into HOMER are shown in Figure 3.39 below.

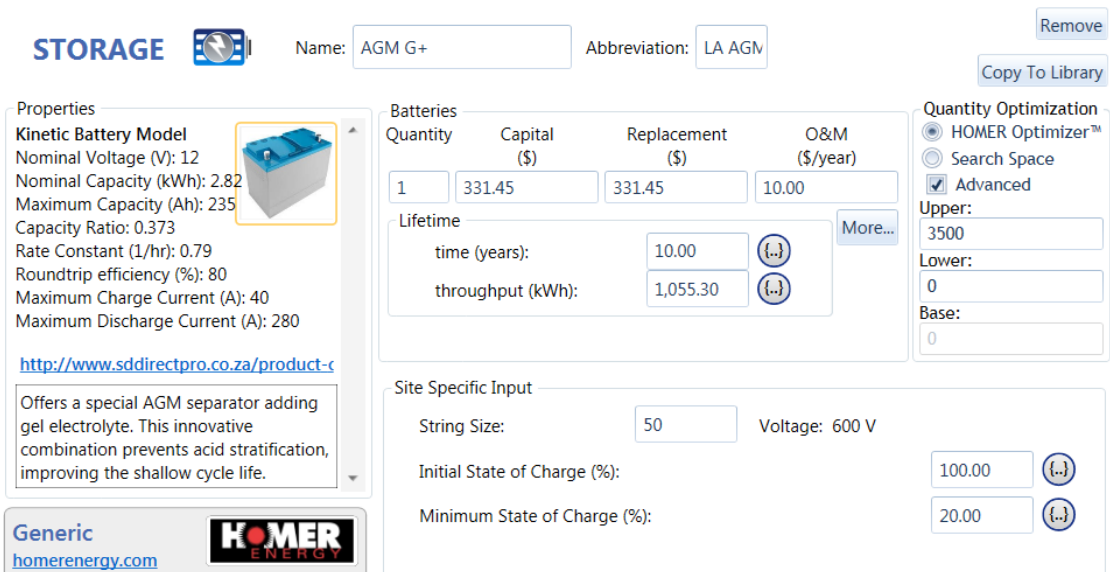


Figure 3.39 Battery characteristics entered into HOMER

The cost of the battery was also added as per Table 3.23 above. The O&M cost of the batteries was $10/year in accordance with [106]. The string size of the battery was selected to be 50. This would mean that the DC bus voltage would be 600V. This DC bus voltage was selected as it is the rated input voltage of the inverter. The initial state of the charge was set at 100% whilst the minimum state of charge was set at 20%, as running the battery to 0% charge would reduce the battery life significantly.

All the components of the PV-battery system were covered in this section. It is noted that the same battery and inverter were used for the wind-battery and microhydro-battery systems. The next section will outline the wind battery system details.

3.5.3 Wind-Battery Systems

The wind-battery system for all three villages are assumed to have similar configuration to the PV-battery systems with the only difference being the renewable generation technology as shown in Figure 3.40 below. The turbines are connected to the DC bus of the system eliminating the need of a converter. The batteries and inverter for the wind systems are the same as those selected for the PV-battery system. The selection process for the inverters and batteries have been covered in section 3.5.2.2 and section 3.5.2.3 respectively.

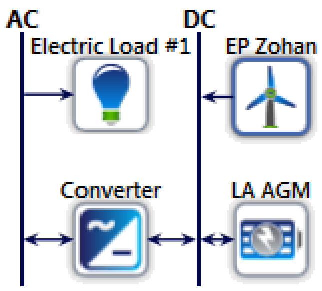


Figure 3.40 Wind-battery system for all 3 villages

According to [107] a report analysing small scale wind energy systems, the cost of a rural, grid connected, pole mounted wind system was broken down in the form of a pie chart as shown in Figure 3.41. This system does not include battery storage.

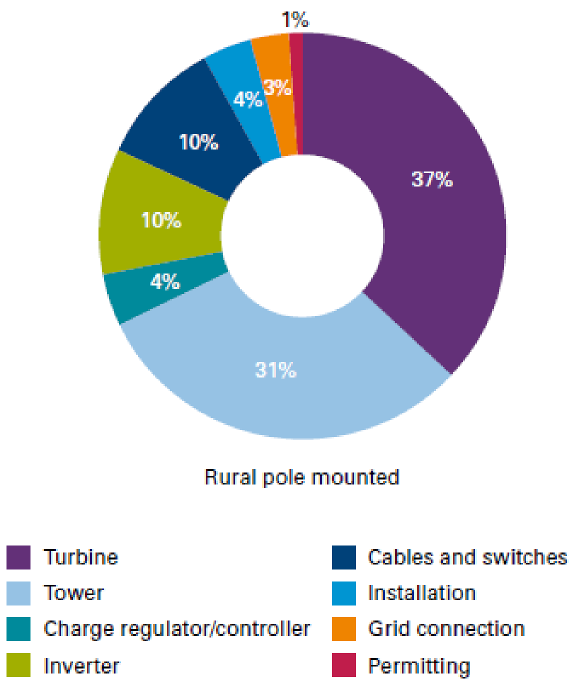


Figure 3.41 Rural grid connected, wind system cost breakdown [107]

The largest costs in the above system are incurred by the turbines and the tower. The pie chart in Figure 3.41 was used as a guideline to determine the cost of turbine, installation and cables and switches. These costs were all included under the wind turbine in HOMER, as was carried out with the costs added to the PV module in section 3.5.2.1. The wind turbine selection and inputs will be covered in more detail in the following section.

3.5.3.1 Wind Turbine

The wind turbine was selected using the same procedure as followed for the components in the PV-battery system. Various turbines and their prices are shown in Table 3.24 below.

Table 3.24 Various wind turbines and their prices

Manufacturer	Model	Size/(W)	Price/turbine	Price/($/W)	Reference
Kestrel	E400N	3500	8744.71	2.50	[103]
Earth Power	Zohan	3000	5616.36	1.87	[103]
Earth Power	Zohan	5000	9368.12	1.87	[103]
Kestrel	E400N	3500	6855.92	1.96	[103]
-	HM7.0	10000	12214.40	1.22	[99]
Average				**1.88**	

From Table 3.24 it was noted that the average price was roughly $1.88/W. The closest turbine to this price was the Zohan 5000, manufactured by Earth Power, at a cost of $1.87/W. The size of the turbine also made it a suitable choice as this would mean less turbines would be necessary due to the higher power rating. The capital cost entered into HOMER also included the other costs mentioned above as shown in Table 3.25 below.

Table 3.25 Capital cost of wind turbine

Component	Price/($)	Reference
Turbines	9,368.12	-
Tower	7,848.96	[107]
Cables and switches	2,531.92	[107]
Installation	1,012.77	[107]
Total Capital Cost	**20,761.77**	

The capital, replacement and O&M costs and the technical details of the selected turbine were entered into HOMER as shown in Figure 3.42 below. The technical data sheet for the turbine is provided in Appendix A. The replacement cost was assumed to be the same as the capital cost as a more conservative approach. The O&M cost was obtained from [102], and found to be $206.35/year for a 5 kW turbine.

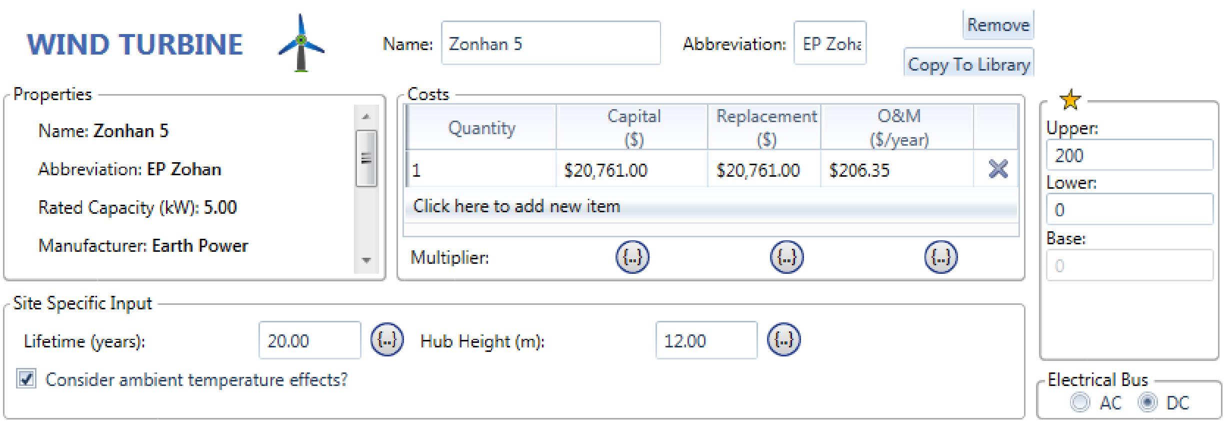


Figure 3.42 Technical characteristics entered into HOMER

The expected lifetime of a turbine is upwards of 20 years, therefore this was selected as a conservative approach [108]. It was also noted that the hub height of the turbine would be 12m, according to the turbine datasheet.

It was noted that the MERRA-2 data provided wind speeds at a height of 50m. The wind speed is affected at lower heights due to obstacles such as buildings, vegetation, etc. HOMER allows the user to translate the wind speed from the measured height to the hub height by using either the power law or logarithmic law. The logarithmic law assumes that the wind speed is proportional to the logarithm of the height above ground and is determined by the following formula [81]:

$$\frac{U_{hub}}{U_{meas}} = \frac{ln\left(\frac{z_{hub}}{z_0}\right)}{ln\left(\frac{z_{meas}}{z_0}\right)}$$ **Equation 3.9**

where,

U_{hub} – the wind speed at the hub height of the turbine (m/s)
U_{meas} – the wind speed at the measured height (m/s)
z_{hub} – hub height of wind turbine (m)
z_{meas} – Measured height (m)
z_0 – surface roughness length (m)

The power law is given by the following equation:

$$\frac{U_{hub}}{U_{meas}} = \left(\frac{z_{hub}}{z_{meas}}\right)^{\alpha}$$ **Equation 3.10**

where

α – the power law exponent

The power law exponent in the Equation $\frac{U_{hub}}{U_{meas}} = \left(\frac{z_{hub}}{z_{meas}}\right)^{\alpha}$ Equation 3.10 above is a dimensionless parameter, which depends on terrain roughness, atmospheric stability, and several other factors. [81]

According to [109], it was noted that there was no significant difference in using either of these laws to predict the hub height wind speed. Furthermore, for the purpose of this research, the prediction model chosen would not really matter as long as it was implemented on all three systems. As a result, the power law was used to model the wind speed at the hub height. The graph of this variation is shown in Figure 3.43 below. Additionally, the power curve for the selected wind turbine was entered into HOMER using the information from the technical datasheet as shown in Figure 3.44 below.

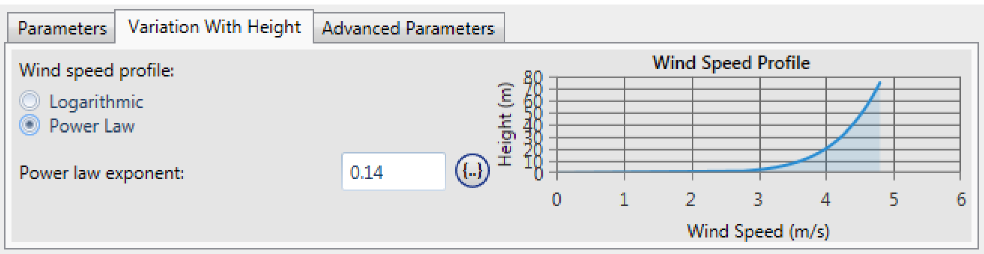


Figure 3.43 Variation of wind speed with hub-height

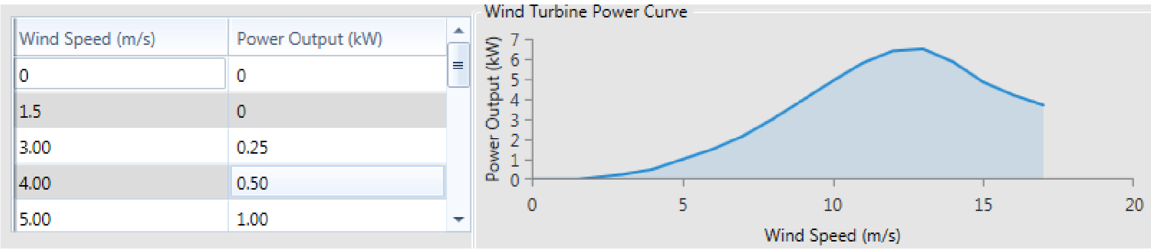


Figure 3.44 Power curve for the selected wind turbine

All the components of the wind-battery system were covered in this section. The next section will outline the microhydro-battery system details.

3.5.4 Microhydro-battery system

It was noted in the previous section that the sources of microhydro power for De Grens and Emntla were the Klipvoor and Lubisi dams, respectively, whilst the Mzimvubu river would be the source of power for KwanGqikiza. The systems for all three villages are shown Figure 3.45 below.

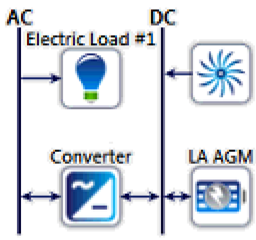


Figure 3.45 Microhydro-battery system for all three villages

The inputs for the battery and inverter have been addressed already, therefore only the microhydro turbine inputs need to be analysed. The hydro inputs for KwanGqikiza are shown in Figure 3.46 below.

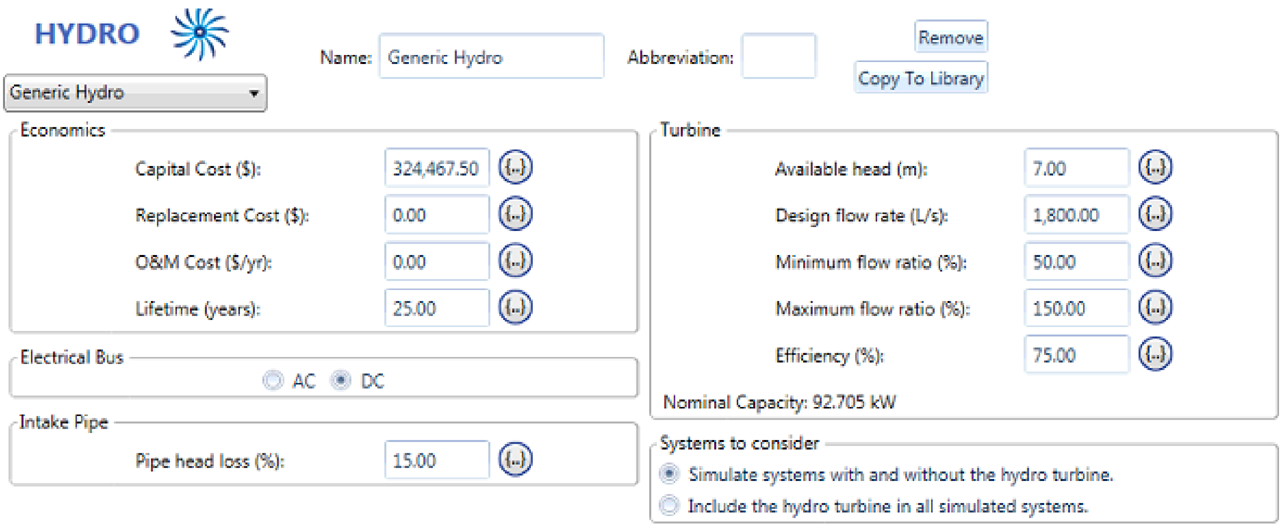


Figure 3.46 Microhydro turbine inputs

Figure 3.47 gives an example of the inputs required. The turbine characteristics are different for each village due to the different site specific characteristics. The turbine inputs for each village are shown in Table 3.26 below.

Table 3.26 Microhydro turbine inputs

Turbine Input	Description	De Grens	Emntla	KwanGqikiza
Head (m)	Vertical drop between intake and turbine.	14.5	32.5	10
Design Flow Rate (L/s)	The flow rate the turbine is designed for.	1,500	1,200	3,550
Min flow ratio (%)	The minimal flow rate of the hydro turbine, as a percentage of its designed flow rate. Any flow rate below this value will mean that no power is generated by the turbine.	50	50	50
Max flow ratio (%)	The maximum flow rate of the hydro turbine, as a percentage of its designed flow rate. Additional flow, beyond this maximum value will not increase the turbine input.	130	150	110
Efficiency (%)	The efficiency with which the hydro system converts the energy in the water to electricity	75	75	75
Nominal Capacity (kW)		160.03	203.25	261.19

The head for De Grens and Emntla in Table 3.29 was obtained from information from the DWAS. The information provided noted the water level height for both dams from 1970 for De Grens and 1969 for Emntla. The average was found and used as the head height. For KwanGqikiza, a different approach was taken as there was no existing dam. A low head, run-off the river system is envisaged for this area. The head was determined using Google Maps. A line (green) on google maps was drawn along the river close to the village as shown in the Figure 3.47. The elevation profile was used to determine the vertical height difference at the start and end of the line. This vertical distance was used as the head for KwanGqikiza.

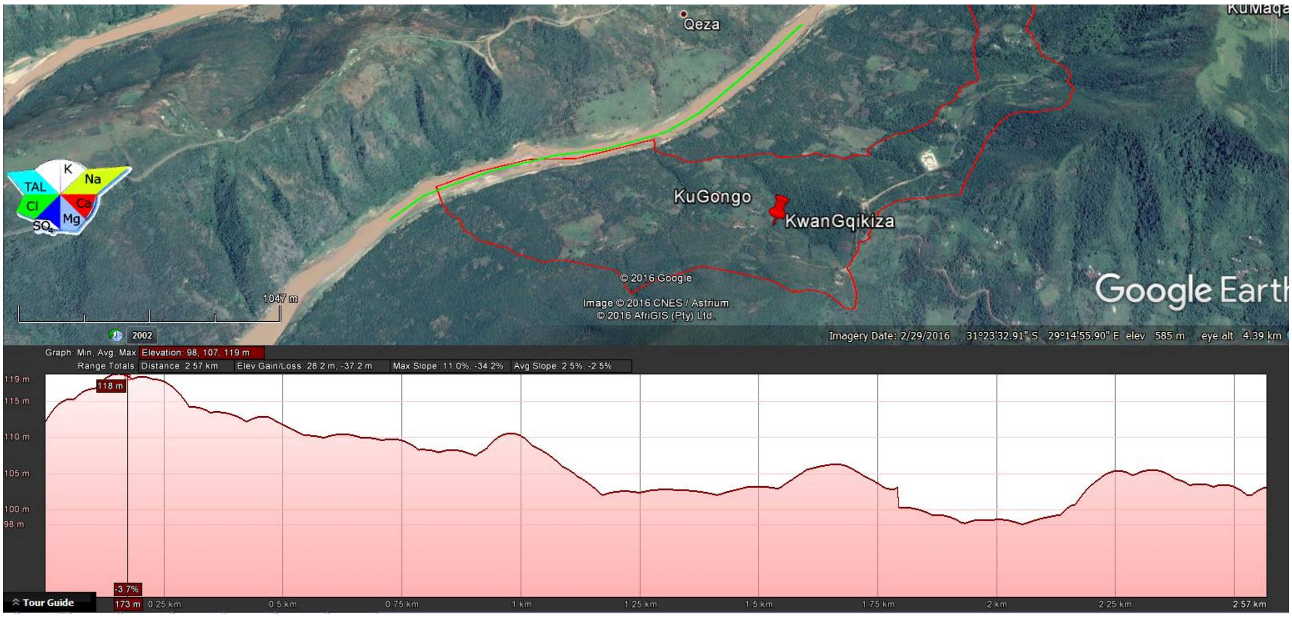


Figure 3.47 Obtaining the head for KwanGqikiza

The design flow ratio was obtained by calculating 50% of the minimum flow rate and adding this to the minimum amount for De Grens and Emntla. Due to the excessive flow at KwanGqikiza, the design flow rate was calculated such that the nominal capacity of the system was less than the load as the turbines have the ability to run above the rated capacity as mentioned below.

The minimum flow ratio was left as default of 50% whilst the maximum flow rate was adjusted depending on the flow rate of the river. i.e. a dam with a faster flow rate does not require a higher maximum flow ratio whilst a dam with lower flow rate will. The selected flow rates were with the maximum default value range of 150%.

The efficiency of hydro systems according [61]is between 70% and 90%. A value of 75% was selected as small scale systems are typically expected to be less efficient than large scale systems.

The head and design flow rate were used to determine the nominal capacity of the microhydro system using the following formula.

$$P_{nom} = \frac{n_{hyd} \times \rho_{water} \times g \times h \times Q_{design}}{1000}$$

where,
P_{nom} – nominal power output of the hydro turbine (kW)
n_{hyd} – hydro turbine efficiency (%)
ρ_{water} – density of water (1000kg/m^3)
h - available head (m)
Q_{design} – the design flow rate of the hydro turbine (m^3/s)

Even though the systems for all three villages were the same, the systems at De Grens and Emntla already have existing dams where as a low head, run-off the river system would need to be implemented at KwanGqikiza. This will have different cost implications as less infrastructure will need to be built in the case of the villages with existing dams. However, if the cost of building a run-off system is included for KwanGqikiza, then it will lead to an imbalanced comparison between the different microhydro systems as dam construction costs are not considered for the other villages. As a result, two cases of the microhydro systems for all three villages will be modelled. The first will include the cost of building the dam/river run-off system at KwanGqikiza the other excluding this cost in order to be comparable with the other microhydro systems.

According to [110], the cost break down of a low head system and high head system for new sites differ as noted in Figure 3.48 below.

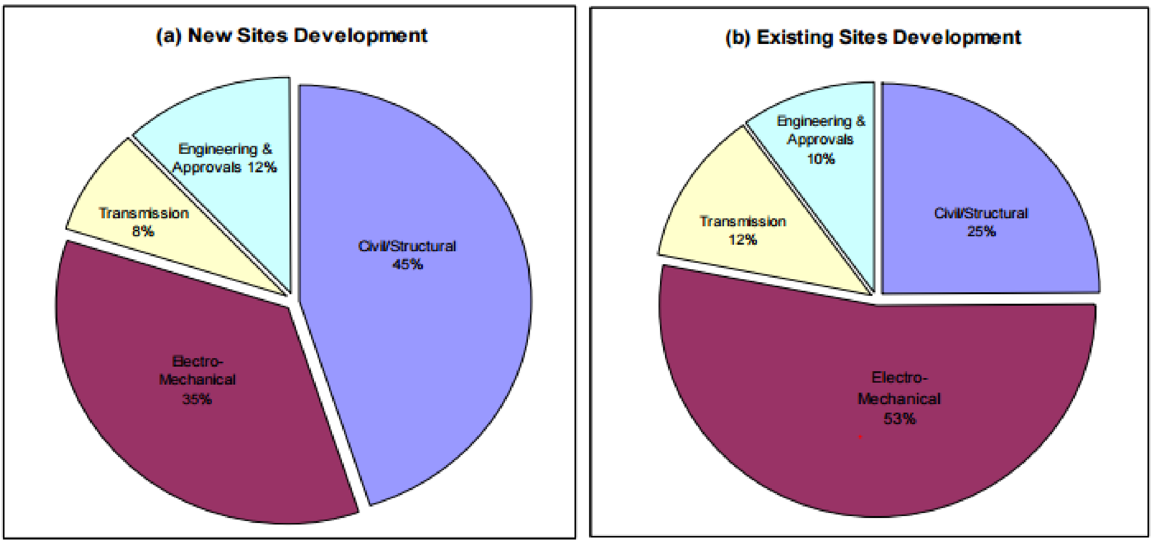


Figure 3.48 Cost comparison breakdown of a new site and an existing site [110]

It is noted that the civil construction works make up a considerable portion of the cost for both sites, however it is more significant for the new site development.

