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A case study investigating renewable energy provision for a rural village in South Africa.

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Project Brief

Access to safe and reliable energy services enables people to experience a greater standard of living, in addition to being more productive, thus fuelling economic and social development. While the South African government has electrified approximately 85% of homes to date, factors like, the increasing cost of electrification by grid connection, due to sparsely populated rural settlements, as well as the rate at which new homes are built yearly; make it clear that effective universal electrification (95% and above) will not be achievable for decades to come. This would affect people in rural settlements most, as their access to basic services and their standard of living would be compromised. New methods and technologies for energy production and supply must therefore be designed and implemented and the most promising of these is Decentralised Renewable Energy Technologies (DRETs) which include; solar PV, hydroelectric, biogas and wind power. South Africa's energy policies on DRETs are comprehensive and supportive and are outlined in the White Paper on Energy Policy (1998) and the White Paper on Renewable Energy (2003). Despite this obvious intent from government and policy makers to make use of these technologies, projects involving DRETs in South Africa tend to underachieve. This is due to a host of reasons however this project aims to improve the efficiency and efficacy of DRET system installers by providing a guide for assessing sites and selecting appropriate technologies as well as the configurations thereof.

SUPERVISOR: *Bruce Kloot*

Word Count: 9847 words

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To my family, friends and The Bowling Club, your love and support got me through the most difficult year of my life. While it is my final year project, it is also signifies the beginning of my journey exploring my passions and without all of you, I could’ve never completed this year, much less this project which means the world to me.

Abstract

Electrification is important for the improvement of a community's standards of living and quality of life. Electricity, in South Africa, is supplied using predominantly coal-fired power stations which supply the grid and this power is then transmitted to the consumer. The South African Government recognises their responsibility to ensure access to electricity for all its citizens, especially for the poor in rural areas. However, the government has fallen short of their Universal Electrification target since the remaining households (not grid connected) are typically situated in deeply rural areas and it is not feasible to connect them via the grid.

Jerusalem Village, in Moletjie under the Aganang Municipality, is one such community. Households within the village were surveyed and it was found that at least 33% of the households spend 10%, or more, of their monthly income on acquiring energy or energy services and therefore are classified as energy-poor. Moreover, some of the energy resources that are available to households are inefficient, hazardous or inconvenient. The residents of the village stand to benefit greatly from the design and implementation of a Decentralised Renewable Energy Generation System. Such a system provides the opportunity for rapidly installed, on-site, renewable electricity generation which wouldn't need to be distributed through costly grid infrastructure. Therefore, a Decentralised Renewable Energy Generation System was designed, for the village, using HOMER Pro. This system comprised of:

- A 500 kW Biogas Generator.
- An array of Solar PV panels with a 58.6 kW generation capacity.
- An array of 3, 100 kWh Lead-Acid Batteries.
- A converter.

The designed system was able to meet residential electricity demand which was calculated and modelled using HOMER Pro. While the designed system was technically feasible, it was found that the cost of electricity production for the system (2.32 R/kWh) rendered it financially unfeasible since this was higher than the current cost incurred by Eskom. This higher cost is predominantly due to the capital, operation and maintenance costs associated with the Lithium-ion batteries used. However, these costs will decrease as the technology is improved, thanks to the extensive investment and research in the field. Therefore, a system of this nature will soon be feasible and advantageous.

CONTENTS

1. Introduction

Electrification is known for increasing a population's quality of life and encouraging growth in a range of socio-economic spheres (Khandker, et al., 2012). The South African Government recognises their responsibility to ensure access to electricity for all its citizens, especially for the poor in rural areas and has managed to increase the national rate of electrification to 88% since 1994 (South African Government, 2020). However, the South African Department of Energy (DOE) found that the remaining households are typically situated in deeply rural areas and that it was economically unviable to electrify these areas in the medium-term, via the grid (2012: 3). This led to the drafting of the New Household Electrification Strategy, which aimed to develop a master plan to increase the efficiency of the planning and delivery of electrification projects; to ensure an increased electrification rate. Critically, this strategy made specific mention of exploring the employment of renewable energy technologies to achieve this objective (Department of Energy, 2013).

Therefore, this project aims to investigate the feasibility of designing and implementing a decentralised renewable energy system for the electrification of a rural village. This will be done by simulating a modelled system and assessing it on its technical and financial feasibility.

1.1 Background

Non-renewable resources are naturally occurring raw materials which are in limited supply; these include wood and fossil fuels such as coal and crude oil (Steinbach & Wellmer, 2010). However, renewable resources are naturally occurring. They are replenished through natural cycles and cannot be depleted (Owusu & Asumadu-Sarkodie, 2016). Renewable resources include bioenergy, wind, solar radiation and several others (Owusu & Asumadu-Sarkodie, 2016).

Therefore, renewable energy systems are technologies which are used to convert this energy into electrical energy. There are various technologies which are in different stages of development and according to Power Technology, renewable energy power generation is rapidly increasing in capacity and the most prevalent technologies used based on installed generation capacity worldwide include hydropower turbines, wind turbines and solar power (photovoltaic etc.) (Verdict Media Limited, 2020).

However, South Africa has historically powered the country predominantly through coal-fired power stations which supply the grid and this power is then transmitted to the consumer. According to GreenCape, coal power accounted for over 90% of the nation's energy production with the rest being supplied by nuclear, hydro and very recently, other renewable energies like wind and solar power (2019: 6). Aside from the high carbon and toxic gas emissions associated with burning coal to produce electricity (Union of Concerned Scientists, 2019), the fact that these plants are very expensive to build and must be built at scale makes them an incredibly one-dimensional solution to a complex problem. Moreover, the electricity generated by these plants must be transmitted via the grid and the dispersed nature of homes in rural villages, along with the secluded nature of these villages makes it unfeasible to connect these communities to the grid (Department of Energy, 2012). It is overwhelmingly clear that the country's dependence on large coal power stations, the ever-increasing cost of expanding the grid network and the rising demand for electricity due to rapidly developing rural areas, are key barriers to achieving the goal of universal electrification set by the DOE.

A study conducted to understand the determinants of the willingness of households to pay for water and electricity services in Moletjie found that 73% of the sampled households within the Aganang municipality were unhappy with the unreliable electricity services, however, 87% were willing to pay for these services (Nkoana, et al., 2019). This is an example of how the traditional methods of electrification by the government and Eskom, to developing rural areas, is not producing the desired result. Therefore, Moletjie serves as an example of how energy generation and service delivery need to be improved.

1.2 Problem Definition

Jerusalem Village is situated within Moletjie, in the Aganang municipality, and has approximately 200 households. Due to the high cost of extending the grid and the time, it would take to put such a project in motion, it is highly unlikely that there will be grid infrastructure for electricity supply in the village, in the near future. This has meant that households have been left to find their own means of accessing the energy they need for daily tasks. Given the mandate of the South African Government and its Department of Energy, this is a problem that must be addressed, and the solution should be both feasible and sustainable.

Decentralised Renewable energy generation systems (DREGS) give the opportunity for rapidly installed, on-site, electricity generation which wouldn't need to be distributed through costly grid infrastructure. Not only would this mean cleaner energy generation for the people of the village, but it would also come far sooner than if a new coal power station or grid network would need to be built. Therefore, a DREGS provides a unique opportunity to solve the problem of energy supply to this village and will be explored by designing and simulating such a system.

1.3 Scope and Limitations

Given the interdisciplinary nature of the problem, due to the diversity of the stakeholders and their interests, the focus of the report will be on the development of a DREGS for the village in question which meets technical requirements and is financially feasible. While it is recognised that socio-economic factors such as community co-operation and income disparities due to unemployment also have a tangible effect on the success of the implementation of such projects, these will not be discussed in detail.

A survey aimed at understanding the energy demand, costs, usage and types of energy sources used by the residents of Jerusalem Village was distributed and the results are discussed. This survey, however, could not be conducted in person by myself due to health and travel concerns surrounding the Covid-19 pandemic. It was instead conducted by a family member who works closely with members of the community. This was done to ensure that the results of the survey remain reliable.

1.4 Plan of development

The report will begin by providing insight into the problem through a literature review, which will analyse the foundational causes of the problem, studies which tackle a similar problem and the technologies that could be used as part of the potential solution. This will give an in-depth understanding of both the problem and its potential solutions. Thereafter, the methodology employed in the formulation and execution of both the survey of the community and the simulation of the DREGS will be discussed. This is done in order to give other researchers the opportunity to not only replicate this work but also find ways to improve upon it. The findings of the survey and simulation will then be presented and discussed in detail, using insight derived from the literature review. Finally, the conclusions drawn from this study and the resulting recommendations will be presented.

2. Literature Review

2.1 What is electrification and what is the case for South African rural villages?

Electrification can be defined as an individual or population's access to reliable electricity services. Itis known for increasing a population's quality of life as well as encouraging growth in a range of socio-economic spheres by:

- improving overall economic productivity through extended business hours,
- allowing children to study at night,
- and reducing indoor air pollution in the case of substituting paraffin or kerosene lighting with electrical lighting, to name but a few (Khandker, et al., 2012).

Electricity is the most advanced and efficient energy source available to modern society however, not everybody has adequate access. Access to modern energy is defined as a household's ability to obtain an energy source. This access is a function of availability and affordability. Availability dictates whether or not the energy supply is within the economic connection and range of supply of the household whereas, affordability brings into question the ability of the household to pay the capital (upfront connection) and usage costs (Watson & Johnson, 2010).

Most rural societies struggle with access to modern energy services due to a combination of both availability and affordability. This results in the often-observed dependence on traditional fuel sources such as biomass (firewood and charcoal). The lack of modern energy services leaves these societies at a disadvantage and often manifests in energy poverty, which can be seen by the fact that these societies remain at the bottom of the "energy ladder". This energy ladder is an energy transition model which describes how households "rise" through energy sources of increased efficiency. Traditional biomass fuels are at the bottom of the ladder and transition fuels, like kerosene and paraffin, are then utilised by households as industrialisation, urbanisation and incomes increase. This gradual increase in urbanisation finally results in the transition to modern energy sources such as electricity (Vermaak, et al., 2014).

