TECHNO-ECONOMIC STUDIES FOR THE INTEGRATION OF SOLAR PV TECHNOLOGY IN TELECOMMUNICATIONS SECTOR FOR SUSTAINABLE DEVELOPMENT:

[A CASE STUDY OF BUDIRIRO]

BY

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DECLARATION

I, KLINE TARCISIUS MAPFUMO do hereby declare that the contents in this dissertation is my original work and have not been previously submitted to any University for the award of a degree or any other qualification.

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This dissertation by KLINE TARCISIUS MAPFUMO is hereby approved as fulfilling the requirements for the award of the Degree of Master of Engineering in Renewable Energy Engineering by the University of Zambia.

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ABSTRACT

The telecommunications industry in Zimbabwe keeps growing with an increase in the number of users yearly. The demand on the national grid and low power supply means long hours of electricity outages, which prompts Internet Service Providers (ISP's) to use generators as backup power to keep base stations online for uninterrupted provision of internet to consumers. Generator systems increase operation expenditure (OPEX) of running base stations, produces GHG emissions and intern attract additional cost of emission. This causes an increase in cost of running the business and consequently internet data prices. A case study was conducted in Budiriro a suburb in Harare, Zimbabwe's capital. A framework was developed which analysed six combinations (Grid + Generator, Generator only, Generator + Solar, Solar only, Grid + Solar and Grid only) of power sources based on sustainability pillars; Economical, Environmental and Social, as well as technical capability. The six alternatives were simulated in HOMER Pro, a system that evaluates designs for both off-grid and grid-connected power systems, to determine the output (power output, investments, costs and emissions) of these individuals systems. Using a sub criterion of 15 pairwise combinations, the Analytic Hierarchy Process (AHP) was used to rank these systems and the best solution chosen based on the main criteria of the sustainability pillars, as well as technical capability. The result shows that Grid + Solar PV system provide the best optimal alternative power system to power base stations for the study area, substituting Grid + Generator system (Existing system). It reduces OPEX by over 1,000 percent offering 37 percent more power and 41.13 tonnes of GHG emissions avoided per year. Socially, power sharing between households and base stations as well as reduction of air and noise pollution. The optimal alternative power source for base station proposed here in this study will help reduce greenhouse gas emission, dependence on grid and operation costs which in turn will reduce data prices, increase internet accessibility at affordable rates and provide a sustainable future of telecommunications businesses in Budiriro.

Keywords: Telecommunications Industry, Sustainability, Renewable Energy, Solar PV, Budiriro

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LIST OF ABBREVIATIONS AND ACRONYMS

AT – Acceptability

CAP – Capacity

CAPEX – Capital Expenditure

CO_2 – CO_2 Emission

EC – Emission Cost

EMP – Employment Creation

FLEX – Flexibility

ISP – Internet Service Provider.

LCOE – Levelised Cost of Energy

LMICs – Lower-Medium Income Countries.

LU – Land Use

MNOs – Mobile Network Operators.

NPC – Net Present Cost

OPEX – Operating Expenditure

PAYG – Pay as You Go.

PBP – Payback Period

PV – Photovoltaic/Photovoltaic Systems.

RA – Resource Availability

REL – Reliability

SUS – Sustainability

USD – United State Dollar

ZESA - Zimbabwe Electricity Supply Authority.

ZETDC – Zimbabwe Electricity Transmission and Distribution Company.

ZWL – Zimbabwe Local Currency

CHAPTER 1: INTRODUCTION

1.0 Introduction

Telecommunication towers, Figure 1-1, are structures built to carry antennae and auxiliary equipment necessary for mobile network and internet connectivity (Law Insider, 2022).