According to [111], the cost of implementing a small scale hydro system on a site with an existing dam can be as low as $500/kW, whilst on the other had a site without adequate infrastructure can cost as much as $3,000/kW – 4,000/kW. The cost of small hydro systems in developing countries was also given in [111] and is shown in Figure 3.49 below.

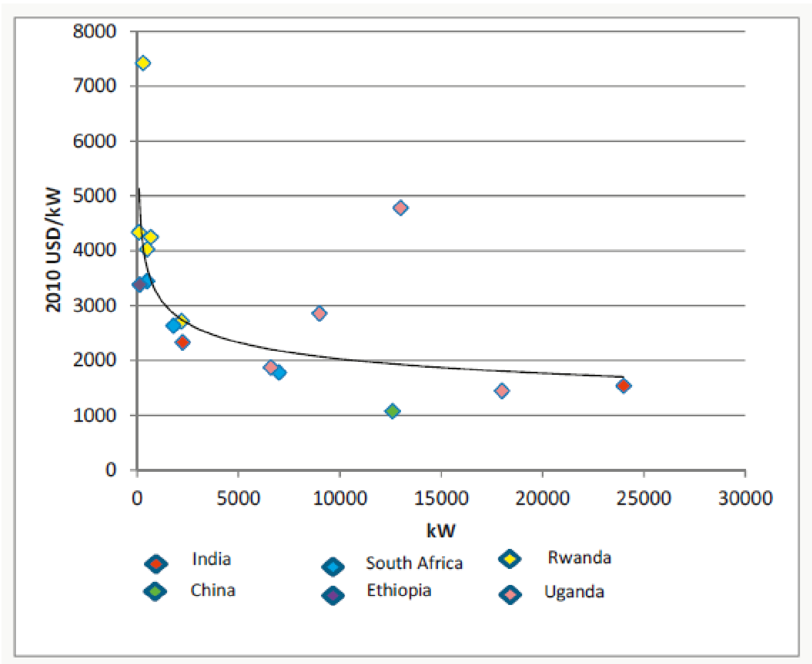


Figure 3.49 Cost of small hydro systems in developing countries [111]

Figure 3.49 notes the price of small hydro systems in South Africa. The South African markers were used as a guideline to determine the cost. The hydro systems for the three villages are not greater than 300kW, therefore this was used as baseline size. Based on this size a cost of $4,500/kW was selected for a new site. A cost of $500/kW was used for sites with an existing dam. The capital cost was obtained by multiplying the hydro capacity in Table 3.26 by these two prices. As a result, two Capital costs were reported in Table 3.27 below. The replacement cost was left as zero, as it was not anticipated that the plant would be replaced during the lifetime of the system. Once built, maintenance is required to keep the plant running efficiently. According to [111] the annual cost of O&M ranges from 1% – 4% of the capital cost of the hydro system (assuming the cost of constructing a dam). This capital was used in order to include maintenance of the dam and not just maintenance of the hydro turbines, which would be the case if the capital cost (assuming a dam exists) was used. A figure of 4% was noted as being appropriate for small scale systems, therefore this is used to obtain the O&M cost. A summary of the economic inputs are given in Table 3.27 below.

Table 3.27 Summary of micro hydro economic inputs

	De Grens	Emntla	KwanGqikiza
Capital Costs (assuming a dam exists)	81,615	101,626	130,595
Capital Costs (assuming a dam does not exist)	720,117	914,630	1,175,360
Replacement Costs	-	-	-
O&M Costs	28,805	36,585	47,014

The process followed in designing the systems simulated in HOMER have been elaborated in this section. Furthermore, the economic and technical inputs used were analysed with motivation being provided on the final values selected. The next step is to propose a number of test cases in order to investigate different scenarios and situations in line with the proposed research. This is covered in the next section.

4 Case Studies

The process followed in designing the systems simulated in HOMER were covered in the previous section. Furthermore, the economic and technical inputs used were analysed with motivation being provided on the final values selected. This section focusses on the selection of test cases for the purpose of investigating different scenarios and situations in line with the proposed research. Three test cases are proposed as follows:

- Case 1 – Renewable technology comparison
- Case 2 – Village system comparison

HOMER has a wide variety of output information that will aid the analysis for each study. LCOE and NPC have been analysed, however these only provide insight from an economic point of view. Other outputs will need to be analysed in order to determine suitability of each system from a technical point of view.

4.1 HOMER Outputs

A table of outputs that will be used to analyse the case studies are given in the table below.

Table 4.1 HOMER outputs

Output	Description
Excess electricity	This is the amount of additional electricity generated when the full load is met.
Capacity factor	This is given by dividing the average power generated by rated peak power.
Capacity	The capacity of the systems will be compared against the load demand.
Batteries	
Lifetime Throughput	The total amount of energy that can be cycled through the storage before it needs to be replaced
Annual throughput	The total amount of energy that cycled through the storage bank during the year
Expected life	The number of years the storage bank will last before it requires replacement
Autonomy	The capacity of the storage bank divided by the average electrical load
State of Charge	A Dmap showing the batteries state of charge over the course of the year, will be used to compare the battery banks in all the systems.
Economics	
Salvage Cost	The value remaining in a component of the power system at the end of the project lifetime.
LCOE	Covered in section 3.1
NPC	Covered in section 3.1

4.2 Case 1: Renewable technology comparison

In this case study, each independent renewable technology will be compared against the same technology in each of the other villages e.g. all the wind systems in all the villages will be compared against one another. The same will be done with all the solar and microhydro systems. This will determine how the strength of the resource will affect the implementation of each system Since 3 technology variables (solar, wind and microhydro) were used, only 3 comparisons will be carried out.

4.2.1 Solar PV Systems

The same components were used in each PV system in order to carry out fair comparison with the other villages. This meant that the difference in cost between all the systems would be due to the strength of the resource in each area. The difference between the GHI values for the three villages is given in Table 4.2 below. Additionally, a comparison of the GHI for each of the villages is given in Figure 4.1.

Table 4.2 GHI of selected villages (kWh/m²/day)

Month	De Grens	Emntla	KwanGqikiza
January	6.77	7.05	5.55
February	6.22	6.36	5.35
March	5.69	5.45	4.74
April	4.97	4.50	4.08
May	4.57	3.76	3.52
June	4.15	3.29	3.00
July	4.52	3.53	3.26
August	5.17	4.46	3.88
September	6.09	5.36	4.61
October	6.26	6.10	4.86
November	6.56	6.82	5.35
December	6.79	7.33	5.62
Average	**5.65**	**5.33**	**4.49**

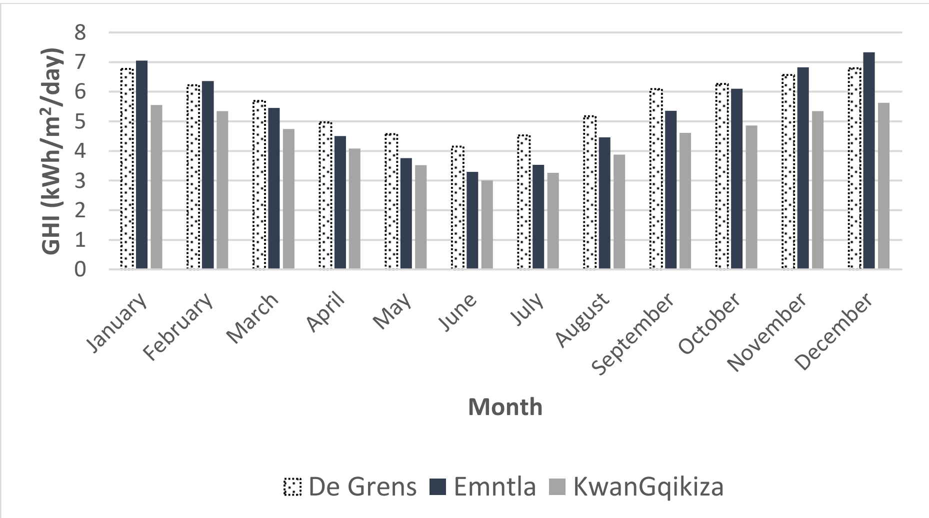


Figure 4.1 GHI comparison of the 3 villages

It was noted from the table 4.1 and figure 4.2 De Grens had the highest irradiation, since it was specifically selected to be the solar village. The irradiation at Emntla was slightly lower whilst the KwanGqikiza had the lowest irradiation. There were some months where Emntla had a higher irradiation than De Grens, however overall, the average for De Grens was greater.

4.2.2 Wind Systems

As with the solar PV systems, the components used on the wind systems in each village were all similar. As a result, the difference in cost between all the systems would be due to the strength of the resource in each area as well as the slight size difference between the villages. The difference between the wind speeds in the three villages is given in Table 4.3 and Figure 4.2 below.

Table 4.3 Wind speed of selected villages (m/s)

Month	De Grens	Emntla	KwanGqikiza
January	4.35	5.08	5.51
February	4.35	4.95	5.41
March	4.03	5.08	5.27
April	3.97	5.67	5.33
May	3.93	6.77	5.73
June	4.19	7.77	6.35
July	4.26	7.59	6.29
August	4.99	7.64	6.33
September	5.49	6.91	6.07
October	5.47	6.16	6.25
November	5.03	5.79	5.97
December	4.42	5.33	5.67
Average	**4.53**	**6.24**	**5.85**

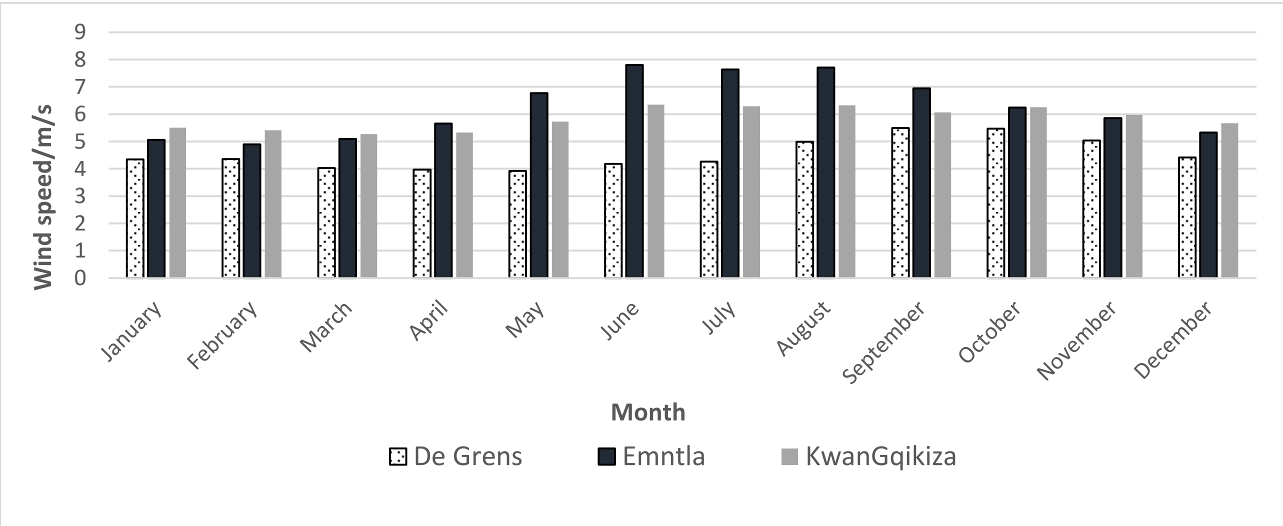


Figure 4.2 Wind speed comparison of the 3 villages

A comparison of the wind speeds in the 3 villages is shown in Figure 4.2 above. As expected, Emntla has the fastest wind speed since it was located in an area of strong wind resource. KwanGqikiza follows closely after, whilst De Grens had the slowest wind speed. It was also noted that the wind speeds in Emntla and KwanGqikiza peaked in Winter whilst for De Grens it peaked in the beginning of summer.

4.2.3 Microhydro Systems

The same components were used in each microhydro system to carry out fair comparison with the other villages. This comparison will be split into two parts. The first will assume that a dam exists at all three villages even though one does not exist at KwanGqikiza. This assumption is made in order to make a fair comparison between the microhydro systems. The second assumes that no dams exist at any of the villages therefore the cost of constructing a dam is included in the model. From this comparison, the effect of the capital cost of building a dam on the overall system costs and LCOE will be determined. The results will feed into the second case study where the wind, solar and microhydro technologies are compared against one another. Then it will be determined whether the cost of implementing a microhydro system with dam infrastructure is more economical than implementing PV or wind systems.

A summary table of the results input into HOMER and a graph comparing the different flow rates of the water sources closest to each village is shown in Table 4.4 and Figure 4.3 below.

Table 4.4 Flow rate data of selected villages (L/s)

Month	De Grens	Emntla	KwanGqikiza
January	6,645.57	1,244.48	176,936.08
February	9,414.80	2,805.38	168,367.90
March	4,159.42	3,743.93	122,807.62
April	2,824.06	1,704.82	97,578.35
May	1,226.55	1,642.74	33,056.35
June	1,020.03	658.26	22,034.95
July	1,265.90	633.37	20,417.76
August	1,612.42	946.56	34,576.42
September	2,342.17	703.43	17,449.39
October	1,813.76	702.04	35,413.27
November	1,540.48	927.77	51,468.03
December	3,172.04	843.75	123,284.75
Average	**3,086.43**	**1,379.71**	**75,282.57**

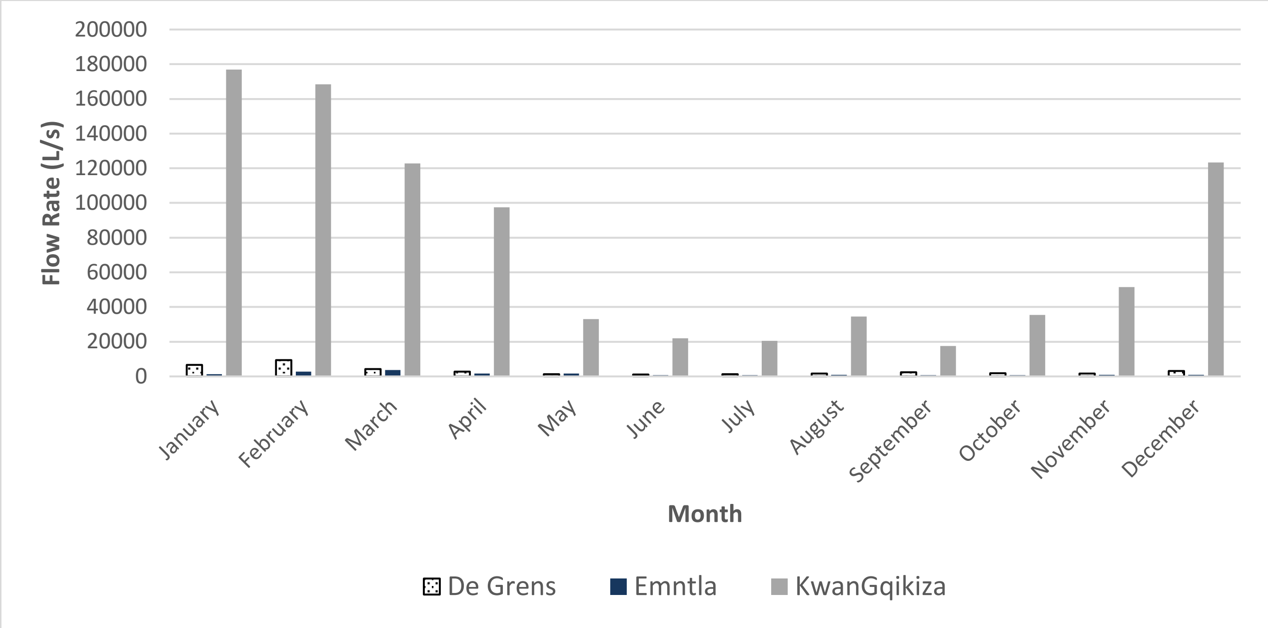


Figure 4.3 Flow rate comparison of the 3 villages

From the graph in figure 4.3 and table 4.4 it is clear that the flow rate of Mzimvubu river is well above the flow rates of both the dams close to Emntla and De Grens village. The higher flow rate will mean a smaller head will be required to generate the required power. The flow rate of Emntla is generally slower than De Grens, with the average flow rate being approximately 5 times less.

4.3 Case 2: Village System Comparison

In this case study, the different renewable technologies, i.e. the solar, wind and microhydro system in each village will be compared against each other to determine the best system to implement for each respective village. Each village was selected in an area of either strong solar, wind or microhydro resource as explained in section 3.2. The resource parameters for each village are detailed in the following sections. From this case study we will be able to determine whether the strongest resource in the area will dictate the type of system to be implemented. i.e. if the areas strongest resource is solar, whether this means that a solar energy system must be implemented on site.

4.3.1 De Grens

De Grens village was selected for its strong solar potential as noted section 3.2.1. A summary of the average annual resource measurements is noted below:

- Solar irradiation – 5.65 kWh/m2/day
- Wind speed – 4.53 m/s
- Flow rate – 3086.43 L/s

The load parameters for De Grens are covered in section 3.3.3.

4.3.2 Emntla

Emntla village was selected for its strong wind potential as noted section 3.2.2. A summary of the average annual resource measurements is noted below:

- Solar irradiation – 5.33 kWh/m^2/day
- Wind speed – 6.24 m/s

- Flow rate – 1379.71 L/s

The load parameters for Emntla are covered in section 3.3.3.

4.3.3 KwanGqikiza

KwanGqikiza village was selected for its strong hydro potential as noted section 3.2.3. A summary of the average annual resource measurements is noted below:

- Solar irradiation – 4.49 kWh/m2/day
- Wind speed – 5.85 m/s
- Flow rate – 75282.57 L/s

The load parameters for KwanGqikiza are covered in section 3.3.3.

The results from the case study will show how much of an impact the strongest resource of a given area has on the LCOE and NPV of the different systems in each village. As a result, it can be determined whether the type of technology selected needs to be in line with the strongest resource in the area or whether it can be selected regardless of the strongest resource.

5 Results and Discussion

Chapter 4 presented the case studies carried out for this dissertation. The results from the HOMER simulations in line with these studies are provided below.

5.1 Case 1

5.1.1 Solar PV

A summary of the economic and technical results for the respective PV system in each village are given in Table 5.1 and Table 5.2 below.

5.1.1.1 Economic Analysis

The economic analysis results are given in Table 5.1 below.

Table 5.1 Economic results of the PV systems of each village

HOMER Output	De Grens	Emntla	KwanGqikiza
LCOE ($/kWh)	0.3715	0,3776	0.4322
NPC ($)	1,621,624	1,909,171	2,616,299
Salvage Cost ($)	293,034	330,551	415,437
Operating Cost ($/year)	47,899	56,851	73,478

According to the information in Table 5.1 above, De Grens has the cheapest LCOE at $0.3715/kWh followed by Emntla with $0.3776/kWh and KwanGqikiza with $0.4322/kWh. The NPC followed the same trend with De Grens being the cheapest at $1,621,624, whilst KwanGqikiza was the most expensive at $2,616,299.

In terms of LCOE, the results are as expected since the costs are in line with the strength of the solar resource in each area, with De Grens having the strongest annual average irradiation of 5.65kWh/m^2/day, hence the cheapest LCOE, whilst KwanGqikiza had the lowest annual average irradiation of 4.49 kWh/m^2/day, hence the highest LCOE. It can be argued that the size of the different systems as given in Table 5.2 overleaf, may have had an impact on the LCOE as the LCOE increased with the increasing system sizes. It is noted, however, that this is not the case according to the definition of LCOE which is a levelised cost. Therefore, the increased size is factored out by the increased demand/load of each village. Furthermore, the fact that the same equipment was used across all systems confirms that the difference in LCOE is due to the difference in irradiation only.

The NPC and Operating Cost followed the same trend; however, we cannot conclude that this was due to irradiation. The NPC correlates directly to the system size i.e. the bigger the system, the more equipment and O&M activities required, therefore leading to a higher NPC. The NPC is determined by adding the Capital, Replacement and O&M cost and subtracting the Salvage cost from the total. A breakdown of the costs for each village as a fraction of the total NPC is given in Figure 5.1. According to Figure 5.1, the Replacement cost was the biggest contributor to the NPC for all three villages, followed by the Capital cost.

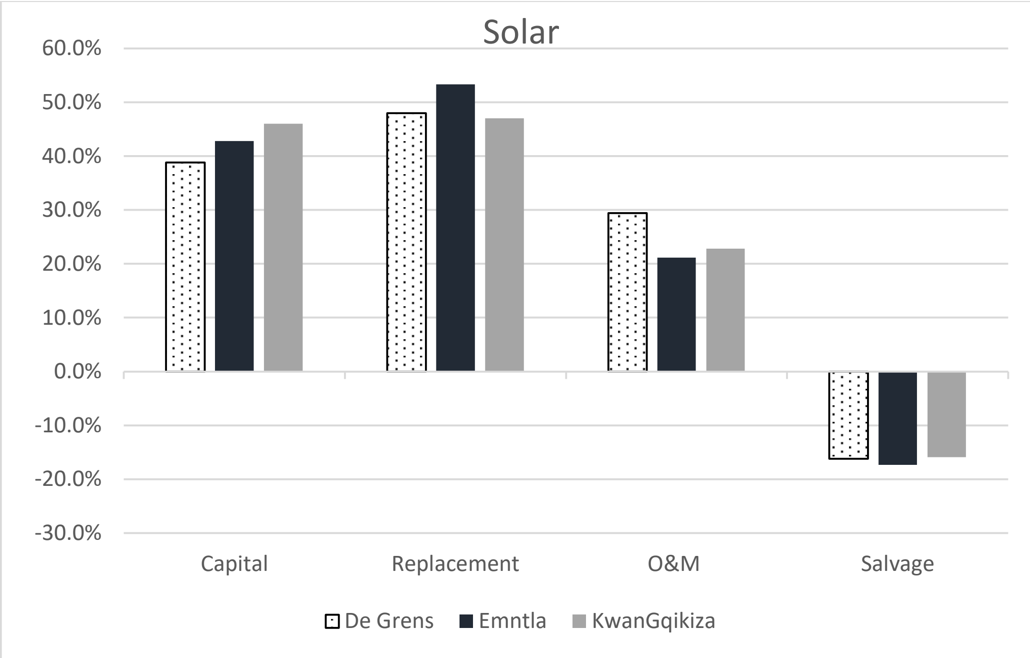


Figure 5.1 Breakdown of costs for each village

A breakdown of the costs for each component over the 20 year lifetime of the system for De Grens, Emntla and KwanGqikiza is shown in Figure 5.2, Figure 5.3 and Figure 5.4 respectively. At year 7, 13 and 19 for Emntla and KwanGqikiza and at year 7, 13 and 20 for De Grens, it is noted that a significant cost is allocated to AGM G+ batteries. This additional cost can be attributed to the replacement of batteries at each of those periods which clarifies the high replacement costs for the villages. Batteries have a shorter lifetime as compared to the other PV system equipment and therefore must be replaced regularly. From Figure 5.2 below, it is noted that a small portion of batteries in De Grens are replaced for a third time at Year 20 as opposed to a large portion being replaced at Year 19 as shown in the other two villages in Figure 5.3 and Figure 5.4 overleaf. The reason for this is that the batteries in De Grens have a long expected lifetime. This is covered in more detail in Section 5.1.1.2. The only other component that was replaced was the converter, which was replaced at year 10 for all villages. The modules have a 25 year lifetime and therefore are not expected to be replaced during the lifetime of these systems.