A study conducted by Ismail & Khembo (2015) aimed at assessing the determinants of energy poverty in South Africa, supports this energy transition model. The point at which a household regularly faces having to make difficult decisions between satisfying their energy needs and spending on other necessities like transport to work is an indicator of energy poverty and there are several different methods for quantifying this point according to Ismail & Khembo (2015):

1. The income approach bases energy poverty on the proportion of a household's income which is used to acquire basic energy services. Through this approach, it becomes evident that the households with the lowest incomes often spend more of their income on energy than higher-income households.
2. The self-reported approach is based on the household's idea of "enough" energy and associated cost thereof.
3. The objective approach calculates the proportion of a household's income that must be spent on energy. The household is usually deemed energy poor if more than 10% of its income is used on energy.
4. The access-adjusted approach analyses the accessibility of energy sources for households in specific areas.
5. The expenditure approach is widely considered to be the universal measure of energy poverty and is favoured by many governments including the UK. Households with energy expenditure that exceeds a predetermined threshold (usually 10-15% of income) are deemed energy poor.

The dependence on the burning of traditional fuels has negative impacts on living standards and productivity namely, exposure to indoor air pollution which affects respiratory health as well as extensive time and effort for collection which reduces the time for productivity (Watson & Johnson, 2010).

The South African Government recognises their responsibility to ensure access to electricity for all its citizens, especially for the poor in rural areas and has managed to increase the national rate of electrification to 88% since 1994, through the Integrated National Electrification Programme (INEP). The INEP was aimed at reaching the target of 'universal electrification' through main grid connections which are supplied by Eskom power stations. This target was set at approximately 92% of formal South African households by 2014 (Department of Energy, 2012).

While the DOE believes that the 90% target is still achievable through the programme, it recognised that the remaining households would need to be electrified through high quality, off-grid, solar home systems or other technologies. This is due to the fact that these remaining homes are typically within rural areas and in 2011, it was determined that it is economically unviable to electrify these areas in the medium-term, via the grid, due to the dispersed nature of rural settlements, the high fixed costs of grid extensions and the ever-rising cost of materials and electricity. Moreover, the environmental benefits of employing renewable energy technologies to bridge this gap were emphasized (Department of Energy, 2012).

This led to the initiation of the New Household Electrification Strategy, which: increased the universal electrification target to 97% by 2025, shifted the focus of electrification to using more high-quality renewable energy systems to reach this increased target (as opposed to centralised coal plants) and aimed to develop a master plan to increase the efficiency of the planning and delivery of electrification projects (Department of Energy, 2013). In addition to this, The Department of Environmental Affairs (DEA) Report on the Sustainability of Decentralised Renewable Energy Technology Systems for off-grid areas was published in 2015. This report makes use of household figures from a University of South Africa study, to make it abundantly clear that the backlog of un-electrified homes given the projected growth rates, will increase and cannot feasibly be covered by grid connections alone. As previously noted, the lack of quality energy services in Moletjie and the Aganang municipality is a prime example of this shortfall.

2.2 Renewable vs non-renewable resources

Non-renewable resources are naturally occurring raw materials which are in limited supply; these include wood and fossil fuels such as coal and crude oil (Steinbach & Wellmer, 2010). The process of fossil fuel formation is characterised by the burial of organic material by sediment, under high pressure and temperatures over millions of years (Stenhouse, et al., 2018). However, the variety of conditions under which this general process occurs, give rise to the different types of fossil fuels, their quality and composition as well as how easily they can be accessed (Stenhouse, et al., 2018). The most commonly used non-renewable resources historically are coal, oil and natural gas (Owusu & Asumadu-Sarkodie, 2016). Given the amount of time for these fuels to be formed, the threat of depletion, despite the perceived abundance of these resources shown by Caineng, et al. is a serious one (2016: 3). This is evident in Krautkraemer's analysis of non-renewable resource scarcity and consumption through the basic Hotelling Model of Non-renewable Resource Scarcity using a known finite supply (1998: 2067). Fossil fuels also have a high carbon content of calorific value in tonnes (t) per Tera Joule (TJ) as a result of their composition of organic material, typically 26.37 t/TJ in coal, 20.1 t/TJ in crude oil and 15.3 t/TJ in natural gas (Caineng, et al., 2016). This is the reason the burning of fossil fuels for energy releases large amounts of CO_2 into the atmosphere which contributes to global warming as a result of the greenhouse gas effect.

According to Owusu & Asumadu-Sarkodie, renewable resources are naturally occurring materials or substances which are replenished through natural cycles and cannot be deleted. These include bioenergy, wind, hydro-energy, geothermal energy, solar radiation and ocean or tide and wave energy (2016: 4). These resources have little to no carbon content and are newer energy resources compared to fossil fuels (Caineng, et al., 2016).

That said, it is imperative that the availability of a renewable resource in a specific location be assessed as this has an effect on the technologies and systems that can be used to generate electricity in the area (Knight, 2016). The decentralised nature of renewable energy generation comes with the constraint of generation at sites where the resource is in abundance. Therefore, "understanding which renewable energy resources exist where, and to what extent, is critical to scaling up commercial development" (Knight, 2016: 3). These assessments are conducted in a variety of ways and depend on the resource in question, however, in general, an analysis of meteorological data as well as site observations and tests are the most important tools available.

2.3 Renewable energy systems

Renewable energy systems make use of renewable resources often by converting one form of energy into another and finally producing electrical energy. Turkenburg & Faaij outline some of these systems, indicating their product and various applications (2000: 221). These technologies include; biomass digesters and gasifiers, wind turbines, solar PV cells, hydro-turbines, geothermal systems and marine energy systems. However, an analysis of the most prevalent technologies used based on installed generation capacity world-wide as of 2018, by Power Technology, indicated that hydropower, wind turbines and solar power were the world's most used renewable energy systems (Verdict Media Limited, 2020).

2.3.1 Hydropower

Hydropower generation can be achieved through various means however, the most common method used today involves the construction of dams on rivers and releasing water from the dam down a gradient to drive turbines. This is therefore, a conversion of the potential energy of the water, as a result of its mass and vertical distance above the turbines, to kinetic energy through the flow of the water and spinning of the turbine (Office of Energy Efficiency & Renewable Energy, 2020).

Hydropower was found to be the most extensively used renewable power source, by far, with a global installed capacity of over 1,295GW. This amounts to more than more than 54% of the global renewable power generation capacity and more than 18% of the world's total installed power generation capacity (Verdict Media Limited, 2020).

China has the largest hydroelectric generation capacity in the world and is home to the world's largest hydropower plant, outputting 22.5GW. The nation accounted for approximately 40% of the total hydroelectric capacity added in the world in 2018. Other countries with significant hydropower generation capacity include Brazil, the USA, Canada and Russia (Verdict Media Limited, 2020).

2.3.2 Wind power

Wind power generation uses the kinetic energy of the wind to turn blades and this kinetic energy is converted to electricity using a turbine (U.S. Department of Energy, 2020). It is the second most used renewable energy technology with global installed power capacity exceeding 563GW. This is approximately 24% of the world's total renewable energy generation capacity (Verdict Media Limited, 2020).

China is once again is the biggest wind energy generator in the world (184 GW), followed by the USA (94 GW). These two countries along with others like Germany, Spain and the UK; produce more than 85% of total wind power produced globally (Verdict Media Limited, 2020).

2.3.3 Solar power

486 GW of global installed capacity as well as the annual growth rate of cumulative solar energy capacity averaging 25% during the past five years, not only makes solar power the third largest renewable power source in the world but also, the fastest growing renewable power source and photovoltaic (PV) technology dominates this (Verdict Media Limited, 2020). PV technology makes use of materials which absorb photons of light and release electrons thereby converting radiant energy

into electricity (NASA , 2020).

Asian countries were responsible for approximately 70% of the global solar power expansion in 2018 while the 1.17 GW Noor Abu Dhabi solar project is the biggest single-site solar power plant in the world (Verdict Media Limited, 2020).

These technologies are being used more frequently and on massive scales, but renewable energy systems also have smaller-scale applications. The most notable of these is solar PV panels used residentially, all over the world and especially recently, in South Africa. It is imperative to note that the use of these panels gives these homes a degree of independence from relying on South Africa’s unreliable, monopoly, power utility; Eskom. This degree of independence depends on the installed capacity and the electricity demand of the household. This can render a home partially or completely off-grid; and this is characterised as decentralisation because the energy consumed by the household is not completely dependent on access to, nor reliability of the grid. DREGS are defined as ‘off-grid’ systems in terms of the electricity network which are powered by renewable energy sources, including: small hydro, biomass, biogas, solar and wind power thereby delivering energy services to end users (Department of Environmental Affairs, 2015).

2.3.4 Biogas Generators

Biogas is a combustible gas mixture, consisting mostly of methane and is produced by anaerobic digestion of organic matter, such as plants and organic waste (Sacher, et al., 2020).

In order to produce biogas a digester is needed and there are various types based on their design, namely: fixed digester (fixed dome), cylinder digester, balloon digester and glass fibre digester (Wahyuni, et al., 2018). Agbeyote & Kusimo concluded that their designed 168 litre biogas production plant produce biogas optimally depending on the waste used. Therefore, their objective of designing building and testing a biogas production plant for use in rural areas was achieved (2015: 87).

A biogas generator is comprised of a combustion engine that converts the chemical potential energy of the gas into mechanical energy which is in turn converted to electrical energy by a generator (Sacher, et al., 2020).

2.4 Important Studies

As previously emphasized; the aim of the project is to model a DREGS for a rural village and in order to do so effectively, similar case studies were analysed with the following findings.

Firstly, primary data for the population demographic, socio-economic and energy statistics are collected either through primary research of a specific sample size or through access to municipal records. Regarding energy statistics, particular emphasis is placed on categorising the energy demand by its use for example; cooking or heating. Meteorological data is used to determine the typical climate over a year as well as make assumptions about the future climate of the area. This helps the researchers rule out any unfeasible renewable energy technologies in their design or from the output of the modelling software.