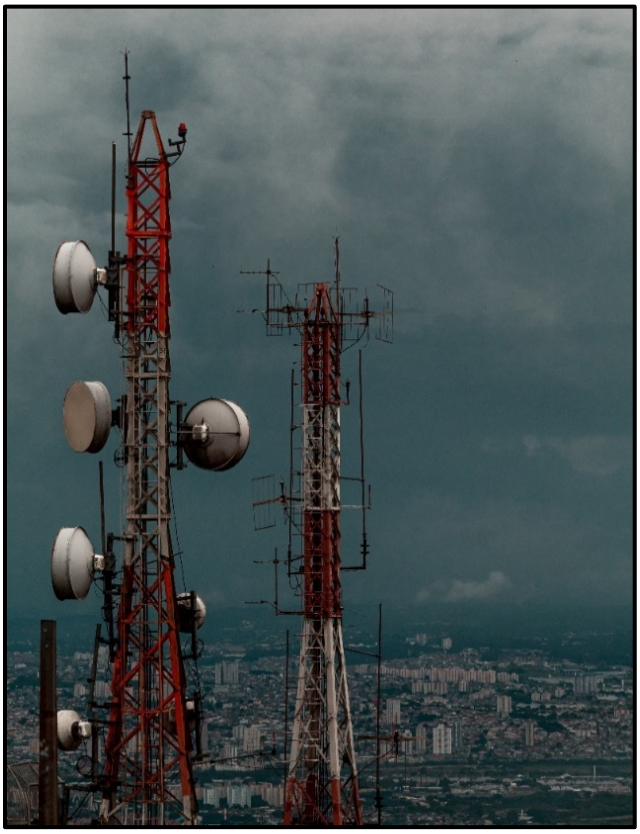


Figure 1-1: *Telecommunication Tower*

A huge number of telecommunication base stations have been erected over the years to be particularly powered by the Zimbabwe national electricity grid. The demand of electricity in other sectors and lack of supply meant these towers needed alternative sources during load shedding, which the industry resorted to use of fossil fuel. The reason to settle for an alternative backup power is to keep systems online for consistent internet supply, failure of which can be catastrophic. This is given by an instance when the whole country lost its internet connection for three days, business slowed drastically and the outage costed the country around $17 million (CNN World, 2019). The telecommunications industry has been one of the leading industries in Zimbabwe.

However, internet data prices increased at an alarming rate over the last five years which has raised a huge concern to the general public who are barely making a living. Internet Service providers (ISPs) attribute the overall price instability to the soaring fuel prices, grid power price increase and huge operating costs of alternative power.

Moreover, these operating costs will continue to surge. Telecommunications industry as we know it, continues to develop each year. According to Humar (2011), approximately 3 percent or 600 TWh of the worldwide electrical energy is consumed by telecommunications industries. With the advent of 5G Hardesty and Linda (2020) suggest that telecommunications companies expect their operation costs to increase up by 5 percent of their 4G counterpart.

To increase internet accessibility in Zimbabwe, there is need to put an end to the data price inflation by deploying alternative energy supply to the base stations that eliminate high OPEX associated with generators which typically increase by 35 percent the total operating cost of a wireless base station (BTS), including skyrocketing fuel and expensive on-site maintenance costs (BHB, 2013). A huge portion of energy used by telecommunications goes to base stations (Yaacoub et al., 2016). Power contributes a quarter of total network costs (Novergy Solar, 2022).

According to GSMA (2021) over half of the World’s population now have access to the internet. As per same report, low- and middle-income countries (LMICs) account for the 93 percent of the world’s population without access to the internet. The main reason being affordability. Reduction of operation and maintenance costs as proposed by available research on deployment of solar will only ensure a decrease in data prices cost and a steady increase of internet usage. Alsharif and Kim (2016) case study discovered that; deploying Solar PV in remote base station in South Korea achieved total operational expenditure savings up to 48.6%. With several other studies showing a substantial reduction in OPEX, there is potential to pose a significant change in Zimbabwe’s local telecommunications industry.

This study focused on identifying, analysing and proposing energy systems based on available sources, with Solar PV technologies and therefore choose an optimal alternative source to power base stations to reduce operation costs for ISPs. This will drive data price stabilisation to make internet which United Nations (2011) declared as an enabler to the enjoyment of basic human rights, accessible. As well, eradicating the burning of fossil fuels is a big step towards achieving net zero (UNFCCC, 2016).