The positive money gain at the end of the system life (year 20), represents the salvage cost. It is noted that the highest salvage cost for Emntla and KwanGqikiza was from the batteries, whilst for De Grens the salvage cost was due to the solar panels.

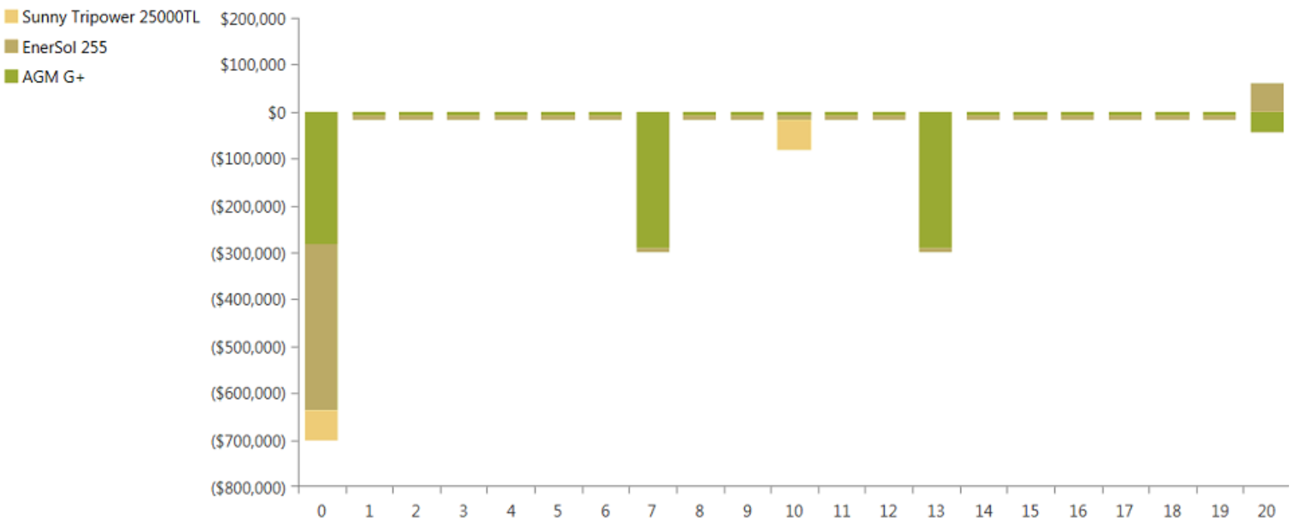


Figure 5.2 Breakdown of component costs over system lifetime in De Grens village

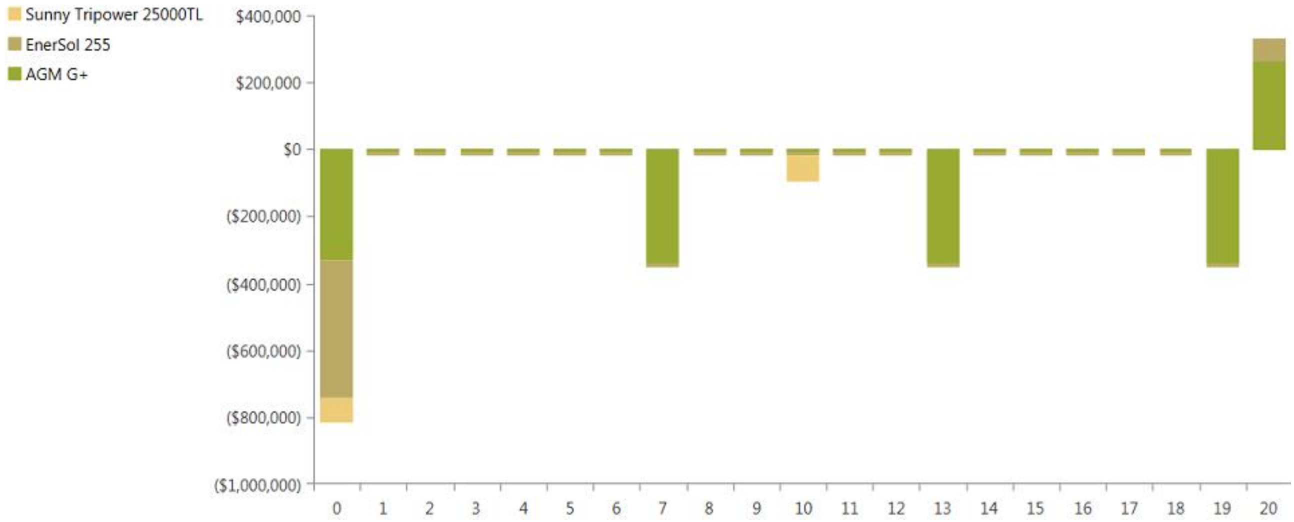


Figure 5.3 Break down of component costs over system lifetime in Emntla village

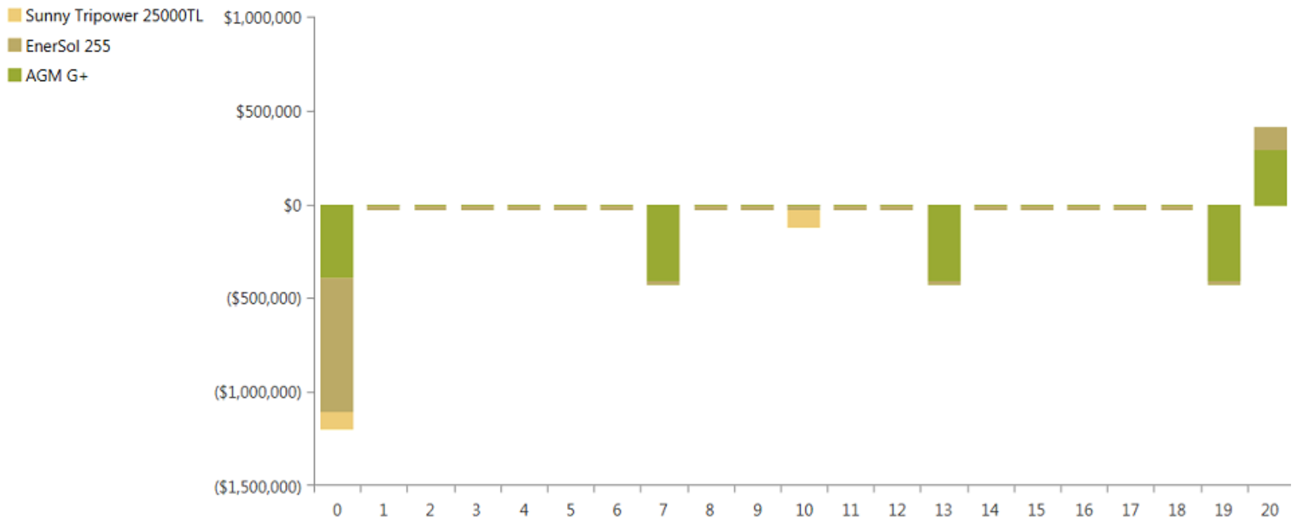


Figure 5.4 Break down of component costs over system lifetime in KwanGqikiza village

5.1.1.2 Technical Analysis

The technical analysis results are given in Table 5.2 below.

Table 5.2 Technical analysis results of the PV systems of each village

HOMER Output	De Grens	Emntla	KwanGqikiza
System			
Peak load (kW)	175.73	210.37	261.05
Average load (kW)	25.94	30.05	35.99
AC primary load (kWh/year)	227,183	261,155	315,054
Capacity factor (%)	18.9	18.9	15.7
Total module production (kWh/year)	297,408	344,430	493,374
Excess electricity (%)	11.9	11.5	26.0
Dispatch Strategy	Cyclic Charging	Cyclic Charging	Cyclic Charging
PV Modules			
DC capacity (kWp)	179	209	359
Mean Output (kW)	34	39.3	56.3
Mean Output (kWh/d)	815	944	1,352
Converter			
AC capacity (kW)	175	200	259

Mean output (kW)	25.9	30.0	36.0
Batteries			
Number of batteries	850	1,000	1,200
Strings in parallel	17	20	24
Nominal capacity (kWh)	2,401	2,825	3,390
Usable Nominal capacity (kWh)	1,921	2,260	2,712
Autonomy (h)	74.1	75.2	75.4
Annual throughput (kWh/year)	140,324	167,338	204,492
Lifetime throughput (kWh/year)	897,005	1,055,300	1,266,360
Expected life (years)	6.39	6.31	6.19
Losses (kWh/year)	31,313	37,368	45,617

The results in Table 5.2 above can be analysed to point out the technical differences between the three PV systems for the three villages. It is noted that each of the systems made use of the cycle charge dispatch strategy which is in line with our expectations, given that batteries were the primary source of energy in the evenings. It was mentioned earlier that the system sizes were different, due to the population difference in each village. As expected, this has led to each village having a differing installed DC (modules) and AC (converter) capacity.

Each system generated excess electricity in relation to their loads, with the system at De Grens generating 11.9% extra, whilst the one at Emntla generated 11.5% extra and at KwanGqikiza generated 26% extra. The excess electricity generated is due to the system being oversized to account for the spike in load demand due to the high-powered stove in every household. i.e. even though the peak scaled load for De Grens is 179kW, the average load is only 25.9kW. This is shown in the load DMap for De Grens in Figure 5.5 below. A DMap is a type of graph showing one year of time series data, with time of day on y-axis and day of the year on the x-axis. Each time step of the year is represented by a rectangle which is coloured according to the data value, which in this case represents the village load. [81] The three light blue bands with hints of yellow and green correspond to the time of day when the stove is being used. The DC capacity for De Grens is 179kWp, which is in line with the peak load but well above the average load. This is explains the excess energy generated, and occurs in each village for the same reason.

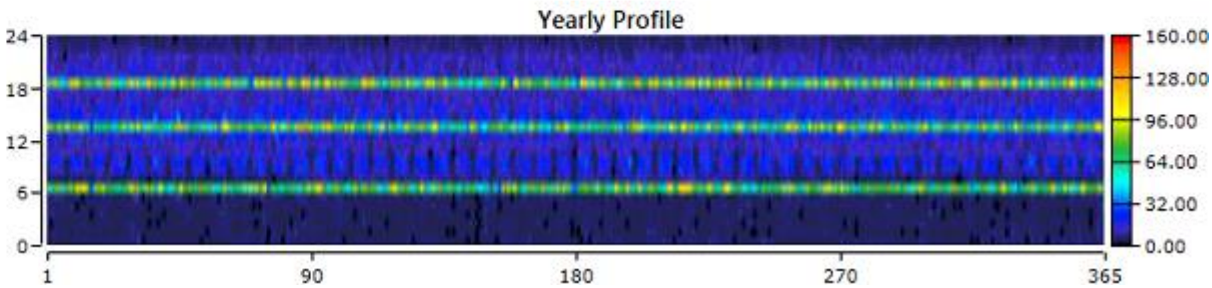


Figure 5.5 Load DMap for De Grens

The capacity factor for De Grens and Emntla was 18.9%, whilst KwanGqikiza had a lower capacity factor of 15.7%. The low capacity factors are in line with what we would expect of a solar PV system, as the plant does not generate for half the day during evening hours. The capacity factor for KwanGqikiza is lower than the other two villages by 3.2%. This difference can be attributed to the lower irradiation in the area, meaning a lot more modules are required to provide the given amount of energy.

The DC module capacity is above the peak load for each village. This is as expected as the excess electricity is also required to charge the batteries. The mean converter output (kW) is in line with the average load as expected. The AC converter capacity, however is below the peak load for Emntla and

KwanGqikiza. Analysing the results for these two villages more closely, it is apparent that the peak load exceeded the AC capacity for a few hours in November only. This difference is considered to be negligible as the load is not met for a very short period.

The batteries were the main contributors to the overall system cost as stated in Section 5.1.1.1 above. The battery bank at De Grens had the highest expected life, although the difference between the other villages was marginal.

DMap (data map) graphs were used to show the state of charge of the batteries for De Grens, Emntla and KwanGqikiza are shown in Figure 5.6, Figure 5.7 and Figure 5.8 respectively.

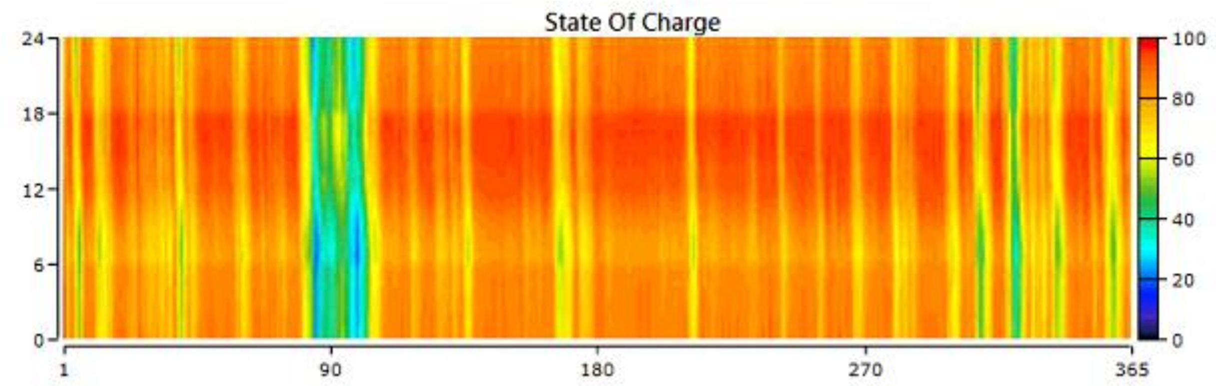


Figure 5.6 Battery state of charge DMap for De Grens village

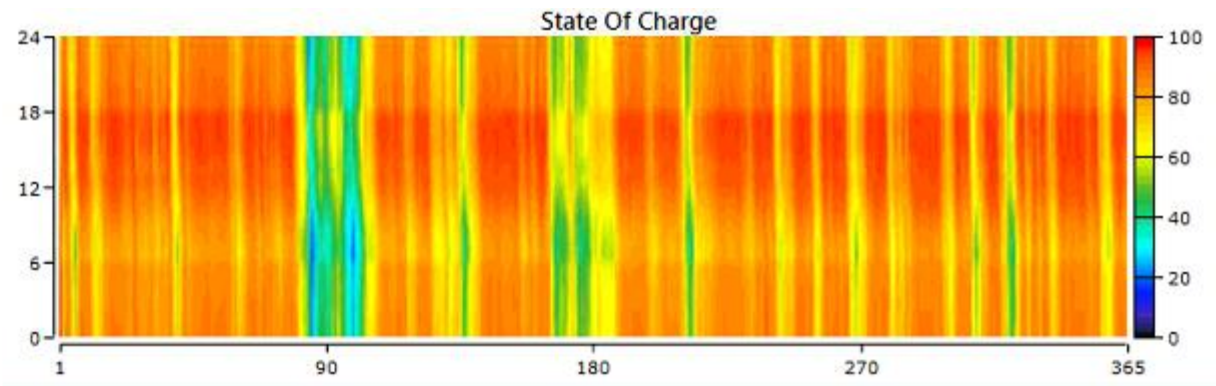


Figure 5.7 Battery state of charge DMap for Emntla village

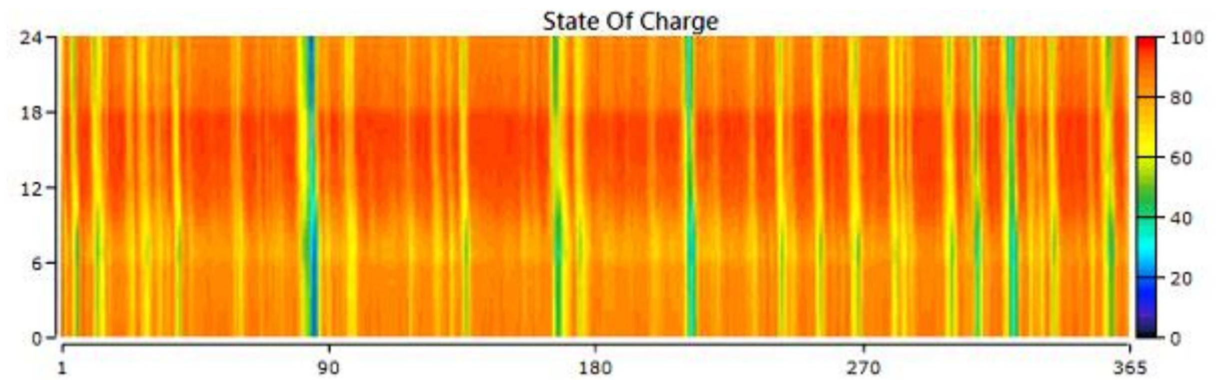


Figure 5.8 Battery state of charge DMap for KwanGqikiza village

The battery banks for all three villages discharge to below 40% around day 90, however this discharge is more notable for De Grens and Emntla.

During the year, the battery bank at KwanGqikiza discharges to below this 40% level more frequently than the other villages even though it is the biggest (village?). This shows that there are a greater number of periods where the on-site irradiation is insufficient to power to the village hence the more frequent battery usage.

5.1.2 Wind

A summary of the economic and technical analysis results for the respective wind systems in each village are given in Table 5.3 and Table 5.4. below.

5.1.2.1 Economic Analysis

The economic analysis results are given in Table 5.3 below.

Table 5.3 Economic analysis results of the wind systems of each village

HOMER Output	De Grens	Emntla	KwanGqikiza
LCOE ($/kWh)	0.7137	0.4172	0.4421
NPC ($)	3,114,700	2,108,603	2,676,150
Salvage cost ($)	187,482	0	0
Operating Cost ($/year)	46,286	39,800	52,190.96

From the results, De Grens has the most expensive LCOE at $0.7137/kWh followed by KwanGqikiza at $0.4421/kWh and Emntla with $0.4172/kWh. The NPC followed the same trend with De Grens being the most expensive at $3,114,700, whilst Emntla was the cheapest at $2,108,603.

In terms of LCOE, the results are as expected and the costs are in line with the strength of the wind resource in each area. Emntla had the strongest mean wind speed, hence the cheapest LCOE, whilst De Grens had the lowest wind speed hence the highest LCOE.

The NPC and operating cost followed the same trend. In the previous section which dealt with PV systems, it was seen that the NPC was affected by the size of the demand for each system and not only solar irradiation; hence it was expected that the same would be observed for wind systems as well. However, this was not the case for the wind systems in each village. If this was the case, then KwanGqikiza should have had the highest NPC whilst De Grens would have had the lowest. On the contrary, De Grens had the highest NPC cost at $3,114,700 even though it had the least demand, whilst Emntla had the lowest NPC at $2,108,603. It is clear that the NPC for the wind systems are largely influenced by the level of wind resources in each village, which clarifies why, Emntla had the lowest NPC. A breakdown of the costs for each village as a fraction of the total NPC is given in Figure 5.9 below. From the results, we can see that the Capital cost was the biggest contributor to the NPC for all villages.

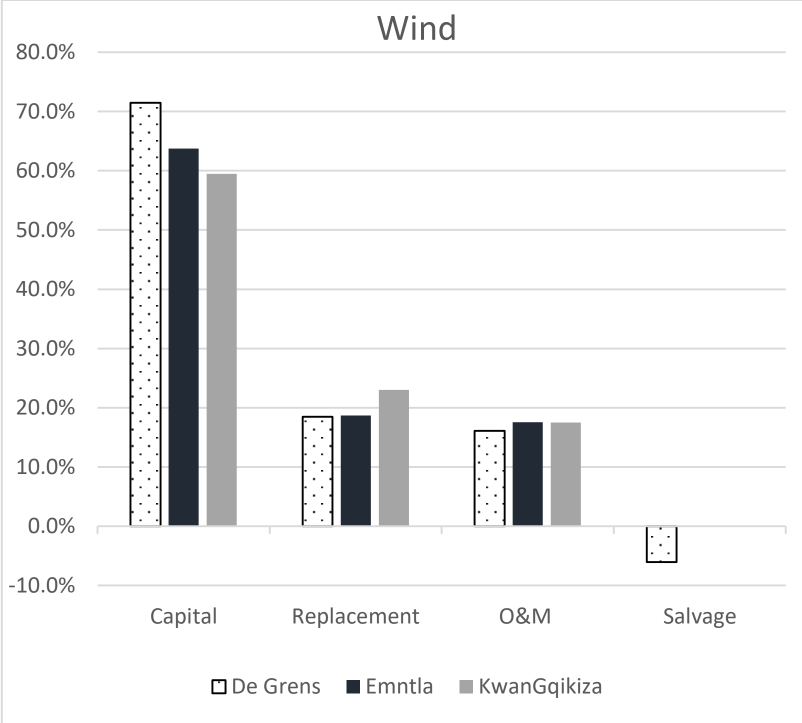


Figure 5.9 Breakdown of costs for each village

HOMER gives a breakdown of the costs for each component over the 20 year lifetime of the system. The breakdown for De Grens, Emntla and KwanGqikiza is shown in Figure 5.10, Figure 5.11 and Figure 5.12 respectively. From the cost break down, it is clear that the high capital cost is due to the cost of the wind turbine.

The bulk of the replacement cost for De Grens, is attributed to the batteries before the end of year 10 and 19. For Emntla and KwanGqikiza, the batteries are only replaced at Year 10. It is for this reason, that there is no Salvage cost for these two villages as all the wind system components reach the end of their product lifetime at the same time that as the 20 year plant lifetime. The Salvage cost for De Grens is from the batteries salvaged from the replacements at Year 19. Further details on the batteries are covered in Section 5.1.2.2 below. The only other component that was replaced was the converter, which was replaced at year 10 for all systems.