The case studies vary in aim from predominantly economic analyses and modelling to a combination of engineering and socio-economic analysis; which results in the different methods for obtaining the model DREGS. Some of the case studies make use of modelling software such as the Model for Analysis of Energy Demand (MAED), which is developed by the International Atomic Energy Agency (IAIAE) and EnergyPLAN which is developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University, Denmark. The review of modelling approaches and tools for the simulation of district-scale energy systems, conducted by Allegrini, et al. shows that there are plenty of options when choosing software. These software are also often tailored to specific industries or for specific outcomes and have varying analysis algorithms and complexity levels. The software typically follows a process as shown in figure 1 below (2015: 1397).

Figure 1: Flow Diagram showing the typical operation of energy modelling software.

3. Methodology

3.1 Survey design

- The aim of the survey was to gather information that could give insight into: the various sources of energy used in different households in the village, what the energy is used for, as well as the costs associated with this energy consumption.

- This in turn, would be used to understand the needs of the village and give a sense of whether energy poverty is a concern for the village.
- The first draft was tested amongst a few friends to assess whether the questions were phrased in such a way that the respondents could understand and give reliable answers.
- The survey was then edited, and a final draft was completed. A consent form describing the purpose of the survey, explaining the respondent's rights and assuring them of their anonymity was also drafted and attached.
- The number of households to be surveyed was first calculated using a sample size analysis:

$$Necessary\ sample\ size = \frac{2 \times (Z.score) \times (StdDev) \times (1 - StdDev)}{(margin\ of\ error)^2}$$

Where:

Z.score – Z score from distribution

StdDev – Standard Deviation

The total number of households in the village was given as 200. This figure was used as the population size. A margin of error of 10%, confidence interval of 90% (z score of 1.645) and a standard deviation of 0.1 were selected.

$$Necessary\ sample\ size = \frac{2 \times (1.645) \times (0.1) \times (1 - 0.1)}{(0.1)^2}$$

$$Necessary\ sample\ size = 30\ households$$

- Thereafter the survey was conducted with three households and monitored via phone call to ensure the process was up to standard.
- The remaining surveys were conducted, and the completed forms were delivered for analysis.
- Due to time and safety concerns surrounding conducting the surveys because of the Covid-19 pandemic, a total of 27 surveys were conducted.
- A copy of the final survey form used can be found in the appendix.

3.2 Decentralised renewable energy system design

The approach for simulating the system was as follows:

- The renewable energy system would be modelled and simulated using software which had to be chosen based on the needs and constraints for the project. Therefore, an analysis of several options best suited to the requirements of this project was completed.
- Thereafter a high-level analysis of the design was done in order to inform the decisions made in the modelling and simulation of the system.
- The system was then modelled and simulated using the chosen software.

3.3 Software analysis and selection

It was imperative to find software that could not only model a proposed energy system for the village but also output the information necessary to be able to complete a technical and financial assessment of the proposed solution. The starting point for the search for the most appropriate software was to work through “The review of modelling approaches and tools for the simulation of district-scale energy systems” by Allegrini, et al. In this article, detailed information on many of the software tools that are available for the simulation and analysis of urban energy systems is given. A breakdown of the software tools which can address different interest areas and the depth to which the software can do so is also outlined.

From the matrix provided on page 1397, the best three candidates were determined using both their capabilities for modelling in the different topic areas, as described in the article, as well as on their websites. The top three were found to be: RETScreen, EnergyPro and HOMER Pro.

All three software tools provide technical and economic analyses of either custom or generated energy systems, however, they are tailored to different applications as well as customers and focus on different aspects as a result. Therefore, the next step in choosing the best software for the project was to do a detailed analysis of each software’s features and capabilities, to assess the best fit. Given the limited funding and time for the project, other factors such as cost and ease of use for each software were also assessed.

3.3.1 RETScreen

RETScreen is a Clean Energy Management Software which is used for energy efficiency, renewable energy and cogeneration project feasibility analysis, as well as continuous energy performance analysis (Natural Resources Canada, 2020).

This software enables professionals to quickly find, assess and optimize the technical and financial viability of potential clean energy projects. It also allows managers to measure and verify the real-world performance of their facilities with ease and can aid in finding extra energy-saving or production opportunities. RETScreen is developed and supported by Natural Resources Canada. A free viewer mode of the premium version of the software is available for download (Natural Resources Canada, 2020).

3.3.2 EnergyPRO

EnergyPRO is used for in-depth technical and financial analyses of existing and new energy projects within a very user-friendly interface. The software can be used in various projects ranging from cogeneration plants to hybrid energy systems with battery storage. Moreover, the software can model most renewable energy technologies such as biogas and geothermal and can be used to model essentially any type of energy plant (EMD International, 2020).

It also offers several technical and economic reports including graphical presentation of the simulated operation which provides an overview and in-depth understanding of the dynamics in the energy system (EMD International, 2020).

EnergyPRO has both university and student licenses of the software available for purchase at special prices depending on the specific needs of the student or institution. There is a free demo of EnergyPRO available for download (EMD International, 2020).

3.3.3 HOMER Pro

The HOMER Pro microgrid software is tailored for the optimization of microgrid designs in all sectors; from village power and island utilities to grid-connected campuses and military bases. It simulates a viable system for all possible combinations of the energy generation technologies and equipment that the designer wishes to consider. It can do this in time steps ranging from one minute to an hour (HOMER Energy, 2020).

It is impossible to control all aspects of a system, and the importance of a particular variable or option cannot be known without running a very large number of different simulations and comparing the results. Therefore, HOMER Pro allows the designer to conduct a sensitivity analysis for the desired system. Sensitivity analyses allow for the comparison of thousands of options in a single run, therefore allowing the designer to see the impact of variables that are beyond their control (sensitivity variables), such as wind speed, fuel costs, etc. This helps the designer understand how the optimal system changes with these variations (HOMER Energy, 2020).

HOMER Pro also has licenses for students, faculties and researchers, which are sold at discounted rates once proof of affiliation is submitted. There is a free 21-day trial of HOMER Pro which is available for download.

The final selection had several factors to consider and a qualitative analysis, using a decision matrix was employed in order to make the final selection.

3.3.4 Decision matrix criteria

Technical evaluation

- Depth of analysis and simulation.
- Variety of energy technologies that can be modelled.
- Technical feasibility metrics and breakdown.

Economic evaluation

- Depth of analysis with various economic metrics.
- Information presentation.

Project Compatibility

- Ability to simulate micro-grid with hybrid generation.
- Built-in climate data function.
- Examples of simulations for projects like this one.

Ease of Use

- Complexity of the design and simulation process.
- User interface complexity.
- Availability of online tutorials.

Cost

- Functional free trial.
- Discounted licensing options for students.
- Total estimated cost less than or equal to R 1 500 budget.

	Technical evaluation	Economic evaluation	Project compatibility	Ease of use	Cost	
Weight	3	2	3	1	1	
RETScreen	4	5	4	4	1	
EnergyPRO	5	5	4	3	2	
HOMER Pro	5	5	5	3	3	
Weighted Scores						Total
RETScreen	12	10	12	4	1	39
EnergyPRO	15	10	12	3	2	42
HOMER Pro	15	10	15	3	3	46

Scale	1	Poor
	2	Below Average
	3	Average
	4	Above Average
	5	Excellent

Figure 2: A Decision Matrix for the simulation software selection.

It was therefore concluded that the HOMER Pro software would be used for this design.

4. Findings and Discussion

4.1 Survey Findings

The survey of households in Jerusalem village was conducted in order to determine the levels of access to the energy of the villagers, the types of fuels or energy sources they use and what these are used for. This in turn would give an indication of whether households are energy poor and the necessity for an alternative solution like the proposed DREGS.

The mean number of inhabitants per household is more than four, as shown in figure 3. This is significant as “a larger household size would cause a transition from wood to kerosene but, decreases the chances that electricity will be used over kerosene or wood (Ismail & Khembo, 2015: 67).” Moreover, it is assumed that the higher the number of people living in a rural household the more likely that the resources, including energy, would be spread more thinly. Thus, resulting in individual energy poverty despite a possible higher household income.

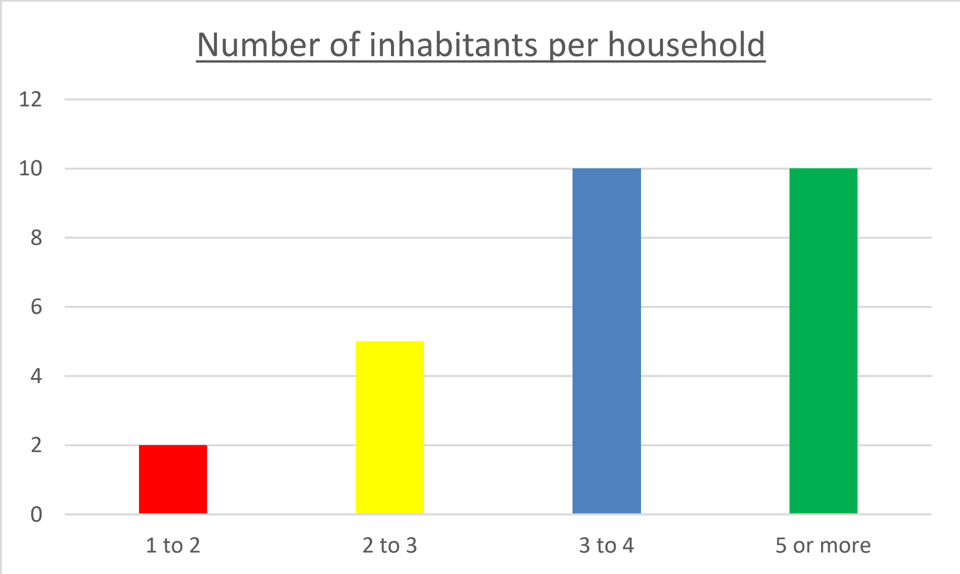


Figure 3: A Bar Graph showing the number of inhabitants per household.