In addition, while the country keeps battling with increasing the supply by discovering and up scaling energy sources, it is important that energy efficiency systems be ready in place, as these, regardless of the supply, will help improve the overall utilisation of energy in the long run. "Global telecommunications network providers are expected to install nearly 121.9 GW of cumulative new distributed renewable energy generation technologies and distributed energy storage systems capacity between 2021 and 2030," (Nastu, 2021). This research will significantly help ISPs in such future prospects.

1.1 Background

Local data prices have been continuously increasing as a result of fuel price hikes, grid power price surge and operational costs, as stipulated by the local Internet Service Providers (ISP) (All Africa, 2021). Following a 20 percent data increase in July of 2021, the price of electricity was reported to have gone up by more than 180 percent, while fuel prices had increased by more than 30 percent. Between October 2020 and July 2021, diesel went up from an average US$1.00 per litre to an average US$1.30 per litre in that period (All Africa, 2021). As of September 2022, diesel sits at **US$1.74** (ZERA, 2022). Studies show that diesel generators increase the overall operation cost in telecommunication industries by 35 percent (Novergy Solar, 2022).

As of date the data prices are overwhelming and projected to keep on rising. The prices shown in Table 1-1 are equivalent in USD prices at the Conversion rate of USD $1.00 to ZWL $132.00 (Reserve Bank of Zimbabwe, 2022) as on 15 March 2022.

Table 1-1: *ISPs Wireless data price comparison ZWL to USD (Source telecel.co.zw| netone.co.zw|econet.co.zw: Telecel Zimbabwe, NetOne Cellular, Econet Wireless)*

ISP	Currency	8GB	15GB	25GB	50GB
ECONET	ZWL $	$4,320.00	$6,600.00	$7,860.00	$12,000.00
	USD $	$32.73	$50.00	$59.55	$90.91
NETONE	ZWL $	$4,500.00	$6,500.00	$10,250.00	$12,500
	USD $	$34.09	$49.24	$77.65	$94.70
TELECEL	ZWL $	$5,500.00	$6,500.00	$11,000.00	$13,000
	USD $	$41.67	$49.24	$83.33	$98.48

Zimbabwe has relatively high data prices as shown in Figure 1-2 below as compared to other countries in Southern Africa, worse still considering the average salaries in the country.

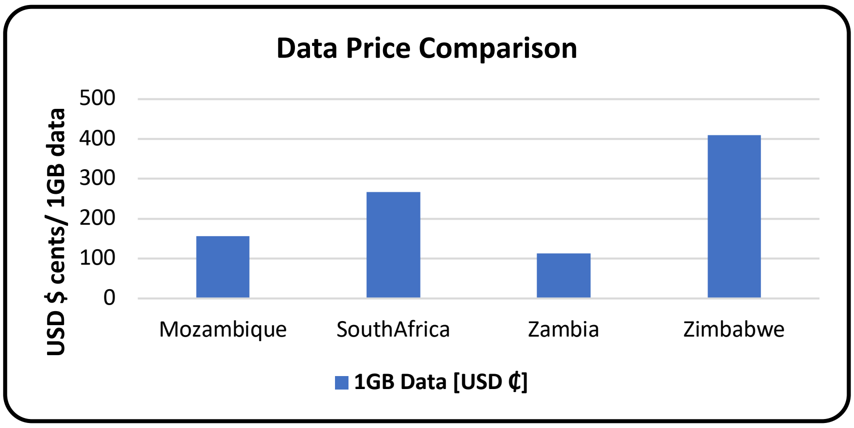


Figure 1-2: *Data and mobile tariffs of some countries in Southern Africa*

(Internet Packages, 2022) , (Statista, 2021) (Vodacom Mocambique, 2022)

The main reason why the main ISPs in Zimbabwe resort to diesel and gasoline generators is the problem of national electricity supply. Zimbabwe's problems are vastly centred on capacity. Little to no developments have been made since the establishment of the two major energy sources in 1955 (Kariba Hydro Power Plant) and 1988 (Hwange Coal Plant) both of which are only producing 60 percent of installed capacity. There is 40 percent national electricity access due to the prohibitive costs of extending national electricity grids (Sustainable Energy for All, 2022).