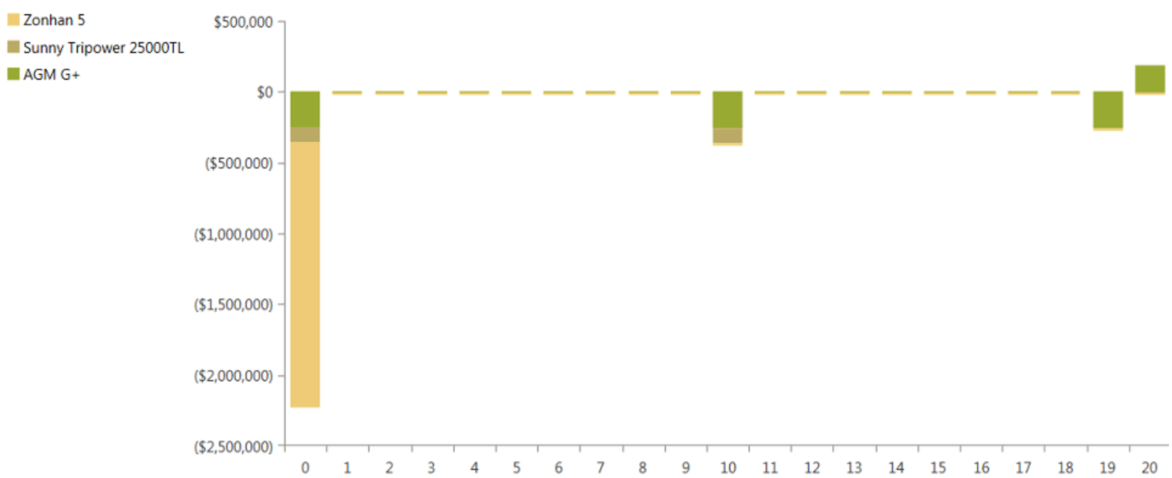


Figure 5.10 Breakdown of component costs over system lifetime in De Grens village

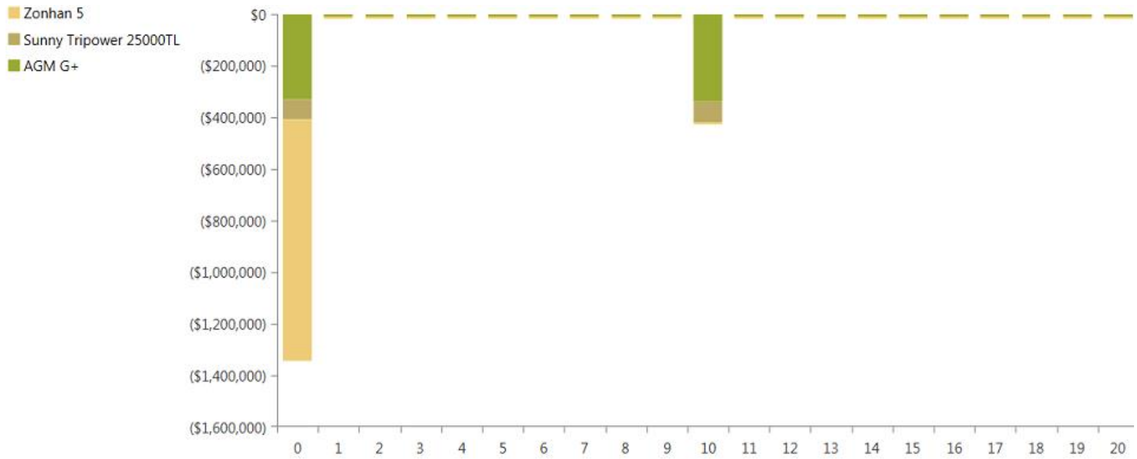


Figure 5.11 Break down of component costs over system lifetime in Emntla village

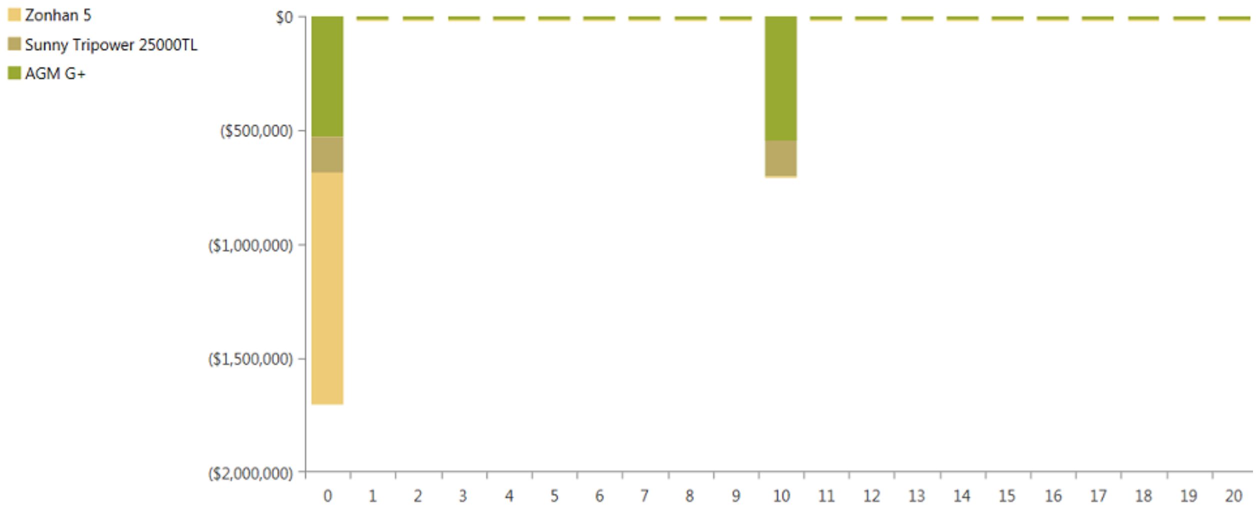


Figure 5.12 Break down of component costs over system lifetime in KwanGqikiza village

5.1.2.2 Technical Analysis

The technical analysis results are given in Table 5.4 below.

Table 5.4 Technical analysis results of the wind systems of each village

HOMER Output	De Grens	Emntla	KwanGqikiza
System			
Peak load (kW)	175.73	210.37	261.05
Average load (kW)	25.94	30.05	35.99
AC primary load (kWh/year)	227,128	263,070	315,015
Capacity factor (%)	13.5	29.1	25.6
Total turbine production (kWh/year)	532,431	573,149	604,676
Excess electricity (%)	53.0	49.5	42.0
Dispatch Strategy	Cyclic Charging	Cyclic Charging	Cyclic Charging
Turbine			
Number of turbines	90	45	54
Rated capacity (kW)	450	225	270
Mean Output (kW)	60.8	65.4	62.6
Inverter			
AC capacity (kW)	293	211	328
Max Output (kWh/d)	175	210	261
Mean output (kW)	25.9	30.0	36.0

Batteries			
Number of batteries	750	1,000	1,300
Strings in parallel	15	20	26
Nominal capacity (kWh)	2,119	2,825	3,672
Usable Nominal capacity (kWh)	1,695	2,260	2,938
Autonomy (h)	65.3	75.2	81.6
Annual throughput (kWh/year)	86,493	101,551	138,407
Lifetime throughput (kWh/year)	791,475	1,015,507	1,371,890
Expected life (years)	9.15	10.0	9.91
Losses (kWh/year)	19,338	22,630	30,879

From the results, it is noted that each of the systems made use of the cycle charge dispatch strategy which is in line with our expectations.

From a sizing perspective, De Grens has the biggest system with a turbine capacity of 450kW whilst KwanGqikiza had a capacity of 270kW and Emntla had the lowest at 225kW. It is expected that the village with the highest load would have the biggest system however this is not the case. This shows that the strength of the wind speed directly affects the size of the plant, and explains why De Grens had the lowest load but the highest wind turbine capacity. The wind strength is not strong enough to generate the required power from a few turbines, therefore a higher number of turbines are modelled in the system to make-up for this. This also explains why De Grens has the highest LCOE whilst Emntla has the lowest, as this cost was mostly due to the high capital cost of the wind turbine.

It is noted that the installed capacities are higher than the peak loads for all villages which is in line with our expectations.

The oversizing of the system at De Grens has led to the village generating 53% worth of excess electricity. KwanGqikiza generated the lowest excess electricity at 42.0%, whilst Emntla generated 49.5% extra. KwanGqikiza generated the least as the system capacity matched the load more closely than for the other villages.

De Grens had the lowest capacity factor at 13.5%, whist the capacity factor for Emntla and KwanGqikiza were 29.1% and 25.6% respectively. The low capacity factor at De Grens is attributed to the lower wind speeds in the village, which has led to the increased number of turbines required to supply the given load.

The AGM G+ batteries were not the main contributors to the overall system cost; however, they were a significant contributor as shown in Figure 5.10, Figure 5.11 and Figure 5.12 . The size of the battery banks number at De Grens was the lowest with 750 batteries, whilst the battery bank at KwanGqikiza was the highest with 1,300 batteries.

The DMaps for the state of charge of the batteries for De Grens, Emntla and KwanGqikiza are shown in Figure 5.13, Figure 5.14 and Figure 5.15 respectively.

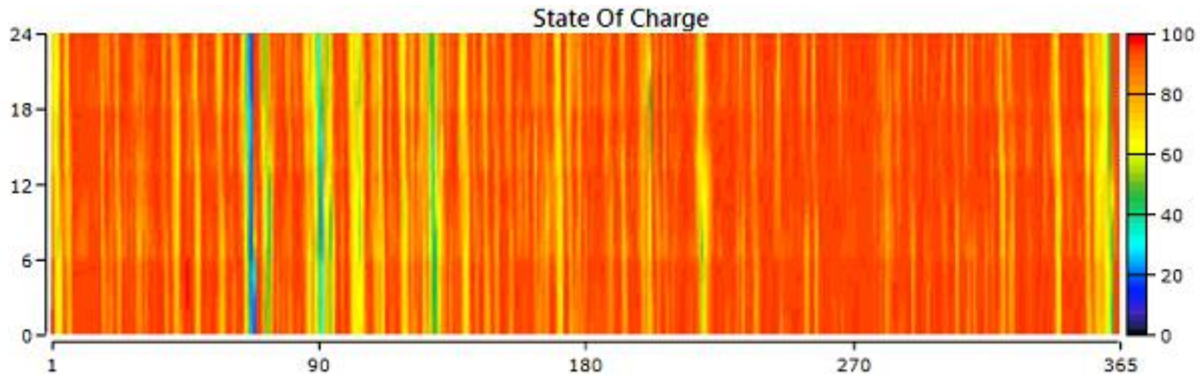


Figure 5.13 Battery state of charge DMap for De Grens village

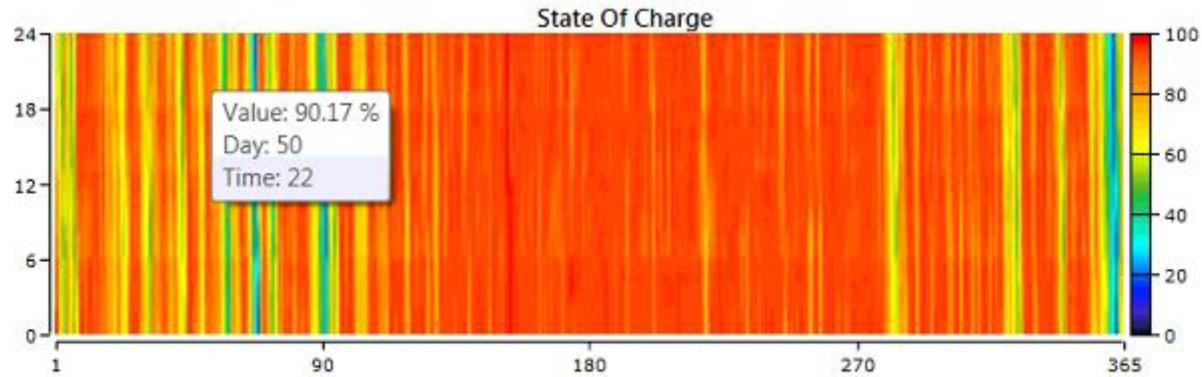


Figure 5.14 Battery state of charge DMap for Emntla village

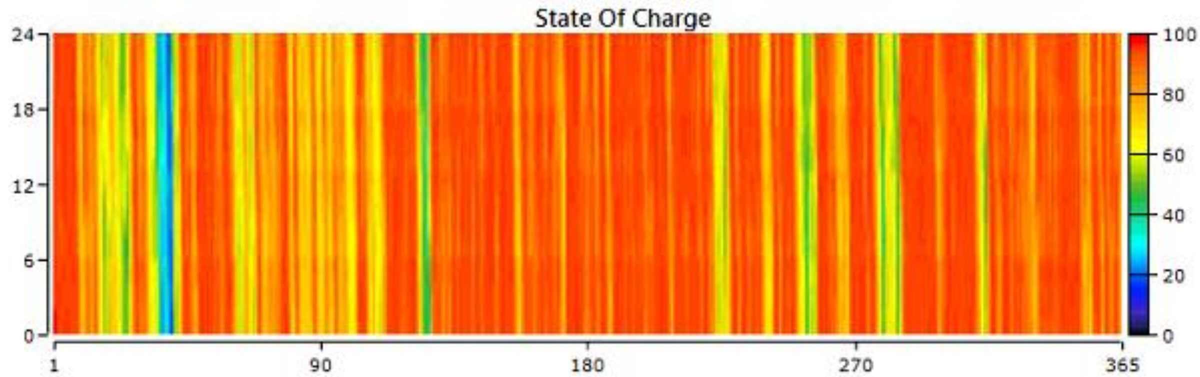


Figure 5.15 Battery state of charge DMap for KwanGqikiza village

The battery state of charge for De Grens and Emntla corresponds to the monthly wind speeds in Figure 4.2. in section 4.2.2 The batteries for these two villages maintains 100% state of charge more frequently during the months where the wind speeds are high. For example, in Emntla, the state of charge is frequently at 100% between May and October. This period is when the village experiences its highest wind speeds. This is the same for De Grens for the period between July and November. The battery state of charge tends to fluctuate more outside of these periods. This shows that the wind speed in these months is not sufficient support the village load and as a result the batteries are used more frequently. This is not the case for KwanGqikiza. Figure 5.16 shows the Battery discharge graph (orange) versus the wind speed (blue). The black circle in Figure 5.16 shows a period where the battery discharge falls below 40%, which corresponds to the two yellow and green bands before and after day 270 in Figure 5.15 above.

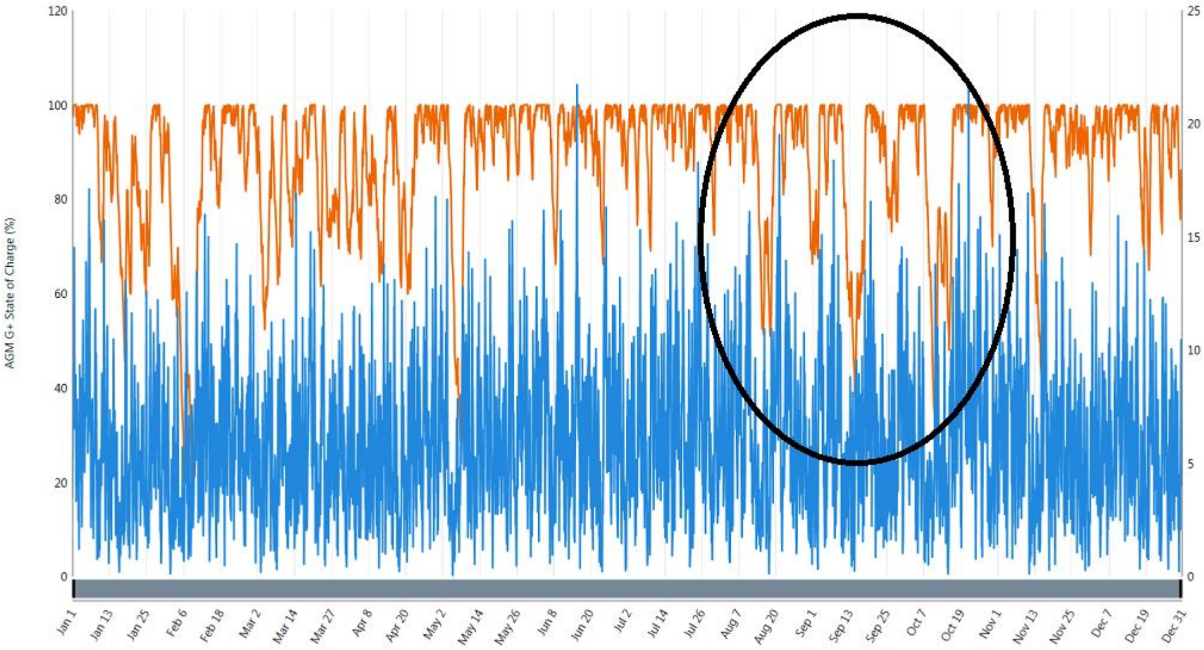


Figure 5.16 Wind speed (blue) vs Battery state of charge (orange)

Figure 5.17 provides a closer look into the period indicated by the red circle in Figure 5.16. From Figure 5.17 it is clear that the discharge of the battery is due to the wind speed being low for a few consecutive days, resulting in the battery bank not being charged. This was the case even though the average wind speed for KwanGqikiza over these two months was generally high as noted in Table 4.3. This shows that even in months where the wind speed is generally high, the fluctuating nature of resource can lead to the load not being met, hence the need for a big battery bank.

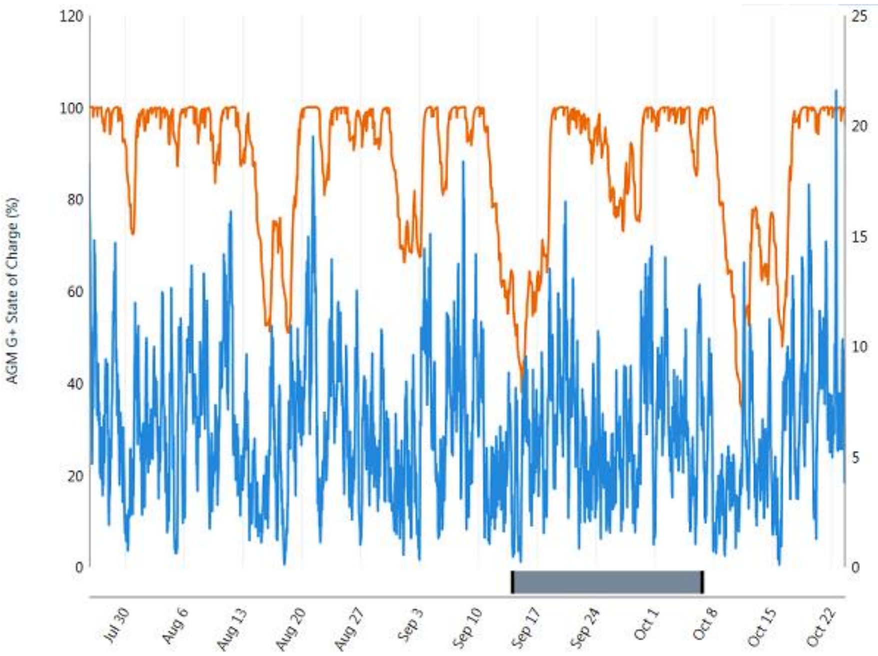


Figure 5.17 Period covered by the red circle in Figure 5.16

5.1.3 Microhydro

A summary of the economic and technical analysis results for the respective hydro systems in each village are analysed in the following sections. As mentioned in Section 3.5.4, De Grens and Emntla had existing dams whilst KwanGqikiza did not. In order to make the results comparable, this case was split into two parts, one assuming that a dam exists in each of the three villages and one assuming that dams had to be built in each village.

5.1.3.1 Dam infrastructure included

This part assumes that each village already has an existing dam, therefore capital costs in building the dam have not been included.

Economic Analysis

The economic analysis results are given in Table 5.3 below.

Table 5.5 Economic analysis results of the microhydro systems of each village

HOMER Output	De Grens	Emntla	KwanGqikiza
LCOE ($/kWh)	0.1823	0.1959	0.2069
NPC ($)	795,918	990,567	1,253,330
Salvage cost ($)	0	0	0
Operating Cost ($/year)	33,165	41,586	52,868

From the results, De Grens has the least LCOE at $0.1823/kWh followed by Emntla with $0.1959/kWh and KwanGqikiza at $0.2069/kWh. The NPC followed the same trend with De Grens being the cheapest at $795,918, whilst KwanGqikiza was the most expensive at $1,253,330. The results indicate that the strength of the microhydro resource do not affect the cost metrics, unlike wind and solar. A breakdown of the costs for each village is given in Figure 5.18 below.

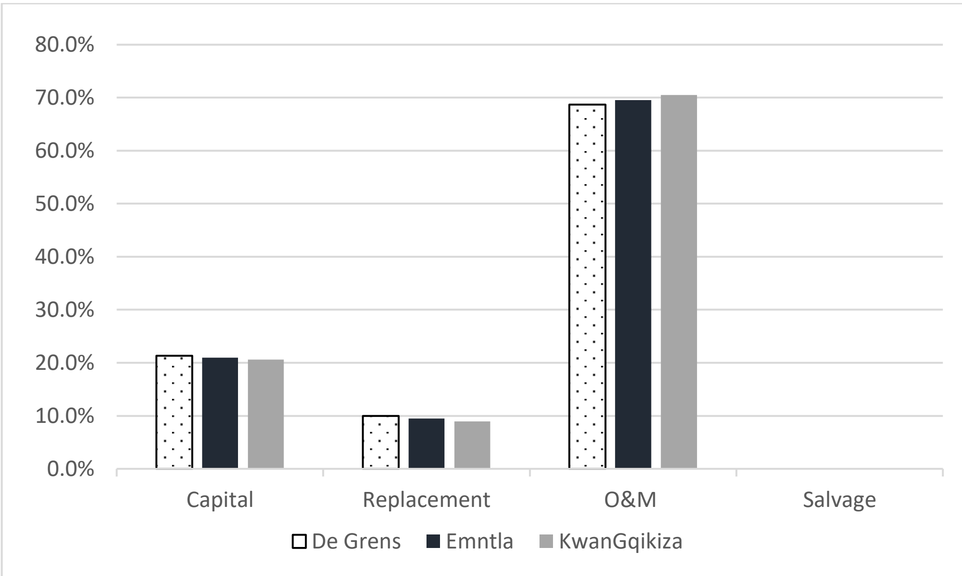


Figure 5.18 Breakdown of costs for each village

It is noted that the O&M accounts for approximately 70% of the total cost. This is as expected, because there is no capital cost associated with building the dam since they are assumed to already exist. Therefore, any capital and replacement costs are associated with the other components. This explains why the LCOE of the systems are not directly related to the strength of the microhydro resource. The O&M cost is directly related/proportional to the size of the system. i.e. the bigger the system the greater the O&M cost. Therefore, any advantages provided by a stronger resource are eliminated by the high O&M costs which are directly proportional to the size of the system.

The breakdown of the costs over 20 years for all 3 villages are shown in Figure 5.19, Figure 5.20 and Figure 5.21 respectively. The cost break down profile is the same for all the villages. It is noted that the annual hydro cost includes the dam maintenance cost, hence the consistently high figure every year. Replacement of the batteries and the inverters occur at Year 10 in line with the lifetime of the components.