The household incomes are skewed significantly toward the higher brackets with most households earning more than R 3 500 per month, as seen in figure 4. This, however, is most likely due to a combination of setting the income brackets too low and the high average number of inhabitants as discussed. Evidence for the former lies in the outlier incomes reported by three households of R 6 000, R7 000 and R 10 000. Therefore, what looks like a distribution which is skewed right is more likely to be the left half of a normal distribution centred around R4 000 – R5 000, in reality.

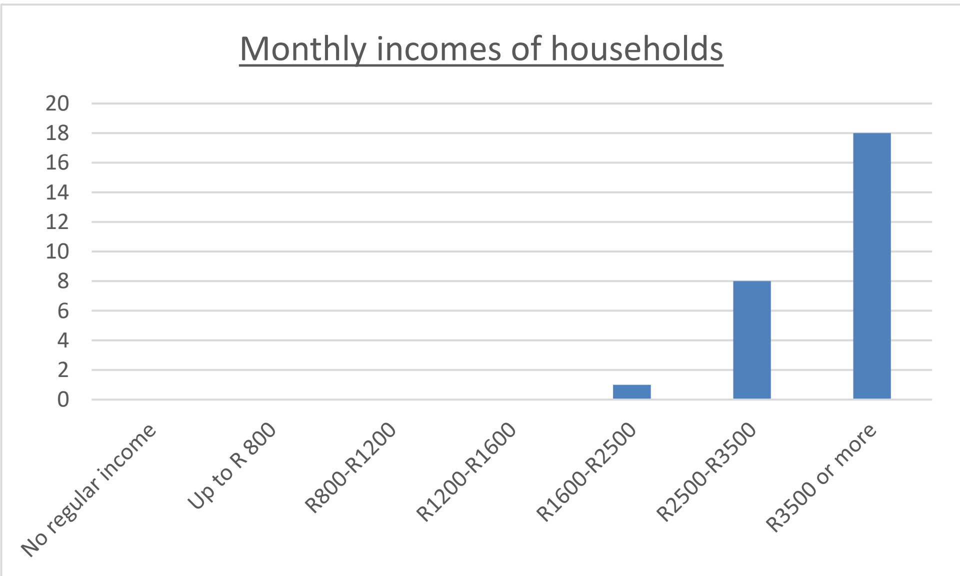


Figure 4: A bar chart showing the monthly income of each household.

The data indicating the preferred energy sources for lighting and cooking indicate that the villagers are forced to use more traditional energy sources, at the bottom of the "energy ladder", as these are accessible and affordable given their context. A summary of this data is shown in figure 5. The negative impacts on health and fire hazards associated with paraffin and firewood especially when used indoors are also a serious concern and could be a reality for many of these households.

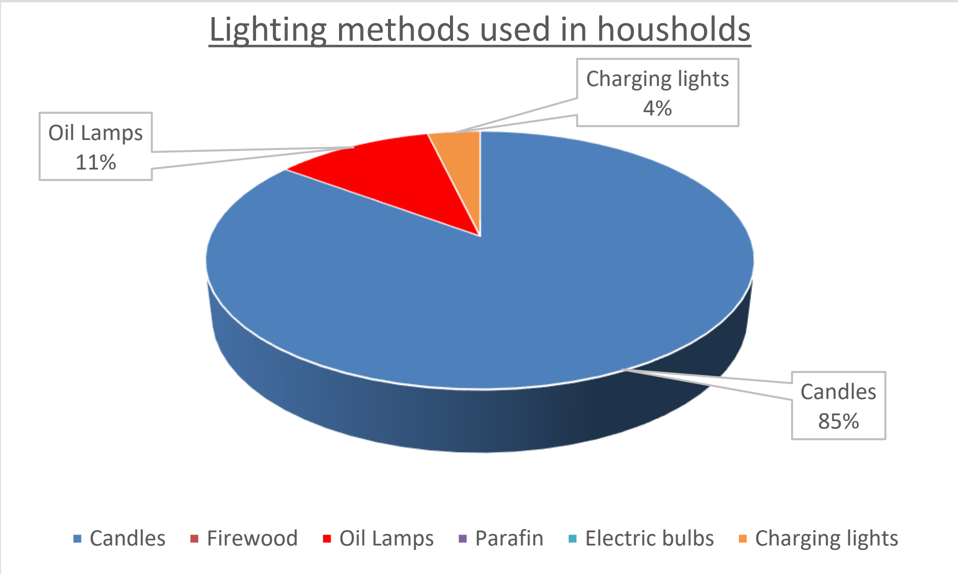


Figure 5: A pie chart showing the lighting methods used in households.

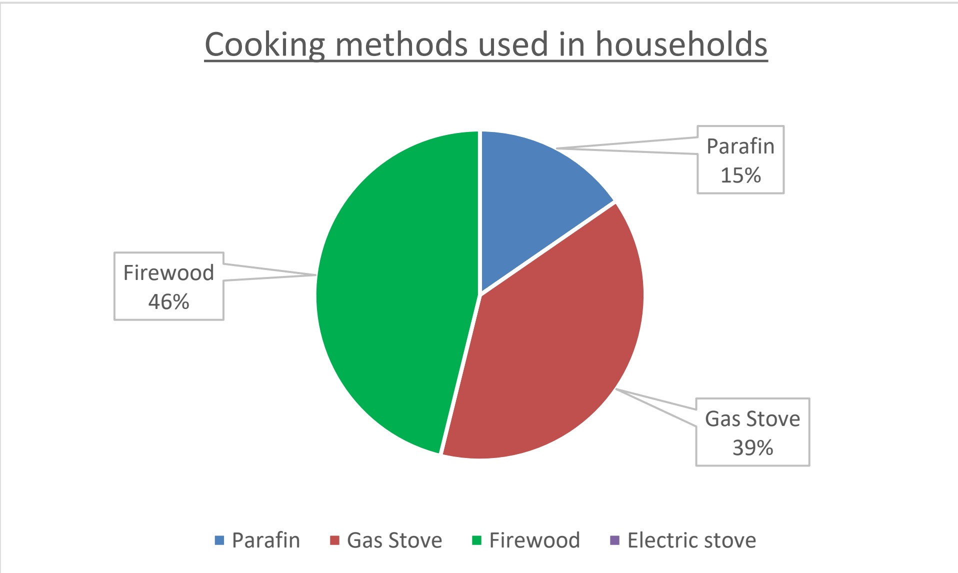


Figure 6: A pie chart showing the cooking methods used in households.

Given the lack of access to electricity, it is not surprising that most households (41%) have no means of entertainment and do not use any electrical devices like laptops, as seen in figure 6. Cell phones are an exception and are vital to modern-day life as a tool for communication as well as banking in many cases. The surveyed villagers reported how they charge/power their electrical devices if used or, how they charge their phones and the results can be seen in figure 8. It was interesting to see that six households reported using a small generator, given that these households did not report using electric stoves, this electricity must be used for other appliances like fridges. Moreover, a third of the surveyed households must walk to their local store to charge their phones.

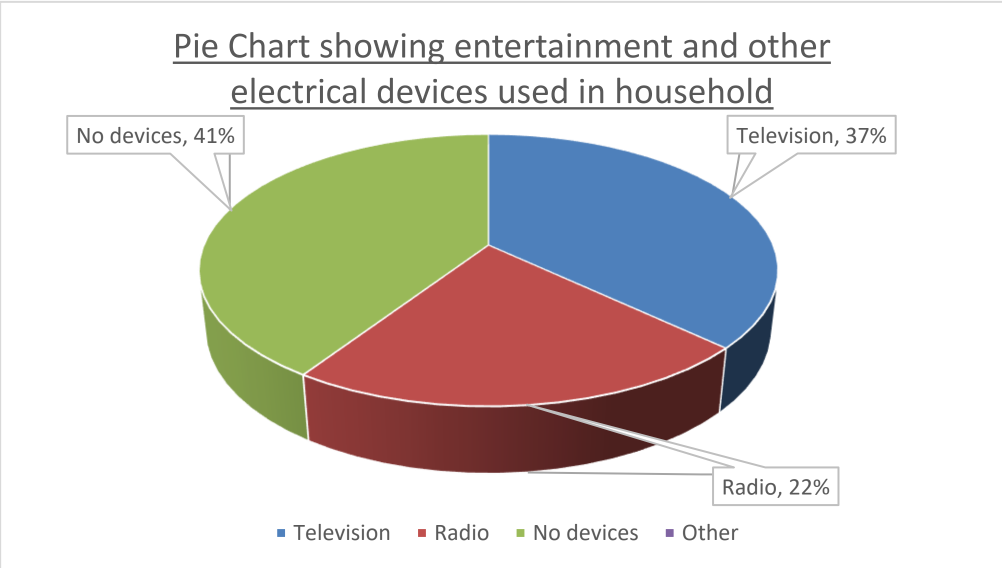


Figure 7: A pie chart showing the entertainment and other devices used in households.

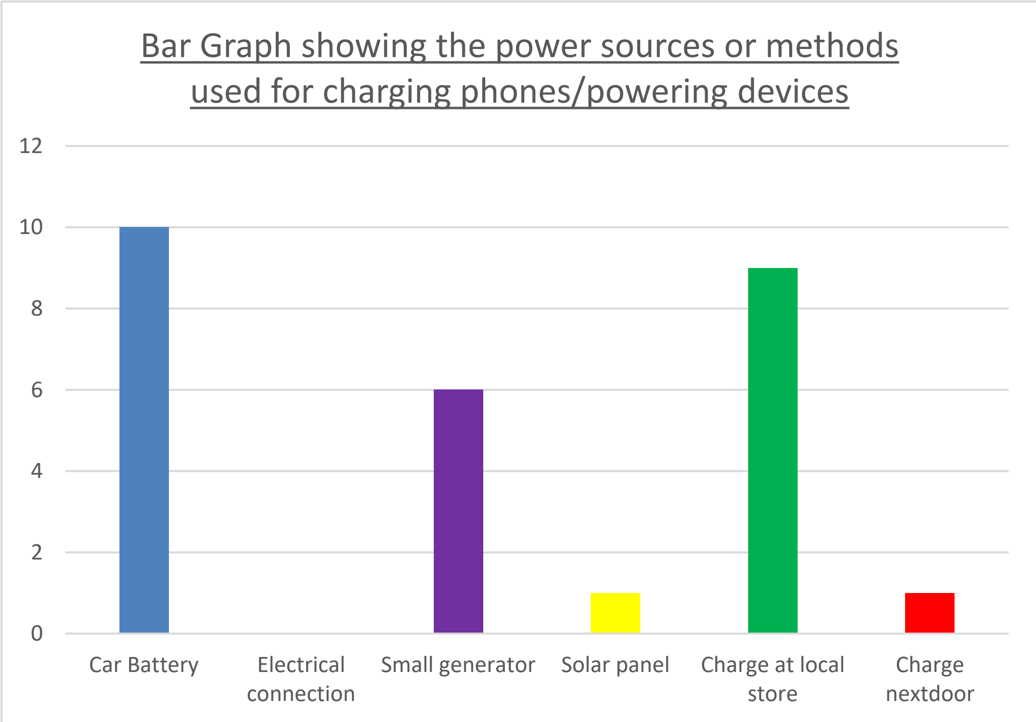


Figure 8: A bar chart showing the power sources used for charging phones/powering other electrical devices.