Every year, the country experiences huge electricity shortages and long hours of power cuts. According to Zimbabwe Power Company (2021), annual electricity production is 845 MW. However, the national demand is approximated at around 2,200 MW while only boasting a 1,940 MW as maximum installed capacity. Since hydropower is reliant on the availability of water, there is significant reduction in the annual production in times of drought. This is a very huge concern especially with Kariba being the largest electricity producer in Zimbabwe, moreover, a shared facility with the neighbours Zambia. In addition to water levels, there are constant breakdowns from a lack of investment in the infrastructure.

With the electricity supply demand gap analysis at around 38 percent in 2016 (Hogan Lovells, 2021), a huge percentage of electricity is imported from South Africa

(400MW), Mozambique (150MW) and Democratic Republic of Congo. This import cost around $19.5 million every month. Economically, more demand and less supply mean prices continue to surge. In light of the above, the telecommunications industry will continue experiencing huge operating cost, and hence price increases due to usage of diesel generators because of electrical grid outages in the city. These costs can even be huge in remote locations with mountains, forests and deserts where the grid is out of reach.

On the other hand, Zimbabwe is endowed with vast renewable energy sources. An opportunity abounds in solar energy which has a capacity of 5.7 kWh/m^2 per day (Solargis, 2022). Increasing usage of renewable power can eliminate costs associated with generators as alternative power and stabilise internet prices. Furthermore, there is need to eradicate fossil fuel generation with GHG emissions that continue to increase global warming and exacerbate climate change.

1.2 Statement of the problem

Zimbabwe's telecommunications services are fairly expensive in comparison to the nation's average salary. An ICT report in 2020 reveals that over 90 percent internet connection is through mobile data, (POTRAZ, 2020). Another side shows, according to Trade Economics (2022) Zimbabwe's average salary is USD $305.00, for a person in the CBD. If a household decide to buy an average internet bundle of 15GB per month, they will be using 16 percent of their salary before paying rent and food. The situation affects even more, government workers, particularly teachers who were learnt to be earning USD$200.00 (Anodolu Agency, 2021), making a 15 GB data plan 25 percent of their salary. With MISA Zimbabwe (2021) reporting even lower salaries of around USD $75.00 this same package can reach up to 67 percent.

These data prices are very much not easy to accept for the local consumers. In some parts of Zimbabwe's high-density suburb most of which around the industrial areas, tenants pay monthly rentals of around USD $50.00 and to see a data bundle at the same price as your rentals is pretty disturbing. Majority of people, especially unemployed youths and those living in the rural areas will lose internet access. With the pandemic (Covid-19) and the evolution of internet learning, many students in colleges and even lower grades, high school and primary schools are going to miss a lot of school because they cannot afford to access the internet.

According to All Africa (2021) ISPs attribute electricity and fuel price increases as the major contributors to higher internet prices in Zimbabwe. This is due to the fact that most of telecommunications towers depend on grid and fossil fuel-based generators for electricity. Hence, any raise in electricity price or fuel prices affect the overall operation cost of the telecommunications business, leading to higher internet prices. Fortunately, due to its location in Sunbelt region, Zimbabwe is rich in solar energy which can be harvested and integrated to power the telecommunications sector to ease and lower the operation cost which will trigger in a long term, lower internet costs. But, this potential hasn't been tapped into efficiently by the internet providers, with Zimbabwe recording zero towers powered by onsite renewable energy (GSMA, 2022).