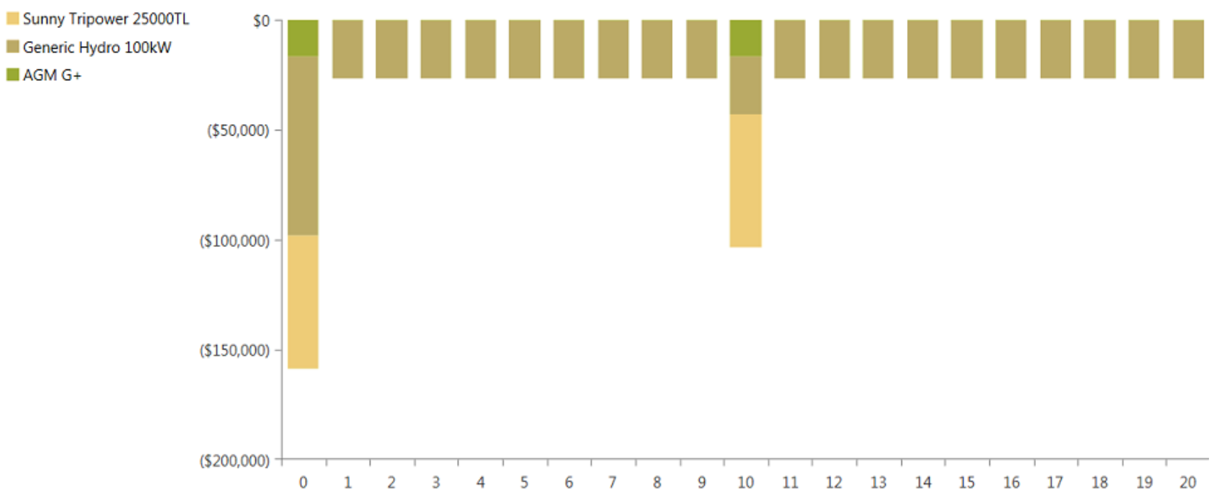


Figure 5.19 Breakdown of component costs over system lifetime in De Grens village

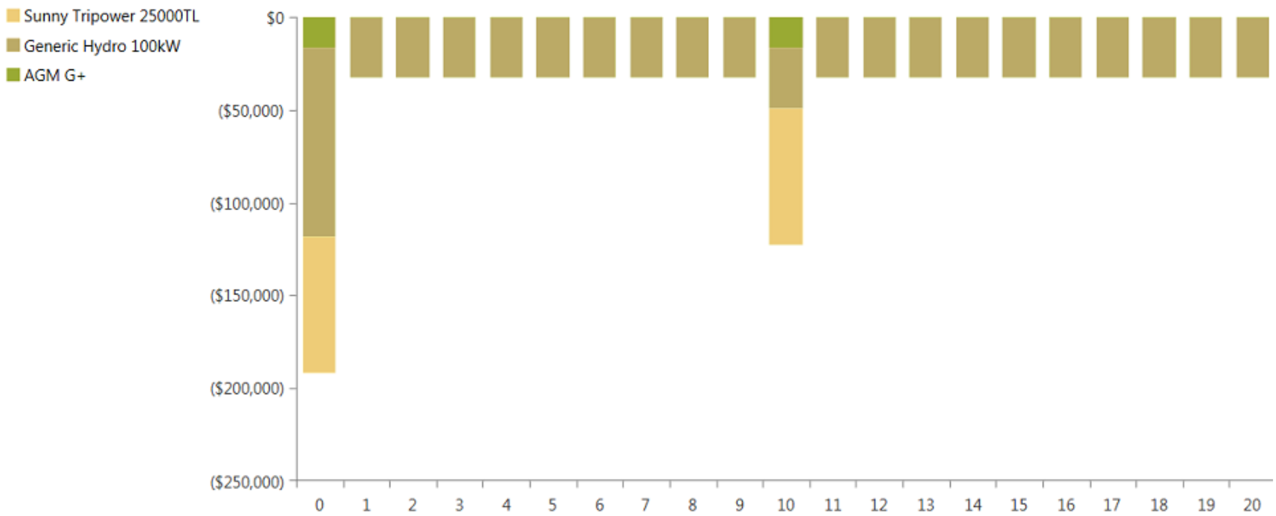


Figure 5.20 Break down of component costs over system lifetime in Emntla village

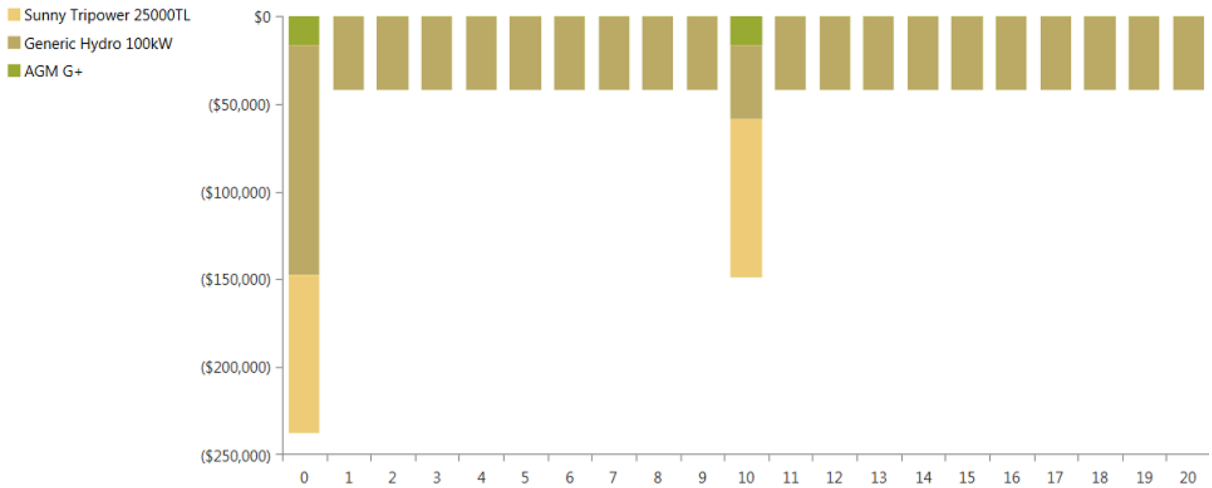


Figure 5.21 Break down of component costs over system lifetime in KwanGqikiza village

Technical Analysis

The technical results are given in Table 5.6 below.

Table 5.6 Technical results of the microhydro systems of each village

HOMER Output	De Grens	Emntla	KwanGqikiza
System			
Peak load (kW)	175.73	210.37	261.05
Average load (kW)	25.94	30.05	35.99
AC primary load (kWh/year)	227,195	263,171	315,202
Capacity factor (%)	95.7	89.6	93.5
Total hydro turbine production (kWh/year)	1,341,947	1,594,765	2,139,313
Excess electricity (%)	82.8	83.2	85
Dispatch Strategy	Cyclic Charging	Cyclic Charging	Cyclic Charging
Hydro Turbine			
Nominal Capacity (kW)	160	203	261
Minimum Output (kW)	93.7	129	244
Maximum Output (kW)	177	216	244
Mean Output (kW)	153	182	244
Inverter			
AC capacity (kW)	163	198	244
Max Output (kWh/d)	163	198	244
Mean output (kW)	25.9	30.0	36.0
Batteries			
Number of batteries	50	50	50
Strings in parallel	1	1	1
Nominal capacity (kWh)	141	141	141
Usable Nominal capacity (kWh)	113	113	113
Autonomy (h)	4.36	3.76	3.14
Annual throughput (kWh/year)	1,609	1,462	53.7
Lifetime throughput (kWh/year)	16,092	14,622	537
Expected life (years)	10	10	10
Losses (kWh/year)	360	327	12

From the results, it is noted that each of the systems made use of the cycle charge dispatch strategy which is in line with our expectations.

From a sizing perspective, the hydro installed capacity is less than the load for each village except KwanGqikiza, where they are the same. The reason for this is that the turbines can generate a maximum output higher than their nominal capacity. This is achieved by altering the maximum flow ratio of the turbine which is above 100%. The turbines also have a minimum output which is altered by adjusting the minimum flow ratio. Both the maximum and minimum flow ratios are defined in Section 3.5.4.

All plants have generated over 80% of excess electricity. This is as expected since all the systems are constantly generating electricity regardless of the load demand.

The capacity factor for all the systems was above 90%, apart from Emntla which had a capacity factor of 89.6%. These values are as expected as is the nature of hydro systems, because they have a more constant flow of electricity. This was the case for Emntla because it had the slowest flow rate, with some months where the flow rate was too little to supply the peak load during cooking hours. This is shown in the graph in Figure 5.22 below. The red graph represents the hydro turbine output whilst the blue represents the AC load of the village and the black spikes represent the battery discharge.

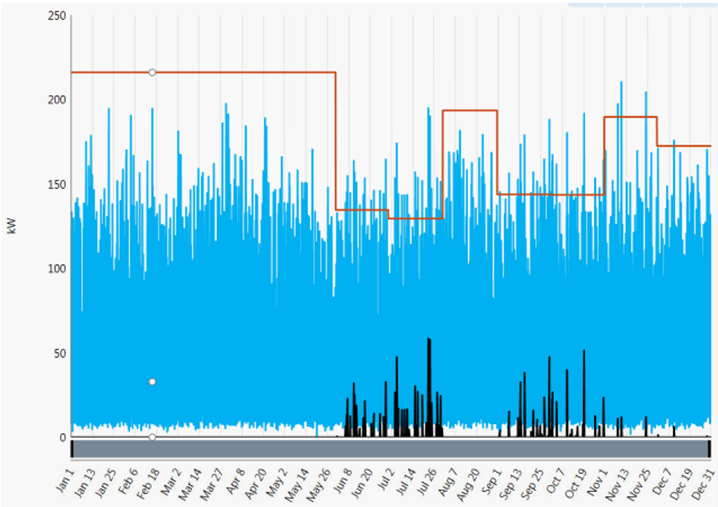


Figure 5.22 Hydro turbine output (red) vs AC primary load (blue) vs battery discharge (black)

From the graph we can see that in the months where the flow rate is low in June – July and September – November, the turbine capacity is not enough to supply the load. However, the black spikes during these periods shows that the batteries provided the excess power, when the hydro turbines could not.

Each system had 50 batteries. This is the minimum amount of batteries each system can have, according to the designed string size which is 50 batteries. The DMaps for the state of charge of the batteries for De Grens, Emntla and KwanGqikiza are shown in Figure 5.23, Figure 5.24 and Figure 5.25 respectively.

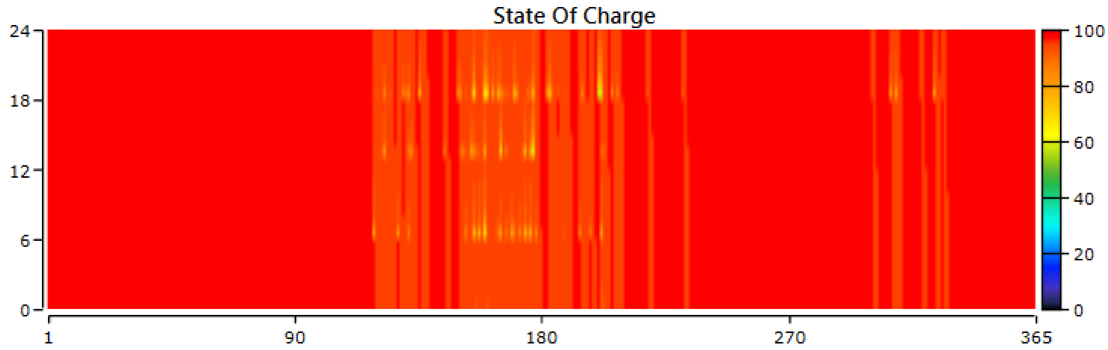


Figure 5.23 Battery state of charge DMap for De Grens village

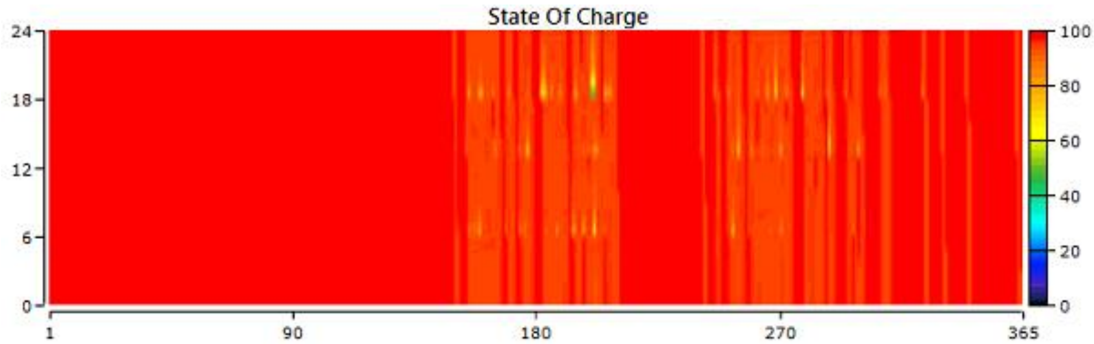


Figure 5.24 Battery state of charge DMap for Emntla village

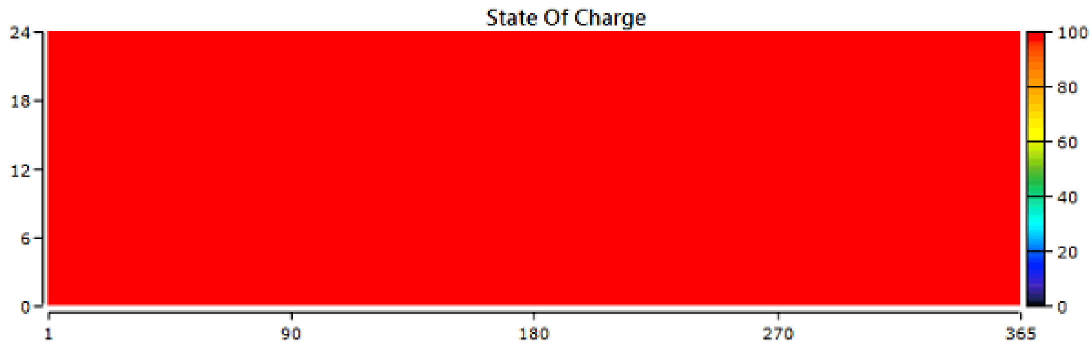


Figure 5.25 Battery state of charge DMap for KwanGqikiza village

The battery state of discharge for De Grens and Emntla corresponds to the months where the flow rates are low as noted in Table 4.4. This link to the flow rate and the battery discharge is shown in Figure 5.22 above. On the other hand, the batteries at KwanGqikiza maintain 100% charge throughout the year. The reason for this is the flow rate at KwanGqkiza is a lot higher than is required for a system of that size. Therefore, the hydro turbines are constantly running at the maximum allowable capacity. It can be argued that the batteries are not necessary for KwanGqikiza as they are never discharged. HOMER ran the hydro system without any batteries as part of its simulation, however a warning was attached to the system stating that the renewable penetration of the system was high and therefore storage was required for stability. As a result, the system with the battery banks was selected.

5.1.3.2 Dam infrastructure excluded

This iteration assumes that there are no existing dams at each site. To simplify the calculations, it was assumed that the dams to be built had the same parameters as those discussed in Table 3.26 in Section 3.5.4. The only difference was the capital cost of building a new dam which was included in the price. From the results it was clear that the economic outputs changed however the technical outputs remained the same as those in Table 5.6. The economic analysis results are discussed in more detail below.

Economic Analysis

The economic analysis results are given in Table 5.7 below.

Table 5.7 Economic analysis results of the microhydro systems of each village

HOMER Output	De Grens	Emntla	KwanGqikiza
LCOE ($/kWh)	0.3286	0.3567	0.3795
NPC ($)	1,434,414	1,803,575	2,298,178
Salvage cost ($)	0	0	0
Operating Cost ($/year)	33,164	41,587	52,870

An analysis of the results concluded that De Grens has the least LCOE at $0.3286/kWh followed by Emntla with $0.3567/kWh and KwanGqikiza at $0.3795/kWh. The NPC followed the same trend with De Grens being the cheapest at $1,434,414, whilst KwanGqikiza was the most expensive at $2,298,178. The results follow the same trend as the iteration where the dam was assumed to already exist, although the prices were 10% - 15% greater in the second iteration. A breakdown of the costs for each village is given in Figure 5.26 below.

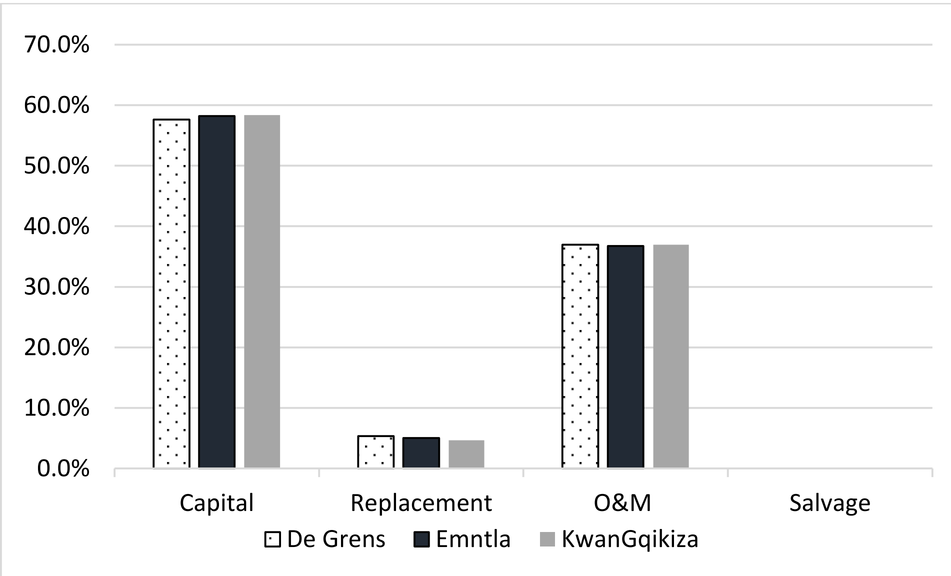


Figure 5.26 Breakdown of costs for each village

The bulk of the extra cost was due to the capital cost of building the dam, as expected. It was also noted that the O&M cost is not the primary cost as was the case in the first iteration.

The strength of the resource did not affect the LCOE or NPV. The reason for this is that the high capital cost cancelled out any advantage a strong resource would have given. The breakdown of the costs over 20 years for KwanGqikiza village is shown in Figure 5.27 below. As the cost break down followed the same trend for the other villages, only the break down for KwanGqikiza was shown. From Figure 5.27 below, it is evident that the greatest cost was the Generic Hydro turbine cost in Year 0 as it included the cost of building the dam. At Year 10 both the Sunny TriPower inverters and the AGM G+ batteries were replaced; however, these costs are insignificant as compared to the capital costs. The other annual costs are attributed to the dam maintenance.

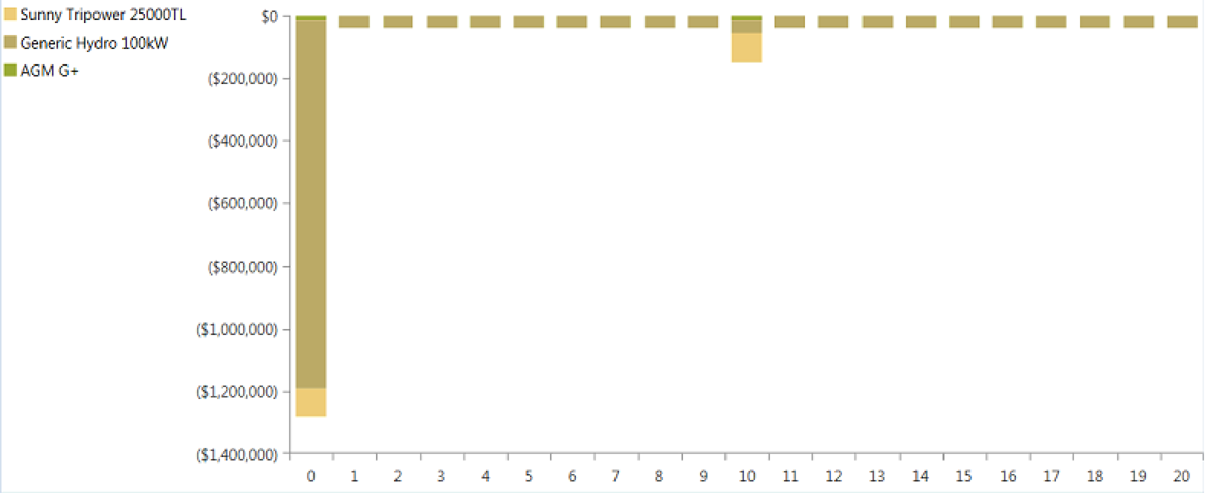


Figure 5.27 Breakdown of component costs over system lifetime in KwanGqikiza village

Technical Analysis

The technical analysis results for this iteration are the same as the results for the iteration where the dam infrastructure existed in the village, as the only variable that changed was increase of the turbine capital cost to include the construction of a dam. These results are covered in Table 5.6 above.

5.2 Case 2

This case study compares the solar, wind and hydro systems in each village to determine which is the best renewable system to implement. Each village was selected based on the existence of one strong renewable resource in each, therefore the case study will confirm whether the system making use of the strongest resource will be the most feasible to implement economically and technically. The microhydro systems results, assuming no dams exist in the villages, were used.

5.2.1 De Grens Village

5.2.1.1 Economic Analysis

As mentioned in previous sections, De Grens village was selected because of the high solar irradiation experienced by the village. The economic analysis results for the solar, wind and microhydro systems in De Grens, as stated in Section 5.1 above are given in Table 5.8 below.

Table 5.8 Economic analysis results of the for the systems at De Grens village

HOMER Output	Solar	Wind	Microhydro
LCOE ($/kWh)	0.3715	0.7137	0.3286
NPC ($)	1,621,624	3,114,700	1,434,414
Salvage cost ($)	293,034	187,482	0
Operating Cost ($/year)	47,899	46,286	33,164

From the results it is clear that the cheapest system in terms of LCOE is the microhydro system at $0.3286 $/kWh, followed by the PV system at $0.3715/kWh. The wind system was the most expensive at $0.7137/kWh and was almost double the LCOE of the other two systems. The NPC followed the same trend with the microhydro system being the cheapest, whilst the wind system was the most expensive.

The results show that the strength of the resource does not impact the LCOE and the NPC. However, we note that even though De Grens was selected for its high irradiation, the flow rate of the microhydro system was considerable. What impacted the cost was the number of batteries required for the solar and wind systems. This is directly related to the constant generation characteristic of microhydro which means reliance on batteries are not required. Another impacting factor is that the systems are oversized for both the wind and solar systems, however the microhydro system is undersized due to its ability to generate at above 100% rate capacity. These factors are covered in more detail in the technical analysis in Section 5.2.1.2.

A cost break down of the different systems in De Grens village is given in Figure 5.28 below, whilst the cost break down in each component in each system is given in Figure 5.29.