Given this analysis, households in the village do struggle with access to energy as defined earlier, predominantly due to availability. Most households use traditional biomass fuels, which are readily available, like wood as well as transition fuels like kerosene, charcoal and candles for cooking and lighting. This lack of access to modern energy services i.e. electricity is an indicator of energy poverty. Moreover, at least 33% of the households spend 10%, or more, of their monthly income on acquiring energy or energy services and therefore are classified as energy-poor by the income and expenditure approaches. Electricity supply, however, becomes a question of affordability as the community could not afford to pay the upfront connection costs of installing grid infrastructure and Eskom deems this exercise to be unfeasible.

Therefore, the village needs a relatively low-cost electricity connection that can be installed quickly. This gives rise to the opportunity for a DREGS in the village, to be the solution to this problem.

4.2 High-level system design

4.2.1 System requirements and constraints

- The system must comprise of only renewable energy generation technologies.
- The designed system must work independently of the grid.
- All generation must be done within a 10 km radius of the village.
- The designed system must supply all energy for the residential needs of the village. Assume a monthly supply of 50 kWh to each household in accordance with Free Basic Electricity.

4.2.2 Resource availability assessment

As mentioned in the literature review, the renewable resources available in a location dictate the technologies and systems that can be used to produce energy in said location. Therefore, the high-level analysis begins with a qualitative assessment of the availability of these resources, in the area surrounding Jerusalem Village.

Solar Radiation

The availability of solar radiation over the Earth's surface differs with location due to factors like elevation and cloud coverage. However, the geographic location of South Africa is suited to solar energy applications. This is evident through the growing nation-wide adoption of solar energy technologies for supplementary electricity supply as well as for water heating applications (Singh, 2016).

In Singh's study, the surface incident shortwave flux (SW_{flux}) found in NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA) data for the period of 1980-2009 over South Africa, was analysed on monthly annual and seasonal scales to perform the scoring and ranking of the provinces (2016: 51).

Three metrics are defined in order to compare the potential for solar energy (mean value) of each province, these figures were calculated by calculating the SW_{flux} for each province and assigning the provinces with the maximum or minimum a 1 or 9 for each time scale (Singh, 2016) :

SEPN – Solar Energy Potential Number

TSEPN – Total Solar Energy Potential Number

SEPR – Solar Energy Potential Rank

Limpopo scored a SEPN of 4 after the Northern Cape, North West and Free State provinces. This indicates that a medium to high level of solar radiation falls on the province annually and Limpopo is favourable for applications involving solar energy. Moreover, Limpopo has the highest SW_{flux} levels during the winter and autumn months of the year which is very advantageous as solar energy can still be relied upon despite it being the colder seasons of the year.

Being an arid climate, Limpopo also experiences little standard deviation in SW_{flux} in comparison to the other provinces, in cooler or warmer months. This is desirable as it minimizes the intermittency of potential solar energy supply, given the intermittent nature of solar radiation.

Knorr, et al. found that some settlement areas East of Polokwane city are eligible for the installation of Solar PV in the "Wind and Solar Resource Aggregation Study for South Africa" (2016: 19). This coincides with the location of Jerusalem Village.

Wind

Wind turbines are able to start generating electricity at wind speeds of about 3-4 m/s, whereas the nominal wind speeds required for full power operation are about 12.5-17 m/s (Eskom, 2007). South Africa is considered to have moderate wind resources compared to Northern Europe and the areas with the highest potential for wind generation are the southern, eastern and western coastlines (Eskom, 2007). The potential in these areas is further supported by the proposed commercial facility north of the Olifants River in the West Coast. Limpopo province, however, doesn't have wind resources that are as abundant, with a mean wind speed of approximately 3 m/s as recorded at a weather station in Polokwane (World Weather & Climate Information, 2020). Therefore, it is unlikely that the use of wind turbines will be feasible for electricity generation in the village.

Biofuels

South Africa has limited agricultural resources such as land and water only 14% of the land is arable and approximately 10% of that land is irrigated, therefore using 60% of the national water supply. While the lack of arable land and scarce water render South Africa disadvantaged in terms of producing biofuels for both residential consumption and exports, the former is still very feasible (Prasad, 2010).

The Department of Minerals and Energy proposed that sugarcane and sugar beet be used for ethanol production whereas sunflowers, canola and soya beans are used for biodiesel in the Biofuels Industrial Strategy of the Republic of South Africa (2007: 3). Jerusalem Village is located in an arid part of the province and is struck by drought, but in summer months the crops most likely to be farmed would be maize. However, maize farming for ethanol production raises food security concerns because of the inevitable rise in price that the fuel demand would cause. This makes it unlikely that farming is a viable option for biofuel production.

Alternatively, the biofuels could be produced by other means given the small-scale application according to Prasad (2010: 13), namely:

• biomass from invasive alien plants and bush encroachment for heat and power generation;

• biogas generation from farm waste;

• biogas generation from municipal solid waste;

• biogas generation from municipal wastewater; and

• biogas from household waste.

The Working for energy project under the Expanded Public Works Programme focuses on renewable energy, energy efficiency and creating green jobs which support the development and the climate (South African National Energy Development Institute, 2020). The Balloon digester at the Tygerkloof Combined School-Waste to energy plant and balloon digester being built in the Melani Village, (Eastern Cape) indicate the viability of biogas generation from waste, for local use at small scales.

Hydropower

While there is a large water body approximately 6 km away from the village in the form of Seshego lake this cannot be applied for Hydropower as there is no gradient, and thus no means to create flow for energy extraction using turbines. Other than Seshego Lake there are no fast-moving water bodies of significant volume within a 20km radius of the village. See figure 9 for reference.

Figure 9: A satellite image showing the distance from Jerusalem Village (red pin) to the nearest large water body (Seshego Dam).

4.2.3 Simulation

HOMER Pro gives the user the ability to select all possible generation technologies and optimizes the model for the best solution. There were inputs and assumptions that had to be made in the process of developing the model system and simulating it, these were as follows:

- Inflation Rate – 2%
- Interest rate – 6.25%
- Project life span – 50 years
- The system must supply electricity for residential demand alone.
- NASA data for wind speed and solar radiation downloaded through HOMER Pro, can be used to model the resources currently at the location, reliably and for the life span of the project.

Electric Load

The first step in simulating the system is modelling the electric load for which the system must supply electricity. HOMER Pro offers pre-set load profiles which can be scaled, and a peak month of the year can be selected. The residential load profile was chosen and the calculation for the kWh of demand per day was completed as follows:

$$Average\ Demand\ \left(\frac{kWh}{day}\right) = \frac{Basic\ Electricity\ per\ household\ \left(\frac{kWh}{month}\right) \times Total\ households}{30\ (\frac{days}{month})}$$

$$Average\ Demand\ \left(\frac{kWh}{day}\right) = \frac{50 \times 200}{30}$$

$$Average\ Demand\ = 333.33\frac{kWh}{day}$$

This figure was automatically scaled to the load profile, to produce the demand for the entire village's households and the peak demand was also automatically calculated. Figure 10 below shows the demand for the village.