Furthermore, fossil fuels are the biggest perpetrators to climate change. CO_2 emissions from petrol and diesel are estimated at around 2.4 kg per litre (Carbon Independent, 2008). Most telecommunications towers have a characterised average power demand around 7.5 kW (Lorincz, Garma, & Petrovic, 2012). The amount of fuel required for that power is approximately [(7.5/0.364 = 20 litres, where 1kW electricity = 0.08 gallon/0.364 litres (U.S. Energy Information Administration, 2021)]. The expression shows there is need for 20.60 litres of fuel to produce 7.5 kWh of energy for the tower. This translates to (20.60 x 2.4 kg = 49.45) kg of CO_2 emissions per hour per tower.

1.3 Research Objective

The research seeks to determine an optimal alternative energy supply system to power telecommunications base stations based on sustainability pillars; Economical, Environmental and Social, as well as Technical, for operation cost and data price reduction to augment internet access to an average person in Budiriro - Zimbabwe as well simultaneously reducing GHG emissions emitted through running these stations.

1.3.1 Research Specific Objectives

i. To investigate the existing energy supply systems for telecommunication base stations in Budiriro, Zimbabwe.
ii. To determine the feasibility of integrating Solar PV for different power system configurations in telecommunication base stations in the study area.

iii. To determine energy supply system approaches for telecommunication base stations in the study area.

iv. To assess the performance of energy supply systems using HOMER Pro based on Sustainability Pillars; Economical, Environmental and Social, as well as technical capability.

v. To determine an optimal energy supply system alternative to power telecommunication base stations in the study area from available energy sources using Analytic Hierarchy Process (AHP).

1.3.2 Research Questions

1. What are the existing energy supply systems for telecommunication base stations in Budiriro – Zimbabwe?
2. How feasible is integrating Solar PV in telecommunication base stations in Budiriro – Zimbabwe.
3. What are the different energy supply configurations for telecommunication base stations in Budiriro – Zimbabwe?
4. How are performances of proposed energy supply systems based on Sustainability Pillars; Economical, Environmental and Social, also technical ability.
5. Which energy supply system is the best alternative to power telecommunication base stations in Budiriro – Zimbabwe based on sustainability performance?

1.4 Research Significance

Various benefits are coupled to this study and huge individual, institutional and countrywide benefits are realised. The study could vastly carry a ton of reasons why it can be vital. Economical – reduction of base station OPEX, technical – increase power produced by base stations, Environmental – Reduction of CO_2 emissions, Social – employment, better health (GHG emission reduction) and social rest (noise and vibration reduction). There are key points that this particular study can tackle, which are both local and replicable.

Since the existence of traditional topologies, development has been slow over the years. Experts in that industry argue why a change in a working system. However, with the advent of environmental consciousness new technologies like energy efficiency have rose to prominence. This essentially means to eradicate energy losses within the old aging systems, smart systems have to be employed. This can be achieved by redesigning of existing topologies to meet the present and future specifications.

With (The World Bank, 2021) projecting the number of people living below the international poverty line to be approximately 6.1 million in 2021, this means 40 percent of Zimbabweans and counting cannot afford the internet, taking the estimated Zimbabwe's population at 15.2 million by (SEforAll Africa Hub, 2016). The deployment of renewable energy to the telecommunications industry can lead to a massive reduction in operations cost as one installation can last a lifetime with proper maintenance. This will have a significant impact on the reduction of data prices making internet accessible to everyone.

Telecommunications companies are used to renting land or towers, which can also be a huge operation cost. With the new design employed, the excess energy can be sold to the grid and the money used to compensate that of rented land or shared with households on which the solar systems are installed – ISPs reduce on security cost and rental costs.

According to the (UNFCCC, 2016) one of the major goals to reach 1.5° Celsius scenario compared to pre-industrial levels is the implementation of green technologies and energy efficiency measures. The implementation of solar PV technology to telecommunication towers can significantly reduce GHG emissions, a big step to achieving the industry's net zero targets by 2050 in line with the Paris Agreement, for sustainable development.