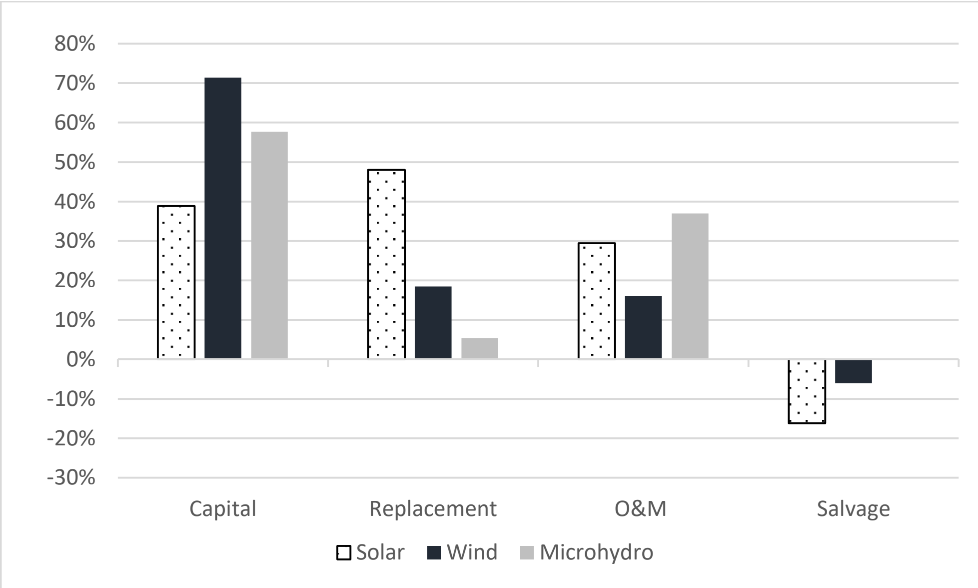


Figure 5.28 Cost break down of the different systems at De Grens

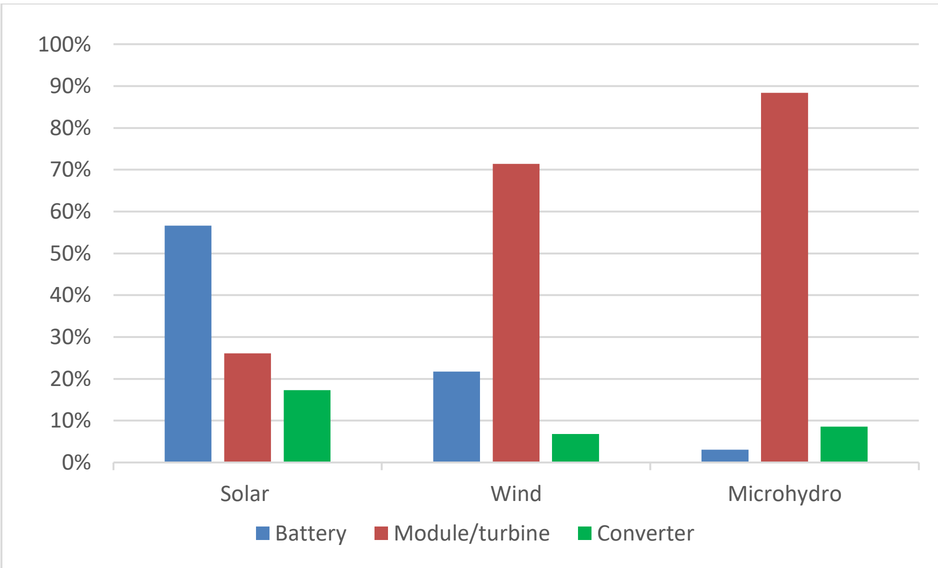


Figure 5.29 Component cost breakdown for each system

From Figure 5.28, it is noted that replacement cost is the biggest contributor to the overall NPC for PV system, whilst the capital cost is the biggest contributor to wind and microhydro costs. Looking at

Figure 5.29, it is noted that the batteries are the biggest cost for the PV system since they are replaced twice over the 20 year lifetime of the plant as shown in Figure 5.2 in Section 5.1.1.1.

5.2.1.2 Technical Analysis

The technical results for the three systems in De Grens are given in Table 5.9 below.

Table 5.9 Technical analysis results for the systems at De Grens

HOMER Output	Solar	Wind	Microhydro
System			
Peak load (kW)	175.73		
Average load (kW)	25.94		
AC primary load (kWh/year)	227,183		
Capacity factor (%)	18.9	13.5	95.7
Total energy production (kWh/year)	297,408	532,431	1,341,947
Excess electricity (%)	11.9	53.0	82.8
Dispatch Strategy	Cyclic Charging		
PV Modules/Turbines			
Rated capacity (kW)	179	450	160
Mean Output (kW)	34	60.8	177
Maximum Output (kW)	-	-	153
Inverter			
AC capacity (kW)	175	293	163
Max Output (kWh/d)	-	175	163
Mean output (kW)	25.9	25.9	25.9
Batteries			
Number of batteries	850	750	50
Strings in parallel	17	15	1
Nominal capacity (kWh)	2,401	2,119	141
Usable Nominal capacity (kWh)	1,921	1,695	113
Autonomy (h)	74.1	65.3	4.36
Annual throughput (kWh/year)	140,324	86,493	1,609
Lifetime throughput (kWh/year)	897,005	791,475	16,092
Expected life (years)	6.39	9.15	10
Losses (kWh/year)	31,313	19,338	360

From the results, it is noted that the microhydro system has a considerably higher capacity factor of 93.6% as opposed to the solar and wind systems which have a capacity factor of 18.9% and 13.5% respectively. This is as expected since the flow rate for the hydro turbine is constant, therefore the system is always generating energy. The only time it is not generating electricity is when the flow rate is below the minimum required. The wind had a lower capacity factor than solar which was unexpected. This was the case however, as the wind resource was fairly weak and erratic and therefore there was no constant generation.

The size of each system impacted the LCOE and NPC. Even though the peak load demand was the same at 175.73 kW, each system was sized differently. The microhydro system was the smallest at 160 kW, followed by the solar at 175 kW and wind at 450 kW. The size of the system follows the same trend as the LCOE and NPC which indicates that they are related. The wind system was considerably larger than the other two systems because the wind speed was considerably low in De Grens, therefore a lot more turbines were required to meet the peak load. On the other hand, the microhydro capacity was less than the peak load demand, however this was the case as the turbines have the ability to run above rated capacity.

The excess electricity generated was highest for the microhydro system at 93.7%. This was followed by the wind system and the solar system with both plants generating 53% and 11.9% respectively. The micro hydro system was generating the most electricity even though the wind system had the highest rated capacity. This was due to the microhydro systems high capacity factor, meaning it was generating electricity most of the time. This shows that the microhydro system is not the most energy efficient system as most of the energy will go to waste. It is noted however, that the load of the system is what has led to the excess electricity. Each system was designed to meet the peak load; however the peak load is only reached for three hours a day. Hence the average load approximately seven times less than the peak load. As a result, the excess electricity is expected. In order to match the load better, a dump load could be added to the village so as to absorb some of the excess electricity. Additionally, the stove could be removed as it is the main contributor to the high peak load. Other alternative energy sources can be sought for cooking such as gas.

The number of batteries required has been a significant contributor to costs, especially with respect to the solar system which had 850 batteries. This further clarified why the replacement costs for this system were so high. This is the same with the wind system which had 750 batteries, although from a cost perspective, the battery cost was over shadowed by the high wind turbine capital cost. This is the case because both systems do not have constant supplies of the respective resources, hence they rely on batteries to supply the load when the wind speed and solar irradiation is low. The microhydro system had the least batteries because it had the most constant energy generation. The batteries were only really required to provide stability to the system.

The expected lifetime of the batteries gives an indication of how much the battery banks were used. Based on this the solar battery bank was used the most followed by the wind, then the microhydro. The DMaps in Figure 5.30, Figure 5.31 and Figure 5.32 below also indicate the battery usage for each system in a year.

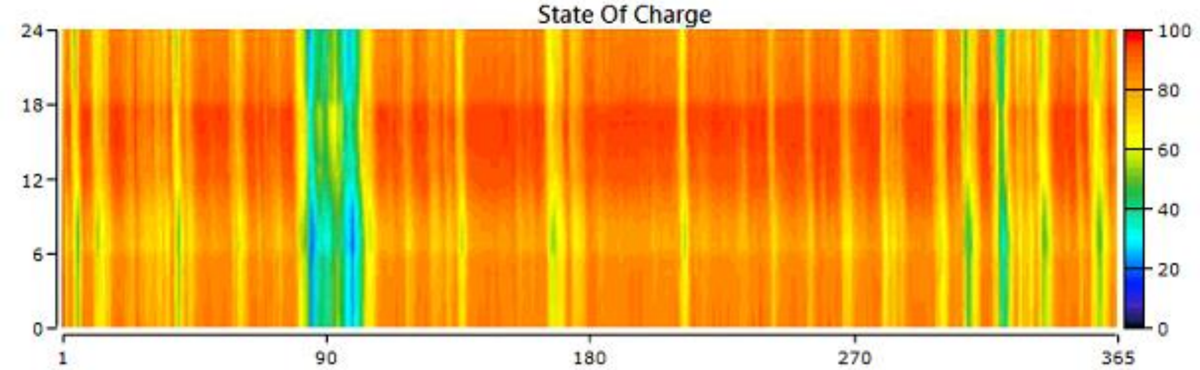


Figure 5.30 Battery state of charge DMap for the solar system

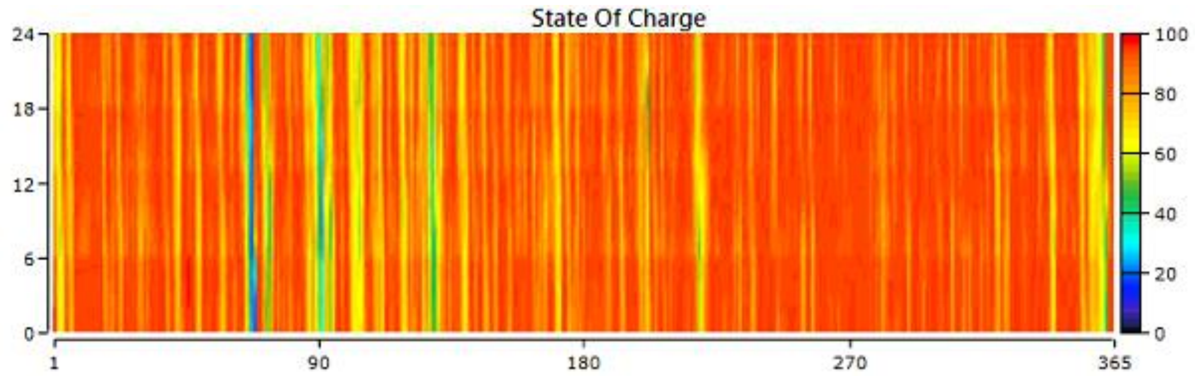


Figure 5.31 Battery state of charge DMap for the wind system

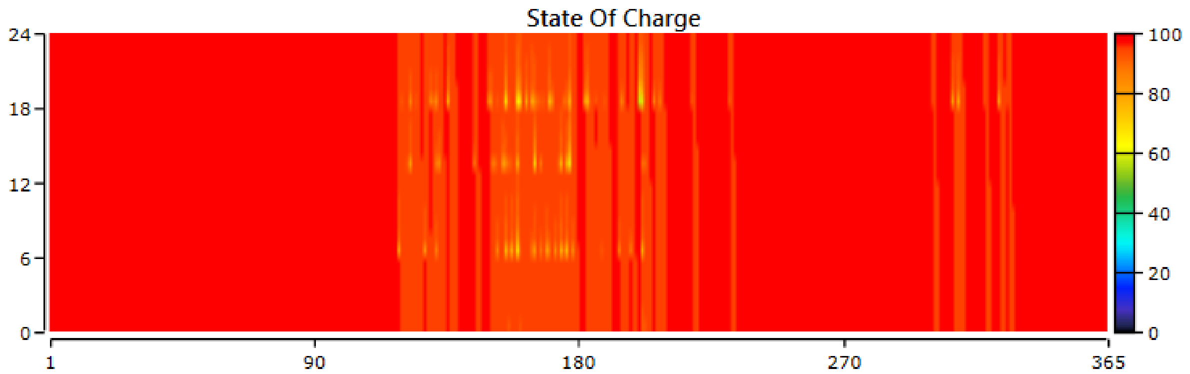


Figure 5.32 Battery state of charge DMap for the microhydro system

The high battery usage for the solar and wind villages is evident in the DMaps above. For both these systems the battery state of charge is constantly changing, whereas for the microhydro system, the state of charge is consistently 100%, indicating their lack of use.

5.2.2 Emntla Village

5.2.2.1 Economic Analysis

Emntla village was selected because of the high wind speed experienced by the village. The economic analysis results for the solar, wind and microhydro systems in Emntla, as stated previously in Section 5.1 are given in Table 5.10 below.

Table 5.10 Economic analysis results of the for the systems at Emntla village

HOMER Output	Solar	Wind	Microhydro
LCOE ($/kWh)	0,3776	0.4172	0.3567
NPC ($)	1,909,171	2,108,603	1,803,575
Salvage cost ($)	330,551	0	0
Operating Cost ($/year)	56,851	39,800	41,587

From the results it is clear that the cheapest system in terms of LCOE is the microhydro system at $0.3567/kWh, followed by the PV system at $0.3776kWh. The wind system was the most expensive at $0.4172 /kWh. The NPC followed the same trend with the microhydro system being the cheapest, whilst the wind system was the most expensive. The margins between the costs, especially between the wind systems and the other systems were a lot closer than was the case for De Grens.

The results once again indicate that the strength of the resource in the area does not dictate the type of system to be implemented i.e. an area with a strong wind resource does not mean that wind system would be the cheapest to implement. In this case, even though Emntla was selected for its high wind speeds, the wind system was still the most expensive option. The major LCOE impact factors were the same as those discussed for De Grens. A cost break down of the different systems in De Grens village is given in Figure 5.33 below, whilst the cost break down in each component in each system is given in Figure 5.34.

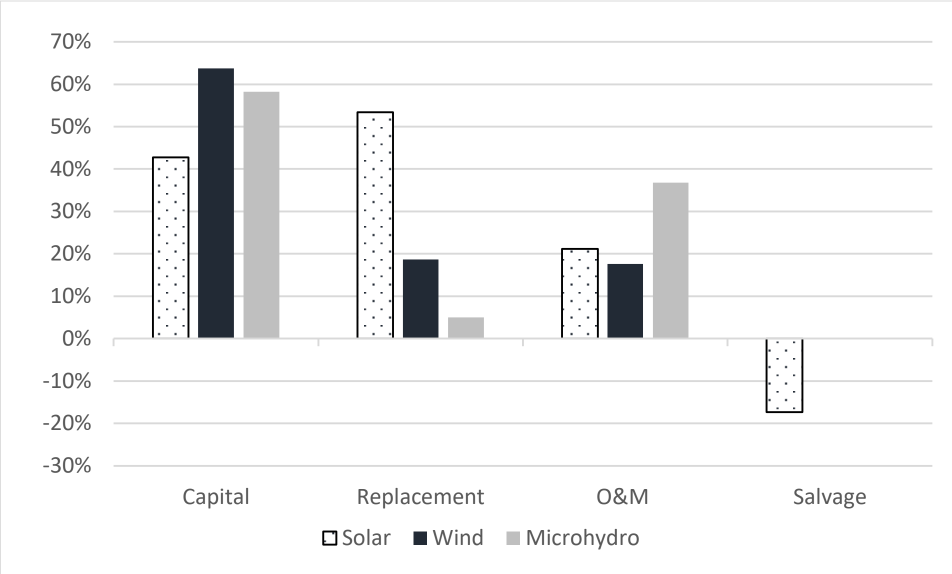


Figure 5.33 Cost break down of the different systems at De Grens

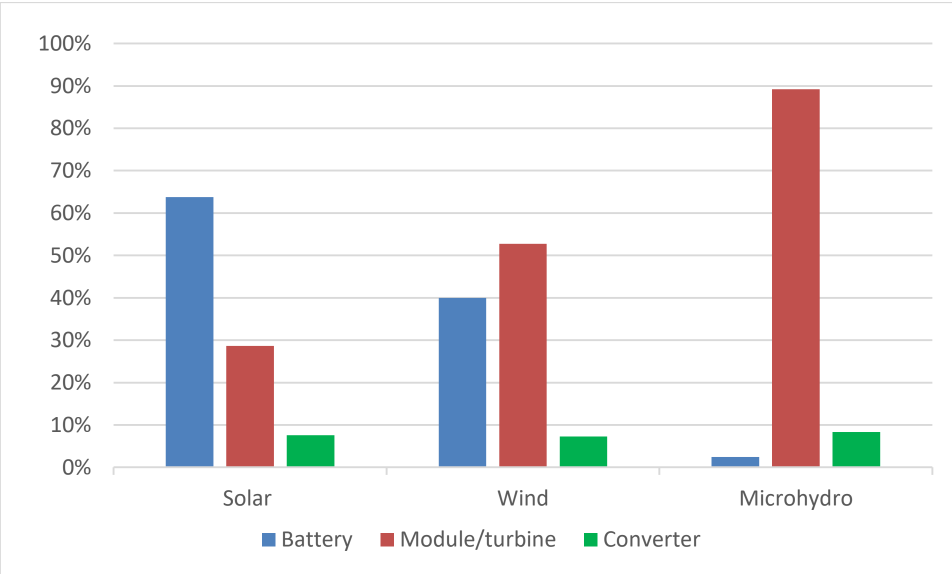


Figure 5.34 Component cost breakdown for each system

From Figure 5.33, it is noted that replacement cost is the biggest contributor to the overall NPC for PV system, whilst the capital cost is the biggest contributor for wind and microhydro costs. This trend is the same as those seen for the systems at De Grens. It is noted that, salvage costs were also a contributor to the solar system but not the wind and microhydro systems. Figure 5.34 further indicates that the batteries are the biggest cost for the PV system mainly due to the replacement of batteries. It is for this same reason that the battery cost is high for the wind system as well, though the highest cost is attributed to the turbines.

5.2.2.2 Technical Analysis

The technical results for the three systems in Emntla are given in Table 5.11 below.

Table 5.11 Technical analysis results for the systems at De Grens

HOMER Output	Solar	Wind	Microhydro
System			
Peak load (kW)	210.37		
Average load (kW)	30.05		
AC primary load (kWh/year)	261,155		
Capacity factor (%)	18.9	29.1	89.6
Total energy production (kWh/year)	344,430	573,149	1,594,765
Excess electricity (%)	11.5	49.5	83.2
Dispatch Strategy	Cyclic Charging		
PV Modules/Turbines			
Rated capacity (kW)	209	225	203
Mean Output (kW)	39.3	65.4	200
Maximum Output (kW)	178	292	182
Inverter			
AC capacity (kW)	200	211	198
Max Output (kW)	200	210	198
Mean output (kW)	30.0	30.0	30.0
Batteries			
Number of batteries	1,000	1,000	50
Strings in parallel	20	20	1
Nominal capacity (kWh)	2,825	2,825	141
Usable Nominal capacity (kWh)	2,260	2,260	113
Autonomy (h)	75.2	75.2	3.76
Annual throughput (kWh/year)	167,338	101,551	1,462
Lifetime throughput (kWh/year)	1,055,300	1,015,507	14,622
Expected life (years)	6.31	10.0	10.0
Losses (kWh/year)	37,368	22,630	327

From the results, it is noted that the microhydro system has a higher capacity factor of 84.7% as opposed to the solar and wind systems which have a capacity factor of 18.9% and 29.1% respectively. The high capacity factor was expected for the microhydro system for the same reasons as those mentioned in Section 5.2.1.2. The wind system capacity factor was higher than the solar capacity factor which was as expected. Solar systems tend to have a lower capacity factor because there is no energy generation at night. The good wind resource in the village was the main contributor to the higher capacity factor. The irradiation at Emntla was similar to De Grens, hence the capacity factors were the same.

The LCOE and NPC followed the same trend as the size of each system. The peak load demand was 210.37 kW. The size of the wind system was bigger at 225 kW, whilst the size of the microhydro was smaller at 203 kW. The size of the solar system was in line with the peak load at 209 kW. The microhydro was less as the turbines have the ability to run above rated capacity as mentioned in Section 5.2.1.2. The wind system was marginally bigger because there were periods during the year where the wind speeds were low therefore the system had to be slightly oversized to cater for this.

The excess electricity followed the same trend as for De Grens village. It was highest for the microhydro system at 80.4%. This was followed by the wind system and the solar system with both plants generating 49.5% and 11.5% respectively. The explanation for the differing capacity factors are given in Section 5.2.1.2. Furthermore, the methods of dealing with the excess electricity are given in Section 5.2.1.2

As with De Grens, the number of batteries required were a major contributor to costs, especially with the wind and solar systems. The microhydro system had the least batteries (50) as it had the most constant generation which was previously explained in Section 5.2.1.2. The solar and wind systems had a significantly higher amount at 1,000 batteries each. This is higher than De Grens, however this was the case as Emntla has a higher load demand. The lifetimes of the batteries between the wind and solar systems were very different even though the number of batteries were the same. The expected lifetime of the solar system was 6.31 years, whilst for the wind system it was 10.0 years. This means that the batteries were replaced at least three times for the solar system and at least two times for the wind system. This explains the significantly high replacement costs for the solar system. The reason that the expected life time is lower, is because the batteries are used more often, especially during the evenings, when the demand is usually higher. The DMaps in Figure 5.35, Figure 5.36 and Figure 5.37 below show the battery usage for each system in a year.