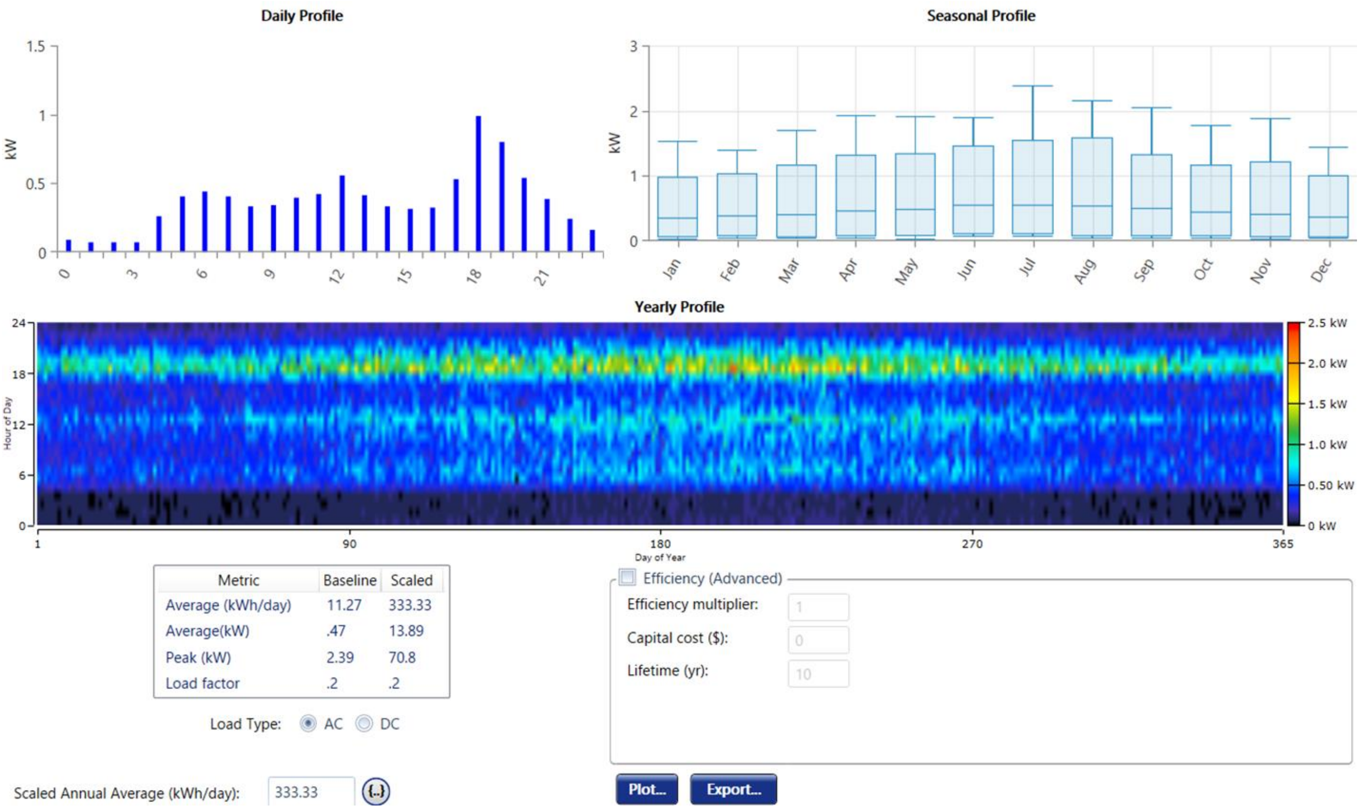


Figure 10: Graphs showing the daily, yearly and seasonal load profiles of the village.

Solar PV panels

Generic 1 kW PV, flat plate panels were chosen for the simulation. This was done to ensure optimization could be completed for this High-level analysis without having to consider the performance or suitability of different brands or models. The same rationale was applied throughout the design. Figure 11 below shows the solar PV panel specifications.

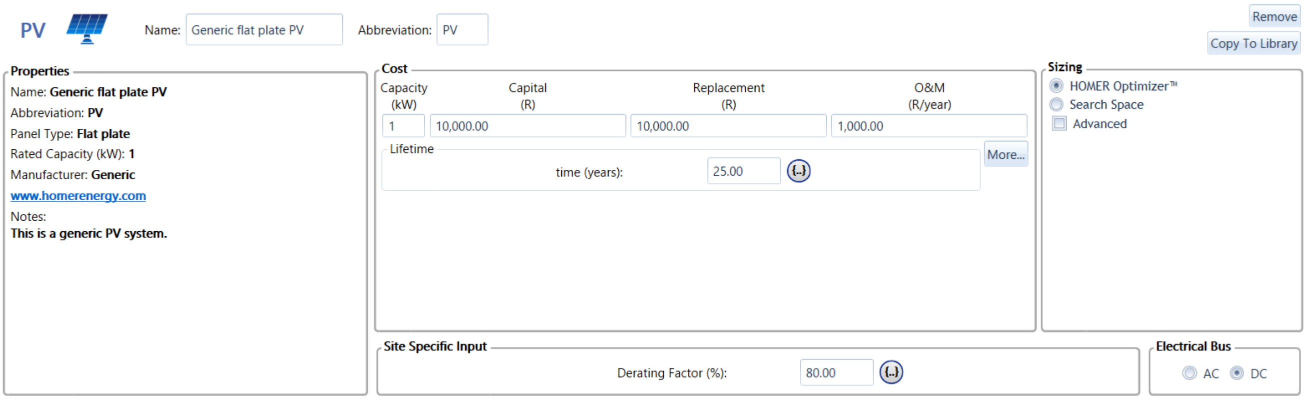


Figure 11: A table showing the specifications of the Generic flat-plate PV panels used in the design.

Biogas generator

A Generic 500 kW biogas generator is the only option on this version of the software, which is seriously oversized considering the fact that the peak daily load demanded by domestic activity is 70.80 kW, however, simulations were completed with and without the generator to determine the best possible system. Moreover, the software required that the average daily biomass available for biogas production be supplied as an input for optimization of the operation of the generator. This information proved very difficult to acquire but a conservative assumption of 1 tonne per day was made using results from (Oelofse, et al., 2018) which showed that an average of 0.69 kg of food waste is generated by Johannesburg households per week. This combined with the potential for partnering with the local poultry farms, Chifundo's Poultry Farm and Bokamoso Pastures, for the management and use of their waste such as manure for biogas production could increase this figure significantly. This would make the inclusion of this generator more sustainable. Figure 12 below shows the specifications of the generator.

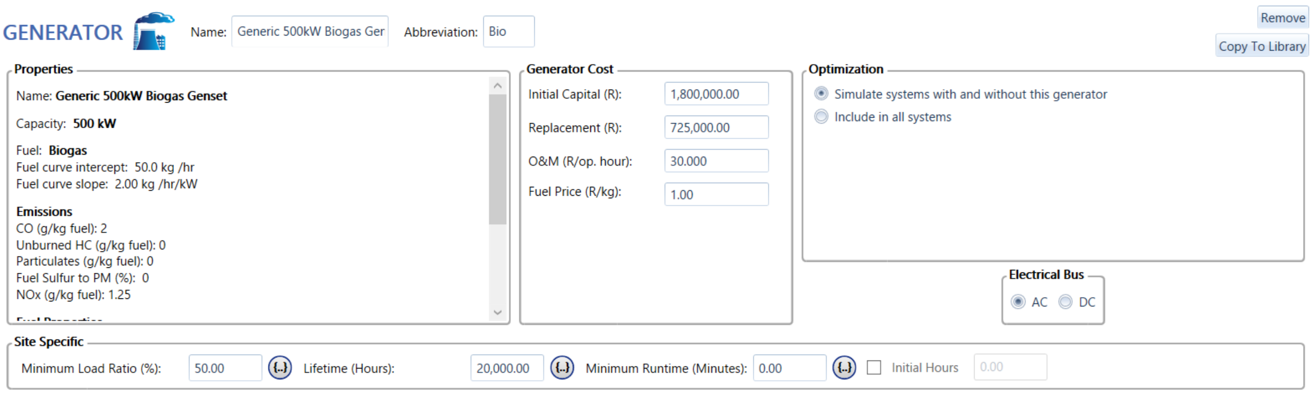


Figure 12: A table showing the specifications of the biogas generator used in the design.

Battery Storage

600 V, 100 kWh Lithium-ion batteries were also included in the system simulation. Battery storage is vital to the design as it allows for excess energy to be stored as well as for electricity to be supplied in emergencies or when the PV panels can't generate electricity i.e. during rain or overcast weather. Lithium-ion batteries were selected because of their improved durability and efficiency in comparison to Lead Acid Batteries. These Lithium-ion batteries are 10% more efficient than the available lead-acid batteries and have 5 years of extra useful life. While they are significantly more expensive, this cost will be offset by the productivity and savings in replacement costs. Figure 13 below shows the battery specifications.

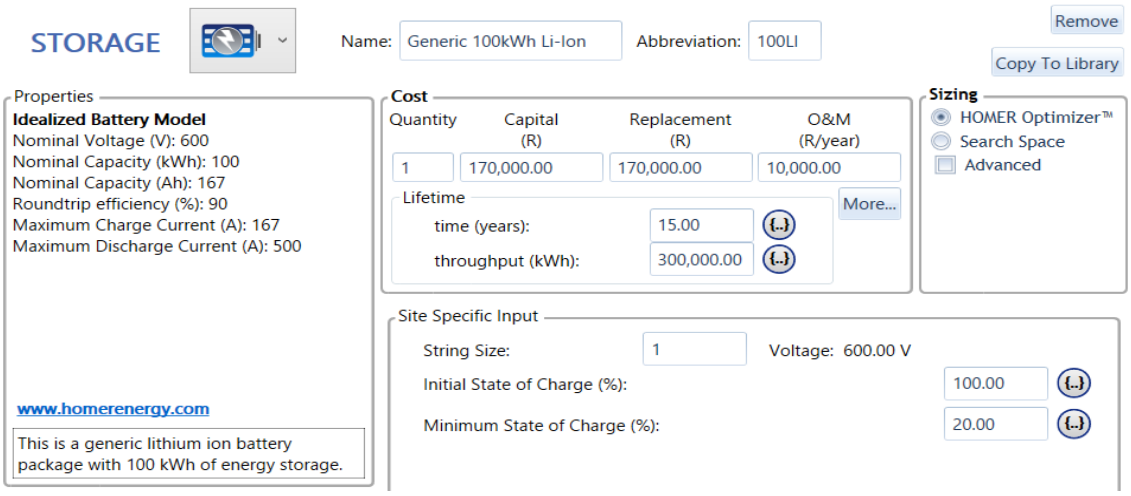


Figure 13: A table showing the specifications of the Lithium-ion batteries used in the design.

Converter

An inverter and rectifier (collectively known as the converter) are needed to convert the Direct Current (DC) produced by the PV cells in the panels into the Alternating Current (AC) used by household appliances and devices. The inverter also allows for the DC output from the batteries to be converted into AC for usage and the reverse process for the charging of the batteries. Figure 14 below shows the converter specifications.