Generators have been condemned by the locals for their acoustic interferences through vibrations as well as noise pollution. Renewables are silent and efficient energy systems which if implemented, will prevent this social irritation by locals who also attribute the faults of local tower lights to the installation of telecommunication infrastructure. Furthermore, the households closer to the towers can benefit free energy usage as excess tower power can be connect off grid to the households and help reduce their power bill significantly.

CHAPTER 2: LITERATURE REVIEW

2.0 Introduction

This chapter identifies the proof from available past research, the significance and feasibility of deployment Solar PV power sources in Telecommunication base stations. As well, it shows the areas with similar setup. By discussing the trends of Zimbabwe's fuel, electricity, internet users as well as the population, it can be ascertained why power supply systems with Solar PV can be a possible solution for the sustainability of the telecommunications industry. For Solar PV systems to operate, certain conditions have to be met i.e., the resource availability in the country and area of study as well the technical systems, which will also be discussed in this chapter. Furthermore, the section reveals the gap the research seeks to fill.

2.1 Past Research on Telecommunications Base Stations Power Systems

According to the (GSMA, 2014) most telecom operators are now moving away from total dependence on diesel fuel for powering base stations, especially in remote and rural locations. Some of these telecommunication companies have acquired integrated renewable energy systems; though higher capital expenditure (CAPEX) is required, lower OPEX is expected in the long run.

(Odoi-Yorke, Woenagnon, & Kalam, 2021) in their Techno-Economic assessment of solar PV/Fuel cell hybrid power system for telecom base stations in Ghana discovered that Levelised Cost of Energy (LCOE) of PV/Fuel cell are 67 percent cheaper than that of a diesel power system.

(Goel & Ali, 2014) observed that the cost of energy (COE) decreases with increasing load for the system in their study of the cost analysis of solar/wind/diesel hybrid energy systems for telecom towers. The results were simulated using HOMER to get the optimum net present cost (NPC), operating cost per year and the energy cost/kWh for different models.

The global demand and coverage of 3G and 4G systems have been on a rapid growth between 2015 and 2018 with 900 million and 2 billion additional people covered respectively (GSMA, 2020). However, increasing coverage means more electricity needs which even strain the supply systems of Lower-Medium Income Countries

(LMICs, e.g., Zimbabwe) where grid power is already not enough. In that regard there is need to employ off-grid power supplies – not receiving power from the grid; and/or bad-grid towers – those exceeding six hours power outages.

Globally, telecommunications companies only cover around 7 percent of their electricity needs with renewable energy resources and only 26 percent of the analysed telecom companies had renewable energy targets (Solex, 2022). This shows there is need for MNOs to adopt the use of renewable energy. Below are some example telecommunication base stations that are powered by Solar PV.

2.1.1 Escotel Africa

The company's business model is based on providing energy services to owners and operators of mobile phone towers. The idea is to own and operate decentralised renewable energy infrastructure offering power as a service with mobile operators focusing purely on wireless services. Escotel's setup is shown in Figure 2-1.

Figure 2-1: *Escotel Solar Powered Mobile Telecommunication Tower*

According to Inspired Evolution (2022), the first solar photovoltaic systems (900) installed by Escotel will prevent the emission of more than 6,240 tonnes of CO_2 each year in Sierra Leone, and 10,092 tonnes of CO_2 each year in Liberia.

2.1.2 iSAT Africa

iSAT Africa aims to transform the way Africa connects with rest of the world through its carrier grade connectivity for voice, data and video applications. Through a partnership with Parallel Wireless, they managed to setup Open RAN 2G and 3G of connectivity of Solar PV, Figure 2-2, for the inhabitants of communities in the Karenga district, Uganda, who were almost 30km away from the nearest mobile network with lack of connectivity.