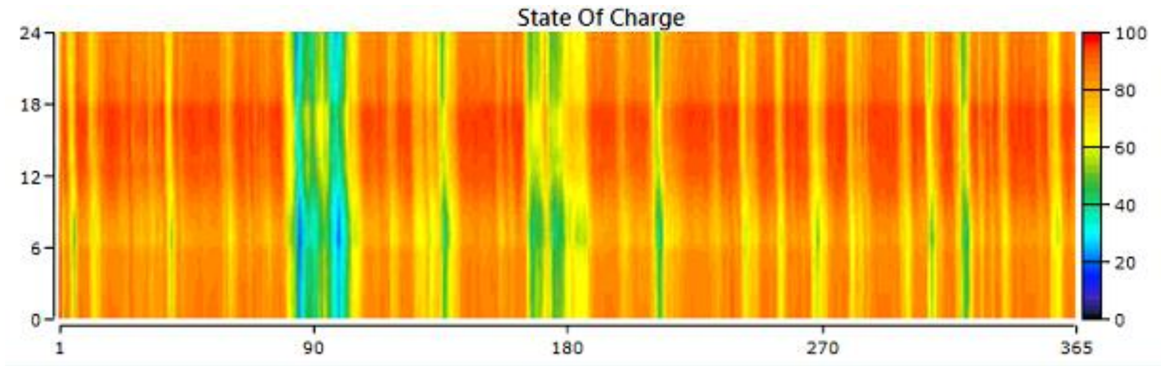


Figure 5.35 Battery state of charge DMap for the solar system

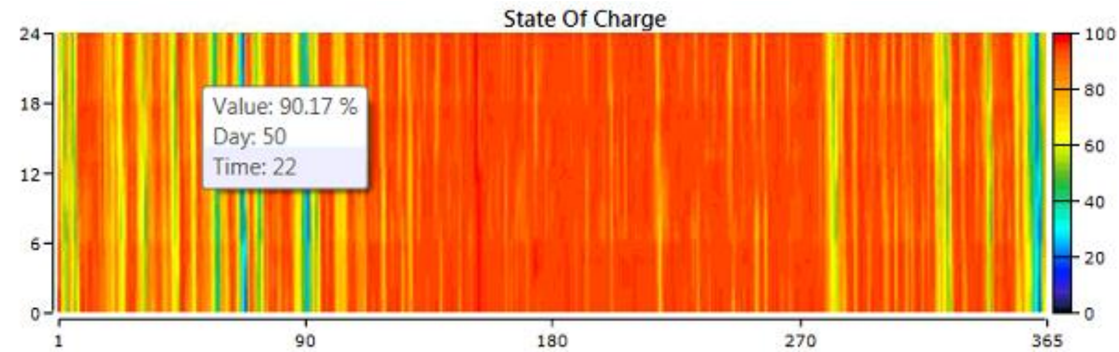


Figure 5.36 Battery state of charge DMap for the wind system

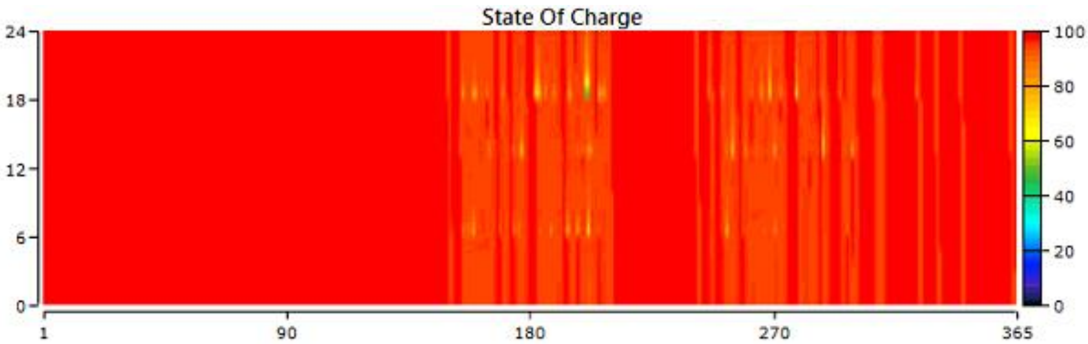


Figure 5.37 Battery state of charge DMap for the microhydro system

The high battery usage for the solar and wind villages is evident in the DMaps above, however it is clear that the batteries in the solar village were used a lot more and the depth of discharge was lower when compared to the wind and microhydro systems. The battery discharge for the solar system between 18:00 and 6:00 is evident in Figure 5.35. For the microhydro system, the state of charge is consistently 100%, indicating their lack of use.

5.2.3 KwanGqikiza Village

5.2.3.1 Economic Analysis

KwanGqikiza village was selected because of its strong microhydro potential. The economic analysis results for the solar, wind and microhydro systems in Emntla, as stated in Section 5.1 are given in Table 5.12 below.

Table 5.12 Economic analysis results of the for the systems at KwanGqikiza village

HOMER Output	Solar	Wind	Microhydro
LCOE ($/kWh)	0.4322	0.4421	0.3795
NPC ($)	2,616,299	2,676,150	2,298,178
Salvage cost ($)	415,437	0	0
Operating Cost ($/year)	73,478	52,190.96	52,870

From the results, the cheapest system in terms of LCOE is the microhydro system at 0.3795 $/kWh, followed by the PV system at 0.4322$/kWh. The wind system was slightly more expensive than the solar system at 0.4421 $kWh. The NPC followed the same trend with the microhydro system being the cheapest, whilst the wind system was the most expensive. The margins between the solar and wind systems were fairly small, especially when compared to the wind and solar systems in the other villages.

Based on the strength of resource, it was expected that the microhydro would be cheapest option since it was the strongest resource, however based on the results from the other villages, microhydro as a technology appears to be cheaper than wind and solar technologies in general i.e. regardless of strength of resource, microhydro is still cheaper than wind and solar for all three villages. The wind and solar costs are very close in value because KwanGqikiza has the lowest irradiation when compared to the other villages, however, it has the second highest wind speed, which on average was only 0.39 m/s less than at Emntla, the village with the highest wind speed. This shows that the strength of the resource in the area can dictate the technology use, however, a certain level of resource per technology needs to be exceeded for a system to be financially viable. i.e. the wind speed in a wind strong area needs to be above a certain level before it becomes cheaper than solar, which is generally a cheaper technology on a small scale. The other factors affecting the LCOE are the same as those discussed in Section 5.2.1.1. A cost break down of the different systems in KwanGqikiza village is given in Figure 5.38 below, whilst the cost break down in each component in each system is given in Figure 5.39.

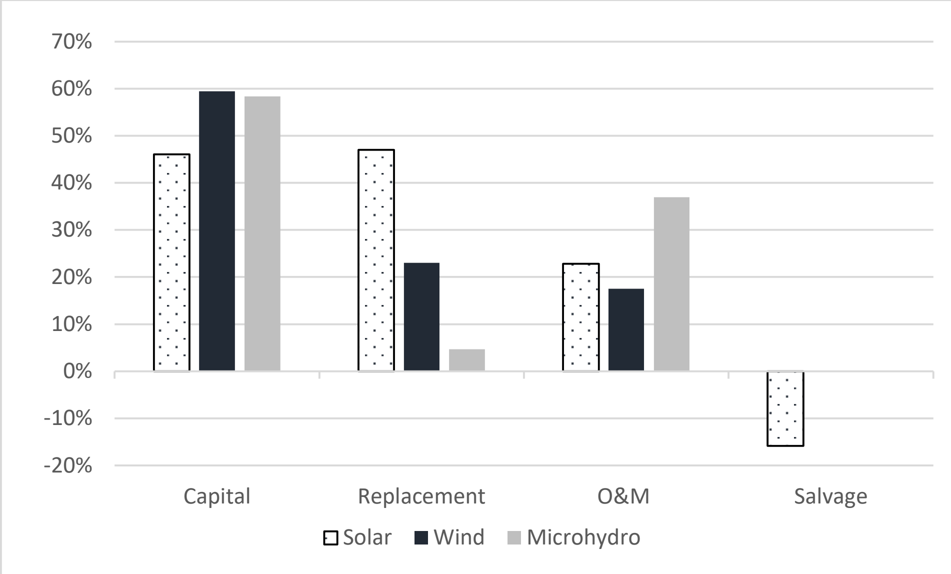


Figure 5.38 Cost break down of the different systems at De Grens

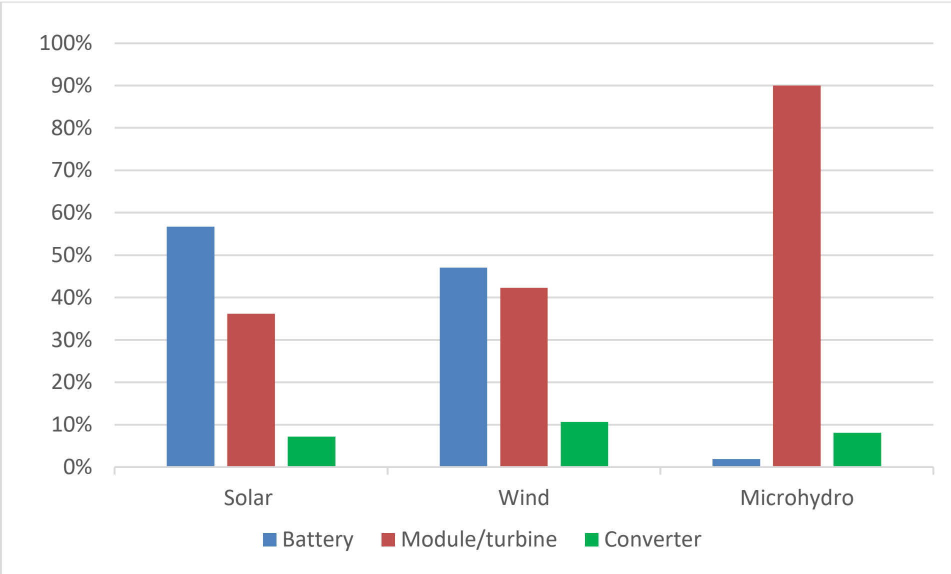


Figure 5.39 Component cost breakdown for each system

From Figure 5.38, it is noted that the costs follow the same trends as the other villages. The capital costs are highest for the wind and microhydro systems whilst the replacement costs are the highest for the solar village. The difference between this village as compared to the others, is that the capital cost and replacement cost for the solar system is fairly similar. From Figure 5.39, it is evident that for the solar system, the batteries contributed most to the cost of the system whilst for the microhydro system, the largest cost contribution came from the turbines. For the wind system it was the batteries that were the biggest contributor which was not the case in the other villages where the turbines were the biggest cost contributor. This was due to the higher demand of the village.

5.2.3.2 Technical Analysis

The technical results for the three systems in KwanGqikiza are given in Table 5.13 below.

Table 5.13 Technical analysis results for the systems at KwanGqikiza

HOMER Output	Solar	Wind	Microhydro
System			
Peak load (kW)	261.05		
Average load (kW)	35.99		
AC primary load (kWh/year)	315,054		
Capacity factor (%)	15.7	25.6	93.5
Total energy production (kWh/year)	493,374	604,676	2,139,313
Excess electricity (%)	26.0	42.0	85.0
Dispatch Strategy	Cyclic Charging		
PV Modules/Turbines			
Rated capacity (kW)	359	270	261
Mean Output (kW)	56.3	62.6	244
Maximum Output (kW)	296	351	244
Converter			
AC capacity (kW)	259	328	244
Max Output (kW)	259	261	244
Mean output (kW)	36.0	36.0	36.0
Batteries			
Number of batteries	1,200	1,300	50
Strings in parallel	24	26	1
Nominal capacity (kWh)	3,390	3,672	141
Usable Nominal capacity (kWh)	2,712	2,938	113
Autonomy (h)	75.4	81.6	3.14
Annual throughput (kWh/year)	204,492	138,407	53.7
Lifetime throughput (kWh/year)	1,266,360	1,371,890	537
Expected life (years)	6.19	9.91	10
Losses (kWh/year)	45,617	30,879	12

From the results, it is noted that the microhydro system has a higher capacity factor of 93.5% as opposed to the solar and wind systems which have a capacity factor of 15.7% and 25.6% respectively. The capacity factor trend for the systems are as expected with microhydro being the highest and solar being the lowest. The reasons for this trend are provided in Section 5.2.2.2.

The peak load demand was 261.05 kW which was the highest of all the villages. Unlike the other two villages, the LCOE and NPC did not follow the same trend as the size of each system. The solar system was cheaper than the wind system, however the rated capacity was 89 kW more than the wind system. The high solar capacity was due to the weak solar irradiation in the area. The cost was however, lower as solar is generally a cheaper technology.

The excess electricity followed the same trend as for De Grens village. It was highest for the microhydro system at 85%. This was followed by the wind system and the solar system with both plants generating 42% and 26%, respectively. The explanation for the differing capacity factors is given in Section 5.2.1.2.

As with the other two villages, the number of batteries has been a major contributor to costs, especially with the wind and solar systems. The microhydro system had the least batteries (50) because it had the most constant generation as explained in Section 5.2.1.2. The solar and wind systems had a significantly higher amount at 1,200 and 1,300 batteries respectively. The high number of batteries was due to the higher demand for this village. For the solar system, the expected lifetime was 6.19 years, whilst for the wind system it was 9.91 years. This confirms that the batteries were used a lot more in the solar system than was the case with the wind system. The DMaps in Figure 5.40, Figure 5.41 and Figure 5.42 below illustrate the battery usage for each system in a year.

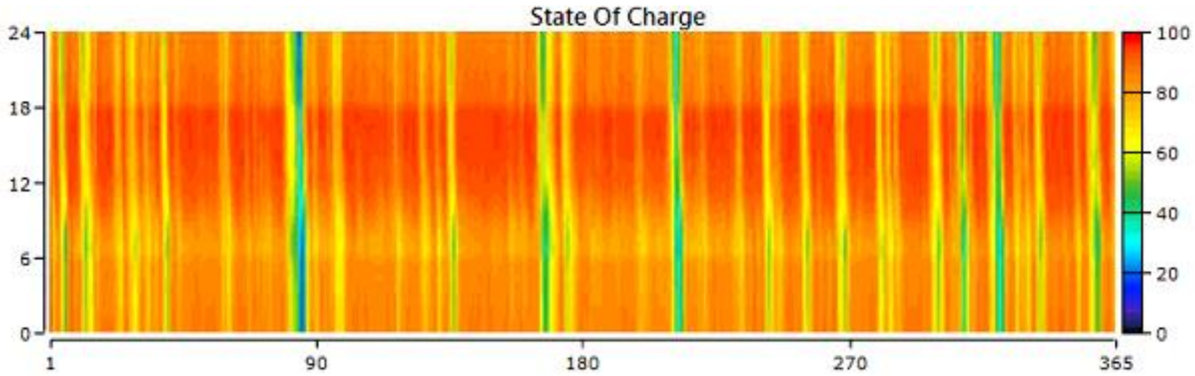


Figure 5.40 Battery state of charge DMap for the solar system

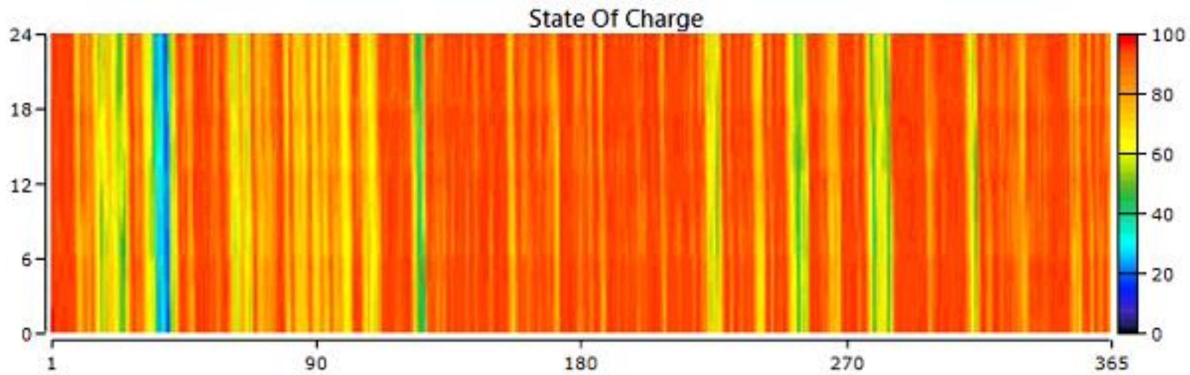


Figure 5.41 Battery state of charge DMap for the wind system

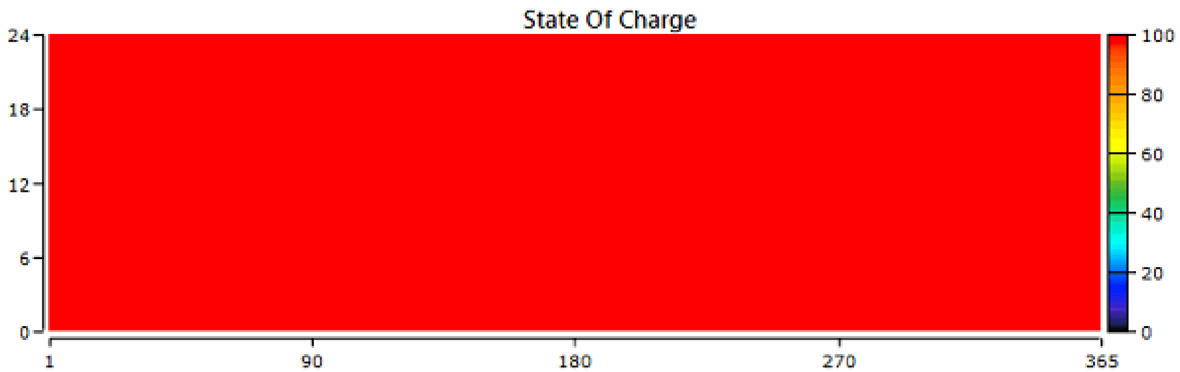


Figure 5.42 Battery state of charge DMap for the microhydro system

It is clear from Figure 5.40 and Figure 5.41 that high battery usage is evident in the solar and wind systems. Of note is that batteries are not discharged for the microhydro system. This was the case as the flow rate for the village was sufficient to meet the village's load throughout the year.

6 Conclusion and Recommendations

In Chapter 5, the results from the different case studies were analysed and discussed. Based on this analysis, it is evident that the choice of renewable resource is not a simple case of determining what the strongest resource is and implementing that system. The aim of this research was to investigate the techno-economic feasibility of standalone, off-grid microgrids for rural electrification with particular focus on solar, wind and microhydro as generation sources. Three villages namely De Grens, Emntla and KwanGqikiza were selected to model each off-grid microgrid system. The conclusions and recommendations of this investigation are given below.

6.1 Conclusions

Strength of resource versus cost for different locations

The first case study compared the renewable energy systems using the same resource and technology in each village, e.g. solar, wind or microhydro. Since the components used were the same for each respective technology, any deviation in cost could be attributed to the strength of resource in the area. For the solar system the LCOE and NPC have a direct correlation to the solar irradiation in each village. As the irradiation increased, the cost reduced. As mentioned in the discussion of results, this result was as expected. A correlation between the irradiation and LCOE based on the results from the three villages is given in Figure 6.1 below.

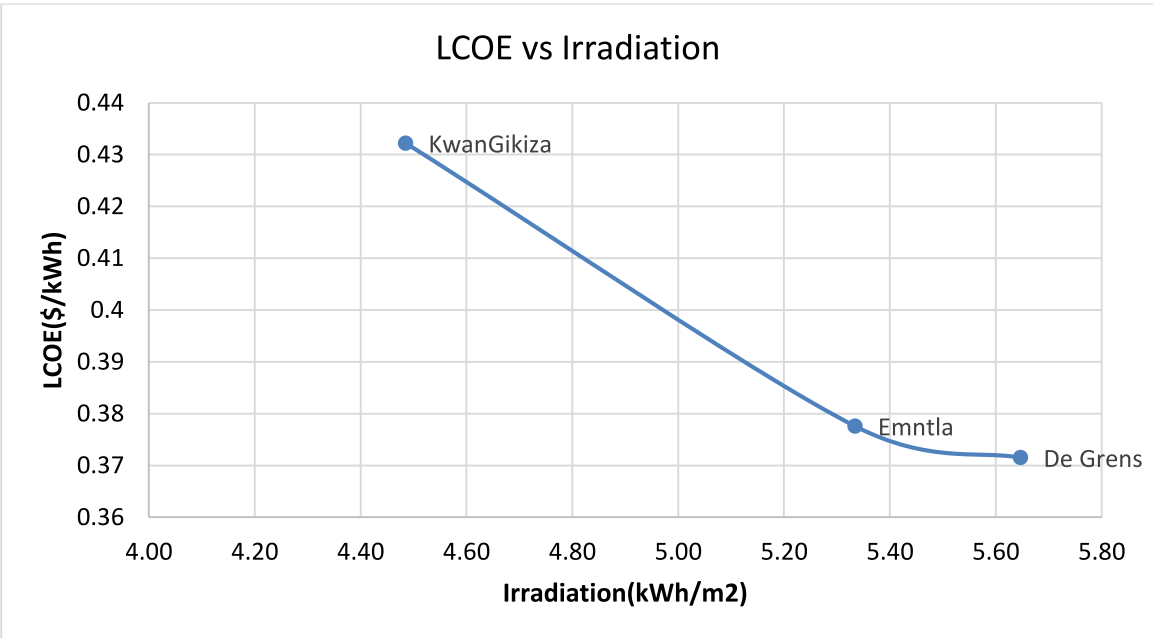


Figure 6.1 Correlation between irradiation and LCOE

The accuracy of this correlation may be compromised by the fact that there are only three data points, however, it does give a general idea of how LCOE and irradiation are related. There appear to be a steep rise in cost when the irradiation falls below 5.2 kWh/m^2 however, the cost levels off when the irradiation is above 5.4 kWh/m^2.

While looking at the wind systems for each village it is noted that they follow the same trend as the solar energy systems. The correlation between wind speed and LCOE for the three villages is given in Figure 6.2 below.

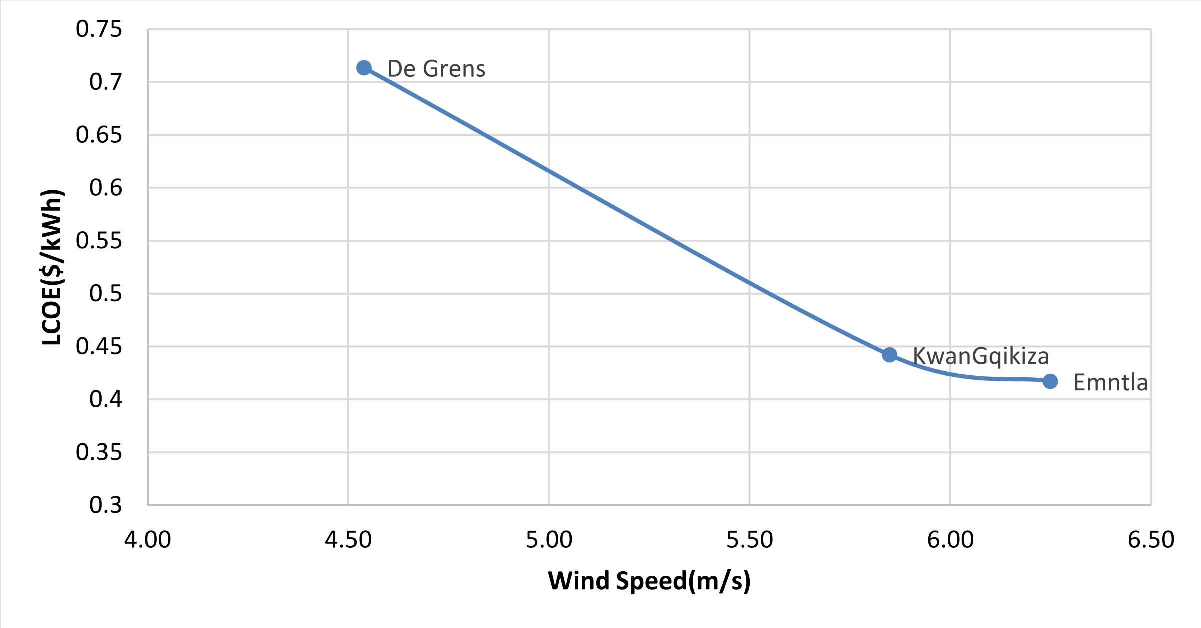


Figure 6.2 Correlation of wind speed and LCOE

The correlation of wind speed to LCOE is similar to the irradiation trend above, although the deviation in cost was much larger between the most expensive and second most expensive system. This shows that the cost of electricity from a wind system is more susceptible to changes in wind speeds, especially if the wind speed is below 6m/s.

The correlation between flow rate and LCOE for the microhydro systems (including costs of building a dam) is given in Figure 6.3 below.