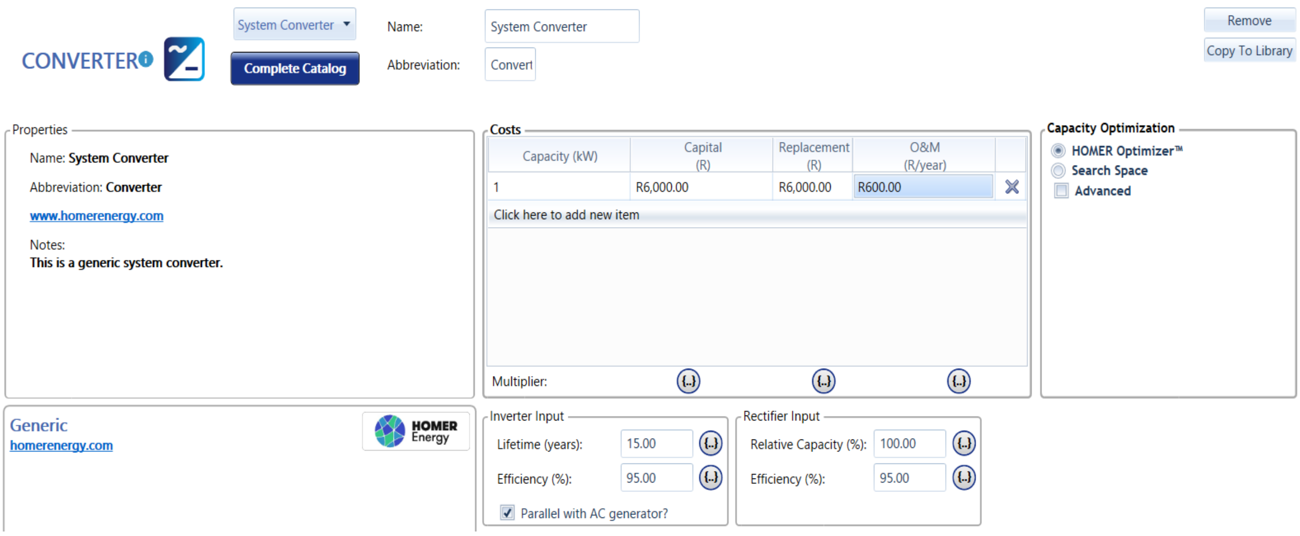


Figure 14: A table showing the specifications of the converter used in the design.

The simulation schematic in figure 15 below shows the components used in the simulations. Note that simulations were completed with and without the biogas generator.

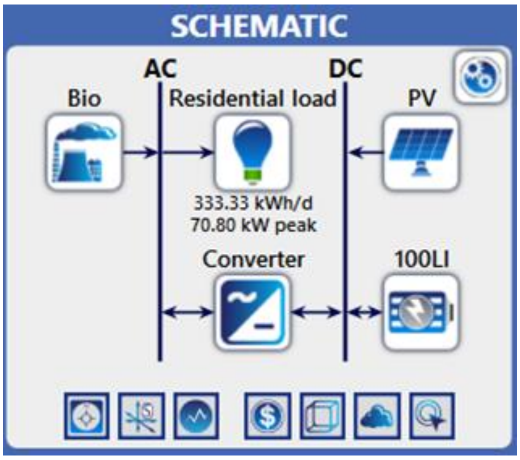


Figure 15: A schematic showing the components used in the simulations.

4.3 Proposed Renewable Energy Generation System

4.3.1 Simulation Results

The simulation was optimized for the lowest Net Present Cost (NPC). In the process of simulating various systems, it was thought that increasing the biomass available for biogas production by using food waste from the homes and farm waste, as well as looking at the farming crop for biomass production would improve the output and efficiency of the generator. In order to test this hypothesis and assess the effects of this on the feasibility of the proposed system, 2 tons/day and 3 tons/day of biomass supply were set as sensitivity cases.

The optimal system is comprised of the solar PV panels, batteries and the converter, while the hybrid biogas generator and solar PV system followed in second place as shown in table 1 below.

Architecture					Cost				System	
PV (kW)	Bio (kW)	100LI	Converter (kW)	Dispatch	NPC (R)	COE (R)	Operating cost (R/yr)	Initial capital (R)	Ren Frac (%)	Total Fuel (tons/yr)
91.7		4	33.2	CC	R9.22M	R2.31	R210,716	R1.80M	100	0
58.6	500	3	41.0	LF	R9.32M	R2.32	R175,479	R3.14M	100	351

Table 1: A table showing the optimal generation systems found by the simulator.

While the simulation factors in the intermittent nature of solar generation due to changing weather and sizes the storage system accordingly, there are concerns regarding having only one generation system. The employment of the Bio-solar hybrid system would allow for a consistent base supply from the biogas generator because the generator would always be running. This would be backed up by solar generation and the storage thereof. This system is less likely to fail and cause shortages for the village due to unforeseen maintenance, repairs or an extended lack of solar radiation. Moreover, the use of the biogas generator in tandem with the solar PV panels allows for reduced land usage due to the area that the array of panels would require. The solar only system requires 91.7 kW of capacity compared to 58.6 kW of solar capacity in the Bio-solar hybrid system. This results in fewer panels used and more space available for new homes and infrastructure etc.

Upon analysis of the separate sensitivity cases, it was found that should 2 tons/day of biomass be made available for biogas production then the Bio-solar hybrid system becomes the optimal solution. This can be seen in table 2.

Architecture					Cost				System	
PV (kW)	Bio (kW)	100LI	Converter (kW)	Dispatch	NPC (R)	COE (R)	Operating cost (R/yr)	Initial capital (R)	Ren Frac (%)	Total Fuel (tons/yr)
47.7	500	2	28.6	LF	R8.74M	R2.18	R168,857	R2.79M	100	707
91.7		4	33.2	CC	R9.22M	R2.31	R210,716	R1.80M	100	0
	500	2	122	LF	R10.9M	R2.76	R226,895	R2.87M	100	721

Table 2: A table showing the optimal generation systems found by the simulator given the daily biomass supply sensitivity cases.

Given this analysis, it was concluded that the Bio-solar hybrid generation system would be proposed as the final concept for this report.

4.3.2 Final Concept Technical Analysis

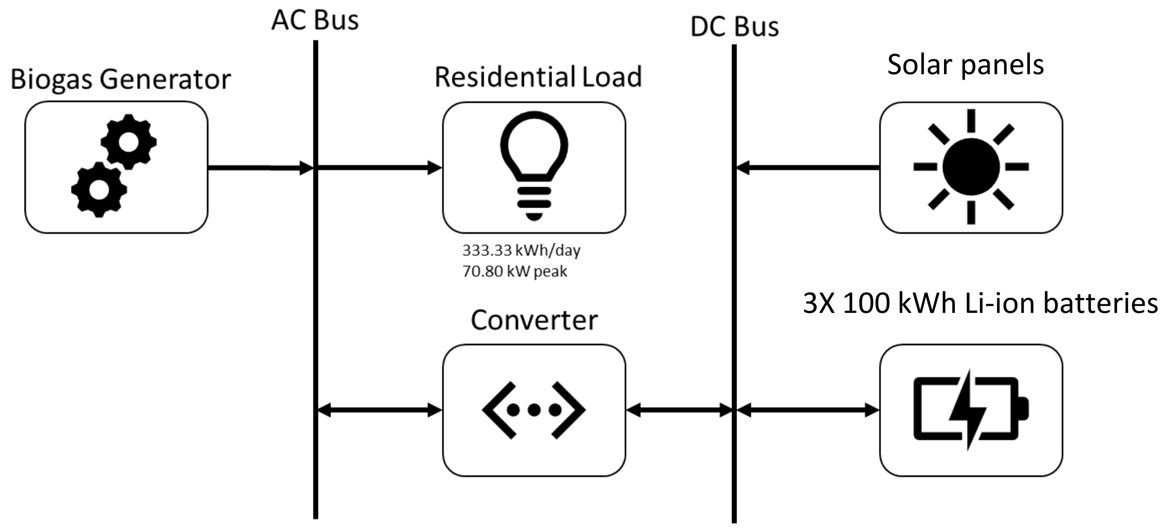


Figure 16: A diagram showing the components used in the final proposed concept and how they interact.

Figure 16 above shows the working schematic of the proposed system which comprises of:

- A 500 kW Biogas Generator.
- An array of Solar PV panels with a 58.6 kW generation capacity.
- An array of 3, 100 kWh Lithium ion Batteries.
- A converter.

The solar PV panels generate DC which travels along the DC Bus to either be stored by the batteries or converted (by the converter system) to AC, to be used by households. The Biogas Generator produces AC which can be supplied directly to homes or passed through the converter via the AC Bus and stored in the batteries via the DC Bus.

This system is sized to meet the daily residential energy requirements of the village and the battery system capacity is designed to cover energy demand in conjunction with biogas generation when solar energy cannot be utilised. The consistent biogas generator supply, the abundance of sunlight in the area and the fact that solar PV panels have no moving parts, make it unlikely that there would be any component failures or major shortages due to weather.

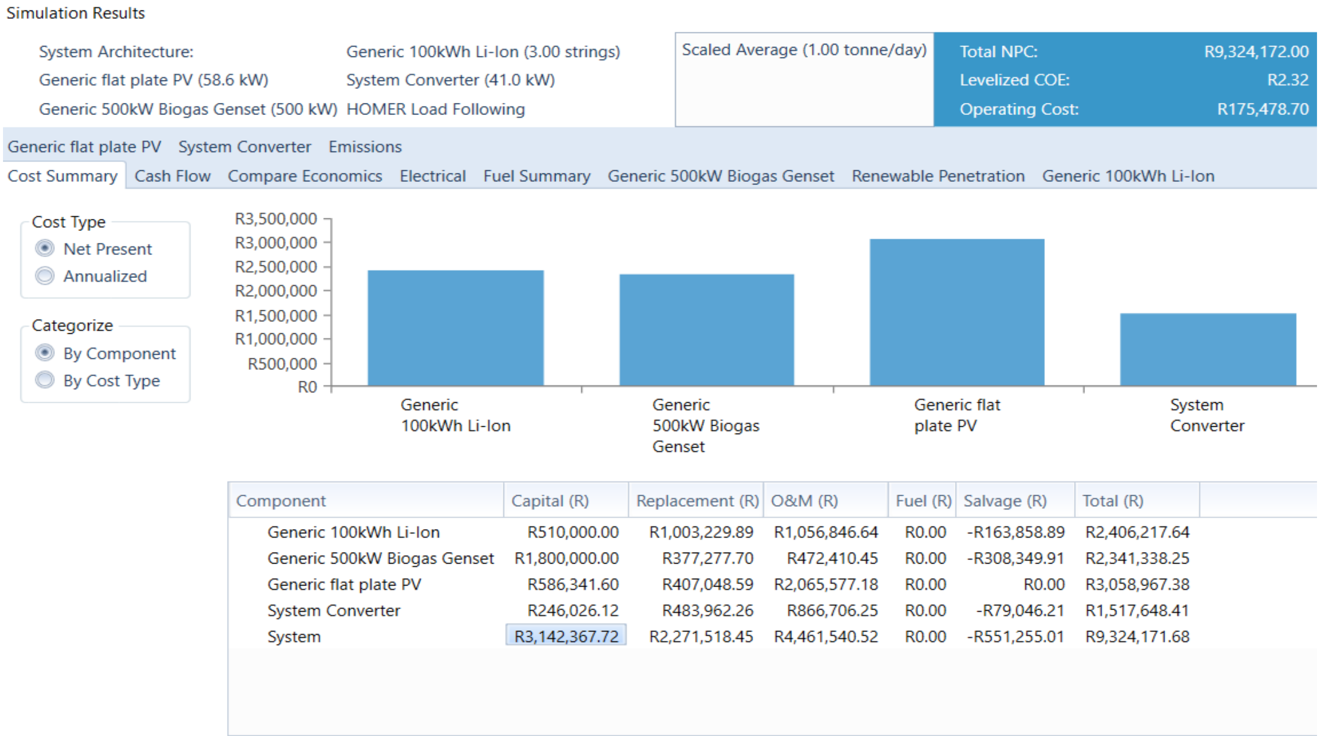
A critical weakness of the design and this system is that it doesn't consider the growth of the village and the increasing demand as a result. However, this would take a significant amount of time to research as well as quantify and is, therefore, not feasible for this preliminary study. Overall, the system meets the requirements and proves technically plausible at this initial phase.