Figure 2-2: *iSAT off-grid Solar System*

2.1.3 Yoma Micro Power solar-hybrid power plant in rural Myanmar

Yoma Micro Power uses solar-hybrid plants as in Figure 2-3 to generate and distribute affordable, reliable and clean energy to telecommunication towers, especially off and bad grids. Off-grid solutions play a critical role as less than 40 percent of Myanmar's people have access to the national grid (Norfund, 2020).

The solar-hybrid plants are powering 250 off-grid telecom towers, which had previously relied on diesel power. According to Norfund (2020), the 250 hybrid-power plants will eradicate an estimated of more than 5,000 tons of greenhouse gas emissions per year.

Figure 2-3: *Yoma Micro Power solar-hybrid power plant in rural Myanmar [Source: Norfund]*

2.2 Zimbabwe Overview

In this section we look at various points that influence the broadcast of internet connection, mainly concentrating on the history of energy deployment, fuel usage and prices as well as population growth influence. By analysing data over a ten-year period, a new perspective can be obtained on the future of energy framework that needs to be adopted for sustainable internet connectivity. The literature looked at, internet users, population projection, energy consumption to forecast future demand. It also looks at fuel prices, GHG emissions and PV deployment.

2.2.1 Zimbabwe Telecommunications Status

According to a dashboard by GSMA (2022), Zimbabwe has a huge number of off-grid and bad-grid towers powered by diesel. This proportion is 90 percent higher than regional average by Eastern Africa.

Figure 2-4 shows a snippet of the GSMA dashboard. The dashboard shows that of the 2,809 total towers in Zimbabwe, none are towered by onsite renewable energy. However, the country has a policy which give incentives for off-grid and bad-grids that include finance for solar, PAYG solar, and CAPEX/OPEX subsidy (MISA Zimbabwe, 2021). This gives a great opportunity for ISPs to deploy solar without extra cost on CAPEX.

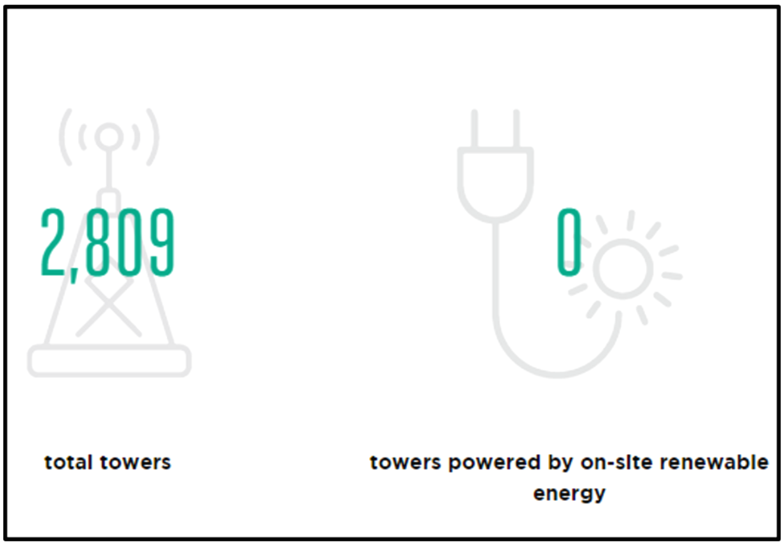


Figure 2-4: *Zimbabwe Tower Data*

2.2.1.1 Existing Power System for Telecommunication Base Stations

The existing system makes use of power from two sources namely, grid electricity and backup generators. These backup in some cases both in the study area and some outskirts (beyond the scope of this study) work as the main source of energy during grid outages or as the sole source of power in off-grid base stations.

2.2.2 Zimbabwe Internet users

Available data from World Bank (2022) over the last ten years, there has been an uptrend in the number of internet users. This is shown in Figure 2-5. As the internet importance keep growing, there is possibility of increase in the number of internet users. This can only mean an increase in the number of telecommunication towers to cater for the always rising demand for internet usage. Which in turn means and increase in demand of energy from the telecommunications industry. If the existing models continue, the data prices will keep rising as more demand for fuel rise, with price soring high to less supply worldwide. Green energy deployment will be the best model to bank on to cater for the exponential growth of internet usage in the coming years.