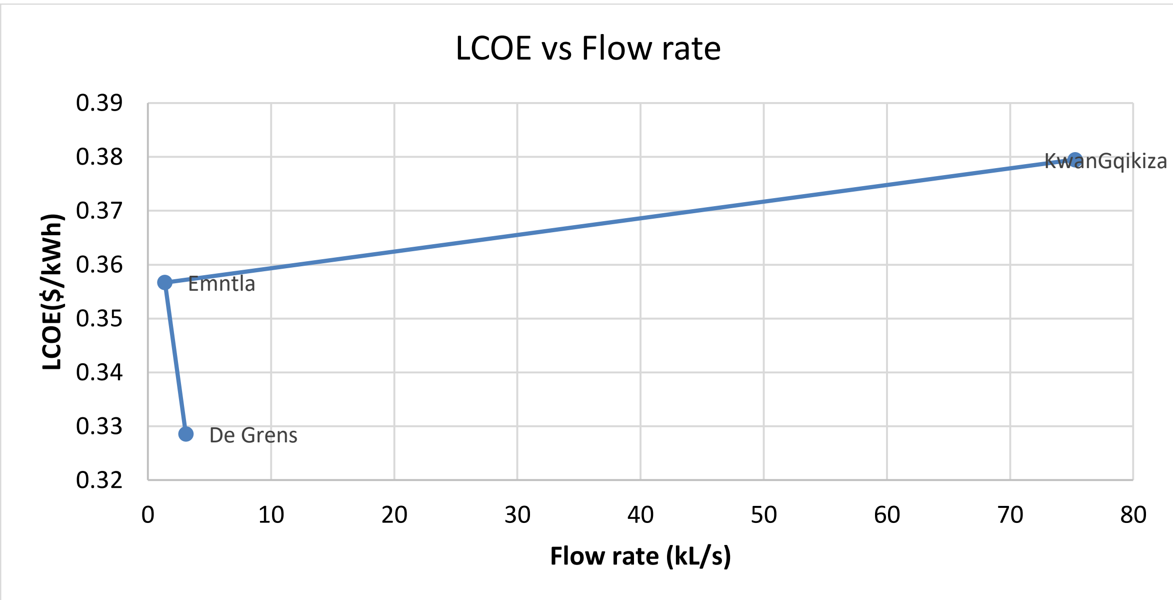


Figure 6.3 Correlation of microhydro flow rate and LCOE

The microhydro systems do not follow the same trend as the solar and wind technologies. The flow rate does not impact the LCOE because the capital costs and O&M costs are so high that they cancel any advantages a higher flow rate would give. Additionally, the capital and O&M costs are directly related to the size of the village.

Based on the results presented and analysed, it can be concluded that the strength of a resource impacts the LCOE for solar and wind systems, but not for the microhydro systems. The level of impact is different depending on the type of technology use, for example, in wind systems, a lower wind speed leads to a greater change in LCOE as compared to the other technologies.

Most appropriate technology for rural purposes

The second case study compares the technologies against one another for each respective village. The wind systems were the most expensive in each village, including the village with the strongest wind resource (wind village). This technology is therefore not suited for small scale rural generation (under 1 MW) and hence is not recommended for this purpose.

In all the villages the microhydro systems were the cheapest even when the construction of the dam was included in the cost. The drawback of microhydro is that only villages close to a water source with a fast enough flow rate can be powered by this resource. As noted in the results, a high amount of excess electricity is generated by microhydro systems because the systems are oversized to meet the village load profile peaks and there is constant generation throughout the day and night. Therefore, this system does not match the load fairly well. Should the system size be reduced, then the village would have a shortage of electricity during peak times. It is noted however, that the existence of a dam in close proximity to the village, further reduces the cost of the microhydro system with the LCOE being almost half of the price of what would be expected if a dam were to be constructed. Therefore, for De Grens and Emntla, a microhydro system would be the best option to supply power due to the presence of the existing dams.

The PV system LCOE came closest to the microhydro system (including cost of dam construction) price with an average difference of approximately $0.05/kWh for the three villages. Solar, although slightly more expensive, is a lot easier to implement. In South Africa, the solar resource is generally quite good, therefore this system does not have the same limitation of microhydro, where there has to be a river flowing close to the village. Solar energy systems have the drawback of not being able to generate at night, when the load is highest, however, this is mitigated by the use of batteries, which are the main contributors to the overall LCOE. Should the cost of batteries reduce or should the technology be improved, then these systems will be cheaper than microhydro systems.

Comparison between modelled costs and costs of similar systems in the literature

The cost of components for the modelled systems were obtained from the public domain (online store, manufacturer websites, etc.), so as provide an accurate, representative LCOE and NPV for the modelled systems. Table 2.3 in Section 2.5.2 provided the cost of different off-grid, hybrid, microgrid systems across the globe.

References [7], [10] and [14] looked at PV/battery systems and provided a LCOE for each. The LCOE costs in the literature ranged between $0.196/kWh - $0.75/kWh. The average LCOE for the systems was $0.395/kWh. The modelled LCOE was below this average for Emntla and De Grens but above for KwanGqikiza village. The modelled results differ from the those in the literature for the following reasons:

- The load profiles were much smoother with substantial peaks occurring during the day unlike the modelled systems where the load was high during the evening time. This meant that less batteries would be required with the systems with the PV/battery systems in the literature.

- The modelled systems took into consideration the O&M costs, whereas the above mentioned papers, with the exception of [10], did not consider O&M cost for PV. Some cost must be attributed to maintaining the system, addressing faults, cleaning the panels, security, etc.
- [7] did not take into consideration any financial assumptions such as inflation.

Only reference [5] looked at wind battery systems for three areas, two in Brazil and one in the United States of America. The LCOE for the villages ranged from $1.373/kWh - $2.797/kWh. High costs in reference [5] are due to the high assumed cost of the turbines. The results support assertions in the literature that wind battery systems are more expensive as compared to the other technologies.

Reference [12] provided a comparison between a PV/microhydro/diesel/battery and a microhydro/diesel. Since there was limited information on microhydro battery systems, the hybrid microhydro/diesel system is compared to the modelled microhydro/battery systems in the three villages. The cost of the microhydro/diesel system was $0.179/kWh. The microhydro system is different than the standard microhydro system as it operates using tidal energy and existing canal infrastructure, therefore no dams need to be constructed. When comparing against the modelled results for the three villages (assuming an existing dam), the results are within a similar range.

In general, a direct comparison with the literature is difficult because different assumptions lead to different results, especially in the case of solar. The trends for wind system and microhydro system, on the other hand, were more or less similar, in that microhydro and is the cheapest technology and wind is not suited for small scale generation.

Feasibility of building dams for microhydro systems

Modelling the microhydro system included comparing the LCOE and NPC of a microhydro system assuming a dam needs to be built versus implementing a microhydro system when assuming a dam already exists. From the results the LCOE difference of when a dam needs to be built is approximately double that of when a dam already exists. In spite of this, a noteworthy finding is that the LCOE including the cost of building a dam, is still cheaper than solar and wind technologies as discussed above.

The issues related to building a dam are not really technical and revolve more around the social and environmental impacts the dam would have on the surrounding area.

6.2 Recommendations for Future Research

Due to the time constraint and limited scope of this dissertation, there were some areas that were not investigated, that could add more value to this investigation. These are identified below.

Reducing excess electricity and avoiding overdesign

A high percentage of excess electricity was a recurring theme in all the systems, although the microhydro systems were particularly affected. This was due to the high peak in the load mainly because of the inclusion of the stove which had a high power rating as compared to the other electric devices used to model the load. As a result, the systems were oversized to meet this peak. In order to avoid this, it is recommended that a dump load is modelled in the village to absorb any excess electricity.

Another option would be to consider hybridised solutions. The benefit of hybrid microgrids is that they are designed to take advantage of the resources as at hand therefore, there is a lot more flexibility in terms of matching the load as well as improving reliability especially where wind and solar systems are concerned. This would lead to an overall more efficiently designed system as opposed to an overdesigned one.

Impact of different battery technologies on the LCOE

The batteries formed a great part of the overall cost especially for the wind and turbine systems. The cheapest battery technology is the lead acid battery; however, they have a short lifetime and hence need to be replaced regularly. A gel type electrolyte battery was selected for this project as it was relatively cheap and had a longer life, however, the battery industry has been growing and with new technologies and systems being developed, including comparisons of these newer battery technologies would be useful as it could lead to PV systems with lower LCOE. This would make them a more viable option even when a fast flowing river is located close to the village.

Detailed microhydro design to provide more accurate costs

The cost of constructing a dam was obtained by using a fixed price of $5,000/kW as sourced from reference [111]. However, using a fixed price means that the design of the dam is limited as the price is linked to the size of the system i.e. $/kW, as opposed to the size of the dam. A more detailed design can be carried out such that the dam is designed based on the flow rate of the dam. Therefore, should a river have a higher flow rate, the head would not need to be as great and thus a smaller dam could be constructed, which would be cheaper. Furthermore, the environmental and social factors related to building a dam can be investigated to determine their impact on the community, if any.

Comparison with biomass technology

This dissertation only focussed on solar, wind and PV technologies, however, South Africa has an abundance of biomass that could be used as a renewable energy option. A village with high amounts of biomass can be included in the investigation and compared against the other technologies. The limitation with this technology is the lack of biomass data.

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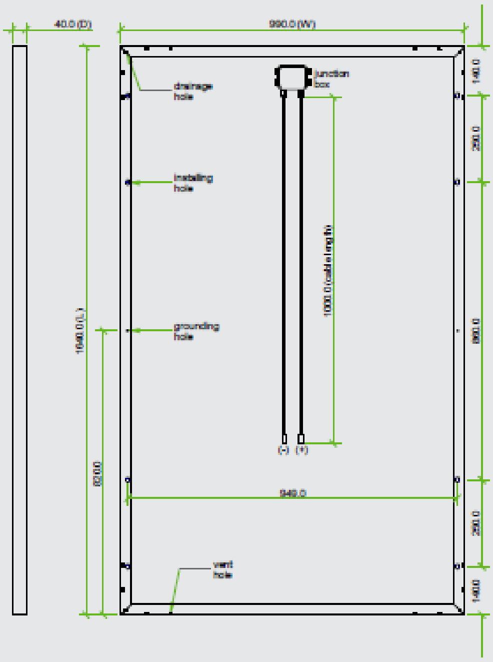
8 Appendices

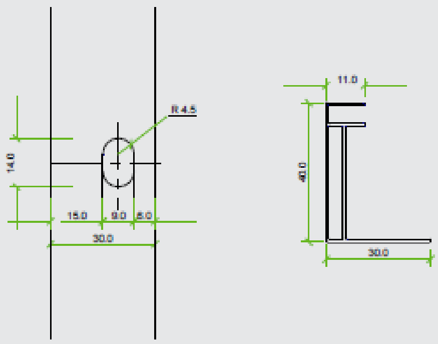
Appendix A – Component Datasheets

PV module – Enersol 255

EnerSol 255



General characteristics	
Cell	polycrystalline solar cell 156 x 156 mm
No. of Cells (Connections)	60 (6x10)
Panel Dimensions	1640 x 990 x 40 mm
Weight	19.0 kg
Connectors and Cables	Connectors and 1m cables



Thermal conditions	
Normal Operating Cell Temperature 800W/m² Irradiance, 20˚C, AM = 1.5	48˚C ± 2˚C
Power Temperature Coefficient	- 0.5%/K
Current Temperature Coefficient	0.035%/K
Voltage Temperature Coefficient	- 0.37 MV/K

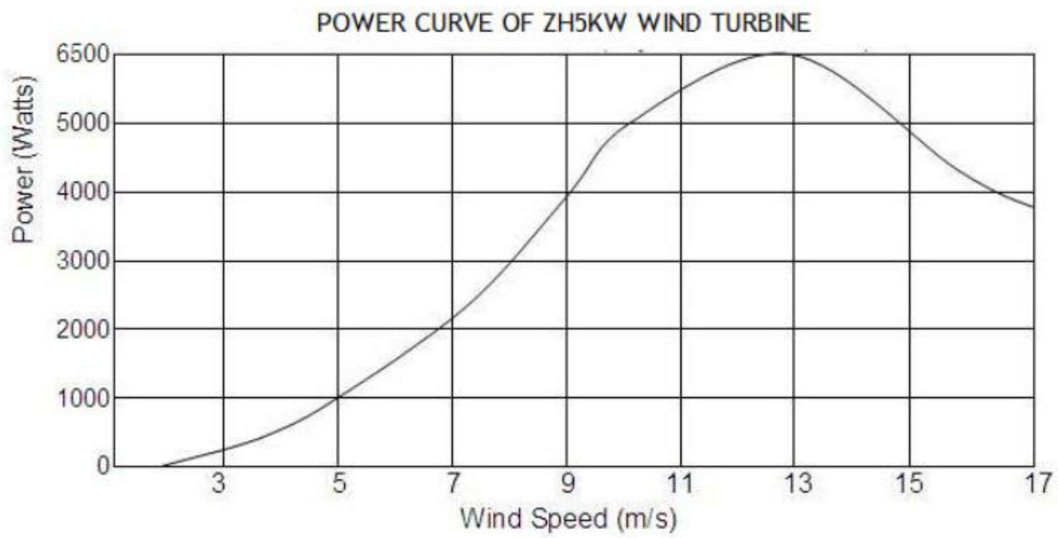
Limits	
Operating Temperature	- 40˚C to 85˚C
Maximum System Voltage	1000V DC

Electric performance at STC *	
Maximum Power	255 Wp
Power Tolerance	0/+5 Wp
Module efficiency	15.7%
Maximum Power Voltage	30.4V
Maximum Power Current	8.39A
Open Circuit Voltage	37.5V
Short Circuit Current	8.86A

*Standard Test Conditions : 1000W/m² irradiance, 25˚C and AM = 1.5

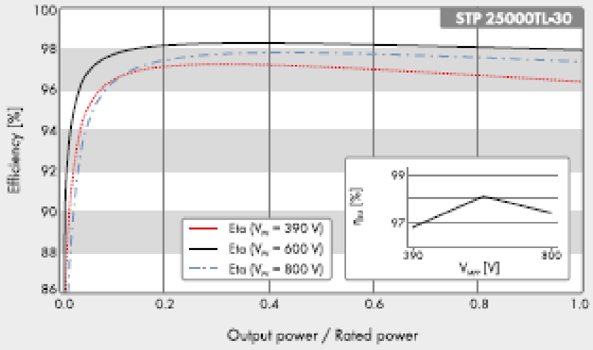
Wind turbine – Zonhan ZH5KW

Model: ZH5KW
Rotor Diameter, Meters/Feet: 6.0/20
Swept Area, Sqm/ Sqft: 28/314
Number Of Blades: 3
Blade Material: Fibre Glass Reinforced
Rated Power, Watts: 5000
@Rated Wind,M/S / Mph: 10/22.3
Peak Power @ 12.5 M/S: 6500
Cut-In Wind, M/S / Mph: 3/6.7
Output Form: 48vdc Nominal (Higher Voltage Optional)
Blade Pitch Control: None, Fixed Pitch
Noise: 55db(A) From 50m With A Wind Speed Of 8m/s
Overspeed Protection: Autofurl
Generator: Permanent Magnet Alternator
Tower Top Weight: 320kg.
Lateral Thrust: 24KN At 50m/s



Inverter – SMA Sunny Tripower 25000TL

Efficiency curve



Accessories


RS485 interface
DM-485CB-10


Power Control Module
PWCMOD-10


DC surge arrester (Type II), inputs A and B DCSPD KIT3-10

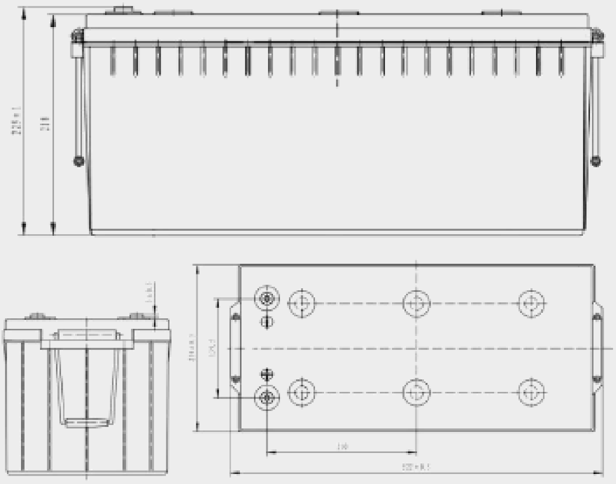

Multifunction relay
MFR01-10

● Standard features ○ Optional features – Not available
Data at nominal conditions
State: January 2016

Technical Data	Sunny Tripower 20000TL	Sunny Tripower 25000TL
Input (DC)		
Max. DC power (at cos φ = 1) / DC rated power	20440 W / 20440 W	25550 W / 25550 W
Max. input voltage	1000 V	1000 V
MPP voltage range / rated input voltage	320 V to 800 V / 600 V	390 V to 800 V / 600 V
Min. input voltage / start input voltage	150 V / 188 V	150 V / 188 V
Max. input current input A / input B	33 A / 33 A	33 A / 33 A
Number of independent MPP inputs / strings per MPP input	2 / A:3; B:3	2 / A:3; B:3
Output (AC)		
Rated power (at 230 V, 50 Hz)	20000 W	25000 W
Max. AC apparent power	20000 VA	25000 VA
AC nominal voltage	3 / N / PE; 220 V / 380 V 3 / N / PE; 230 V / 400 V 3 / N / PE; 240 V / 415 V	
AC voltage range	180 V to 280 V	
AC grid frequency / range	50 Hz / 44 Hz to 55 Hz 60 Hz / 54 Hz to 65 Hz	
Rated power frequency / rated grid voltage	50 Hz / 230 V	
Max. output current / Rated output current	29 A / 29 A	36.2 A / 36.2 A
Power factor at rated power / Adjustable displacement power factor	1 / 0 overexcited to 0 underexcited	
THD	≤ 3 %	
Feed-in phases / connection phases	3 / 3	
Efficiency		
Max. efficiency / European Efficiency	98.4% / 98.0%	98.3% / 98.1%
Protective devices		
DC-side disconnection device	●	
Ground fault monitoring / grid monitoring	● / ●	
DC surge arrester (Type II) can be integrated	○	
DC reverse polarity protection / AC short-circuit current capability / galvanically isolated	● / ● / –	
All-pole sensitive residual-current monitoring unit	●	
Protection class (according to IEC 62109-1) / overvoltage category (according to IEC 62109-1)	I / AC: III; DC: II	
General data		
Dimensions (W / H / D)	661 / 682 / 264 mm (26.0 / 26.9 / 10.4 inch)	
Weight	61 kg (134.48 lb)	
Operating temperature range	−25 °C to +60 °C (−13 °F to +140 °F)	
Noise emission (typical)	51 dB(A)	
Self-consumption (at night)	1 W	
Topology / cooling concept	Transformerless / Opticool	
Degree of protection (as per IEC 60529)	IP65	
Climatic category (according to IEC 60721-3-4)	4K4H	
Maximum permissible value for relative humidity (non-condensing)	100%	

Battery – SDDirect Pro AGM G+

AGM G+ 12-200



Product characteristics at 25°C

Dimensions	522 x 234 x 223 mm
Weight	58 kg
Expected life	10 years*
Internal resistance	3.00 mΩ
Self discharge rate	≤ 1.5% per month
Max charge current	40A
Max discharge current	1400A/5 sec

Rated capacity at 25°C and 1.8V per cell

C20	C10	C5
200 Ah	186 Ah	170 Ah

C20, C10, C5 = capacity at 20, 10, 5h discharge

Charge Voltage at 25°C

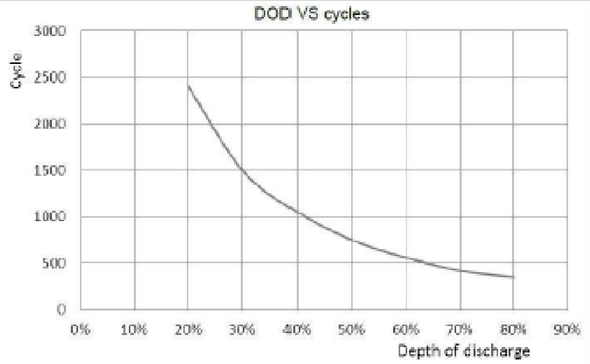
Cycle use	14.4 V
*Standby use	13.5 V

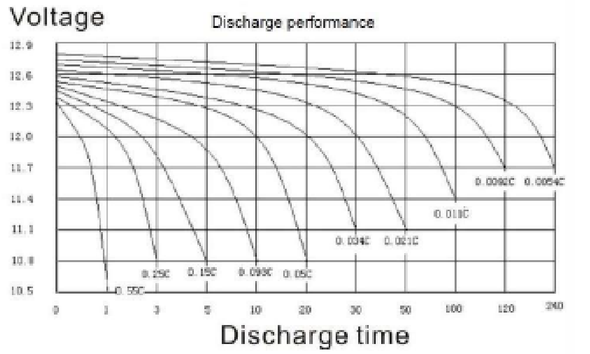
Constant current discharge at 25°C (A)

End voltage (V/cell)	1h	3h	5h	10h	20h	50h	100h	120h	240h
1.70	111.30	51.27	34.86	19.95	10.13	4.52	2.59	2.30	1.18
1.75	110.00	50.79	34.29	18.88	10.06	4.35	2.37	2.09	1.10
1.80	105.00	50.00	34.00	18.60	10.00	4.29	2.30	1.93	1.08
1.85	97.91	47.06	32.21	17.99	9.65	4.20	2.25	1.87	1.06
1.90	94.01	46.65	29.75	17.07	9.34	3.91	2.20	1.84	1.04

Constant power discharge at 25°C (W/cell)

End voltage (V/cell)	1h	3h	5h	10h	20h	50h	100h	120h	240h
1.70	201.0	86.80	60.5	36.0	19.5	9.80	5.02	4.20	2.15
1.75	194.5	83.20	59.0	35.0	19.3	9.75	4.93	4.15	2.10
1.80	189.0	81.60	57.5	34.5	19.0	9.60	4.86	4.10	2.06
1.85	183.0	78.90	56.0	33.5	18.5	9.50	4.81	4.05	2.04
1.90	177.5	76.45	54.5	32.5	18.2	9.30	4.73	4.02	2.02





Appendix B – Assessment in Ethics in Research Projects

Application for Approval of Ethics in Research (EiR) Projects
Faculty of Engineering and the Built Environment, University of Cape Town

APPLICATION FORM

Please Note:
Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form **before** collecting or analysing data.The objective of submitting this application *prior* to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the **EBE Ethics in Research Handbook**(available from the UCT EBE, Research Ethics website) prior to completing this application form: http://www.ebe.uct.ac.za/usr/ebe/research/ethics.pdf

APPLICANT'S DETAILS		
Name of principal researcher, student or external applicant		Himal Patel
Department		Electrical Engineering
Preferred email address of applicant:		Himalpatel1989@gmail.com
If a Student	Your Degree: e.g., MSc, PhD, etc.,	MSc
	Name of Supervisor (if supervised):	Dr Sunetra Chowdhury
If this is a researchcontract, indicate the source of funding/sponsorship		Self-funded
Project Title		Techno-Economic Comparison of Standalone Microgrids for Rural Electrification in South Africa

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	Signature	Date
Principal Researcher/ Student/External applicant	Himal Patel		**20 Jun 2017**

APPLICATION APPROVED BY	Full name	Signature	Date
Supervisor (where applicable)	Dr. Sunetra Chowdhury		4/7/17 Click here to enter a date.
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section1; and for all Undergraduateresearch (Including Honours).	E. Boje		Click here to enter a date.
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.	Click here to enter text.		Click here to enter a date.