4.3.3 Final Concept Financial Analysis

The average system capital cost for a 20A grid connection in South Africa in 2012 was R 15,000 and is completely subsidised (Department of Environmental Affairs, 2015). This figure assumed that the cost per connection remained constant despite the inefficiencies associated with more remote households. Factoring in inflation (assumed to be 2%), the cost of the same system in 2021 will be approximately:

$$Present\ Cost = 15000(1 + 0.02)^9 = R\ 17\ 926.89$$

For the 200 households in the village, this would amount to R 3,585,378. This is higher than the initial capital required for the proposed decentralised system, R3,142,367.72, as can be seen in figure 17 below. This is a significant cost saving of 12.4% and proves the cost advantage of the proposed system in comparison to including the village in the grid extension program. Moreover, the advantage of saved time as a result of the rapid installation of this system, compared to the work required to develop grid infrastructure in these areas is also advantageous. A summary of the financial information of the proposed system can be seen in figure 17.



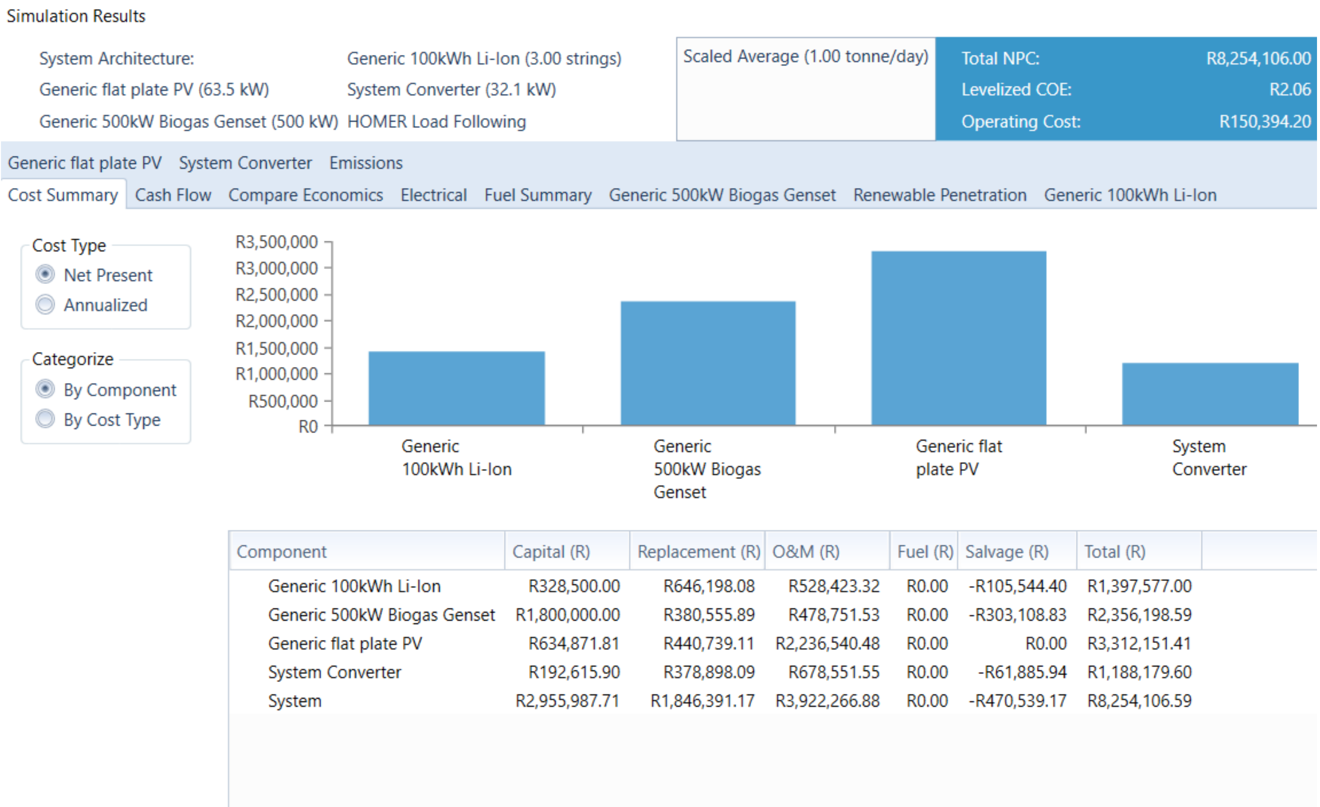
Component	Capital (R)	Replacement (R)	O&M (R)	Fuel (R)	Salvage (R)	Total (R)
Generic 100kWh Li-Ion	R510,000.00	R1,003,229.89	R1,056,846.64	R0.00	-R163,858.89	R2,406,217.64
Generic 500kW Biogas Genset	R1,800,000.00	R377,277.70	R472,410.45	R0.00	-R308,349.91	R2,341,338.25
Generic flat plate PV	R586,341.60	R407,048.59	R2,065,577.18	R0.00	R0.00	R3,058,967.38
System Converter	R246,026.12	R483,962.26	R866,706.25	R0.00	-R79,046.21	R1,517,648.41
System	R3,142,367.72	R2,271,518.45	R4,461,540.52	R0.00	-R551,255.01	R9,324,171.68

Figure 17: A diagram showing the financial details of the final proposed concept.

The proposed system has a Cost of Electricity (COE) of 2.32 R/kWh, which is 1.81 times the standard tariff proposed by Eskom for 2021, 1.28 R/kwh (Bottomley, 2020). Even though most of the villagers are willing to pay for their electricity services as suggested by Nkoana, et al. (2019: 50) they would likely refuse to pay for electricity at a rate as high as this (especially because a profit margin would be included). However, this system supplies the Free Basic Electricity subsidised by government which means no revenue could be generated from village residents for this energy plant. Therefore, cost-saving both in operations and maintenance as well as replacement costs must be made to reduce the COE.

A final simulation was done in order to determine the effect of reduced battery costs and increased efficiency of Lithium-ion cells. This is a plausible scenario given the millions of dollars being invested in the research and development necessary to make lithium-ion batteries, for both cars and large-scale energy supply applications, more durable and efficient. This is being pioneered by companies like Tesla as well as QuantumScape, an electric vehicle battery manufacturing company which is backed by Bill Gates. This is further emphasized by the projection that the average cost of a lithium-ion battery cell will fall below \$100/kWh by 2023 (which was the assumed cost used in this design) and could be reduced to \$73/kWh by 2030 (Radowitz, 2020). For the purposes of this final simulation, it was assumed that this system would be built in 2030 where the average cost of a lithium-ion battery cell will be $80/kWh and the annual operations and maintenance costs for the batteries will be halved.

This final simulation confirmed the hypothesis but still resulted in a system with a COE of 2.06 R/kWh which is significantly higher than that of Eskom at 0.896, assuming Eskom has a profit margin of 30% factored into their proposed standard tariff for 2020. The financial details of this project are summarised in figure 18 below.



Component	Capital (R)	Replacement (R)	O&M (R)	Fuel (R)	Salvage (R)	Total (R)
Generic 100kWh Li-Ion	R328,500.00	R646,198.08	R528,423.32	R0.00	-R105,544.40	R1,397,577.00
Generic 500kW Biogas Genset	R1,800,000.00	R380,555.89	R478,751.53	R0.00	-R303,108.83	R2,356,198.59
Generic flat plate PV	R634,871.81	R440,739.11	R2,236,540.48	R0.00	R0.00	R3,312,151.41
System Converter	R192,615.90	R378,898.09	R678,551.55	R0.00	-R61,885.94	R1,188,179.60
System	R2,955,987.71	R1,846,391.17	R3,922,266.88	R0.00	-R470,539.17	R8,254,106.59

Figure 18: A diagram showing the financial details of the final simulation of the proposed concept (with decreased battery capital and operation & maintenance costs).

5. Conclusion & Recommendations

While the concept of decentralised renewable energy generation and supply is plausible, the issue of storage of this energy is critical and proves to be a stumbling block. This was proven in the technical and financial analysis of the proposed design. More efficient and durable energy storage systems need to be developed in order to make systems like these feasible enough to draw the kind of investment and subsidies necessary to make them a reality. Improvements in solar PV panel efficiency and costs will achieve a similar effect.

The proposed system is not feasible because the COE remains too high, however, a similar project to this one which could apply alternate energy storage technology such as Green Hydrogen storage could prove the concept to be feasible, in the near future, at least. Moreover, extended research into decentralised renewable energy systems for rural applications like this one would undoubtedly uncover any inefficiencies in this design that haven't already been mentioned. These studies should also investigate designing systems that can account for the growing demand associated with rapidly developing rural areas and communities.

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