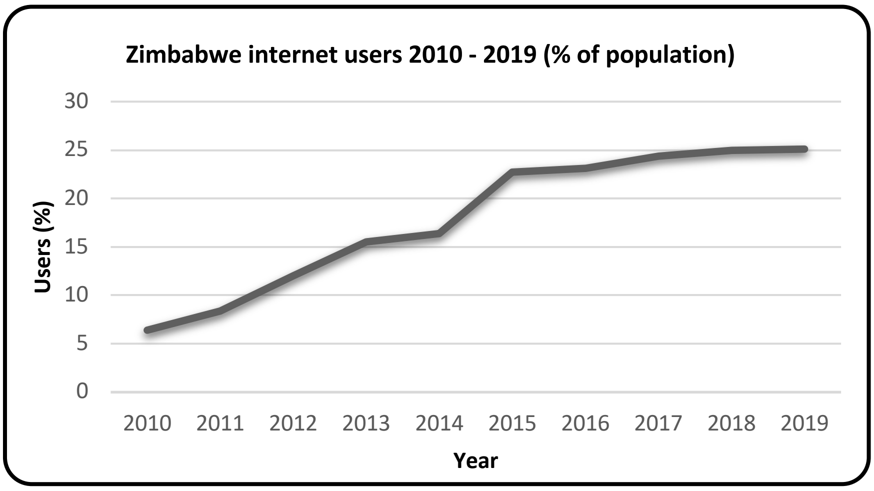


Figure 2-5: *Zimbabwe internet usage 2010 – 2019 (Source: World Bank)*

2.2.3 Zimbabwe projected population

The following data (United Nations, 2019) show a linear increase in the projected population which is important in the analysis of existing telecommunication models. This data add justification for the deployment of green energy as internet data will continuously increase. Estimates also show that 63 percent of the total population are aged 13 and above, which is mainly the number of people with potential mobile phones and internet connectivity.

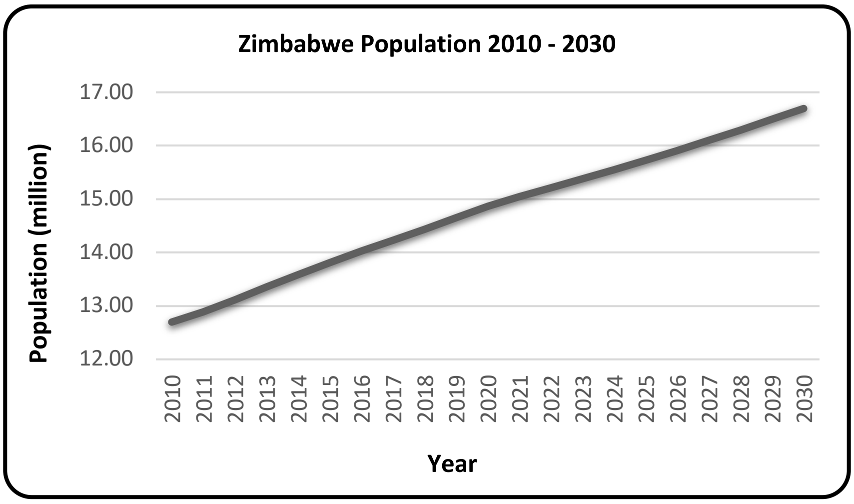


Figure 2-6: *Zimbabwe population projection (Source: United Nations)*

2.2.4 Zimbabwe electricity consumption

As seen in Figure 2-7, there is an upward trend establishing. This means that, backed with data in Figure 2-6, there is going to be more demand of energy in the future. More energy demand and little supply will incessantly shoot the energy prices even higher, of which the effects will continuously reflect on the data prices (US. Energy Information Administration, 2022). Deploying solar PV to telecommunication industry could reduce network power costs, shun the constant internet data price hike.

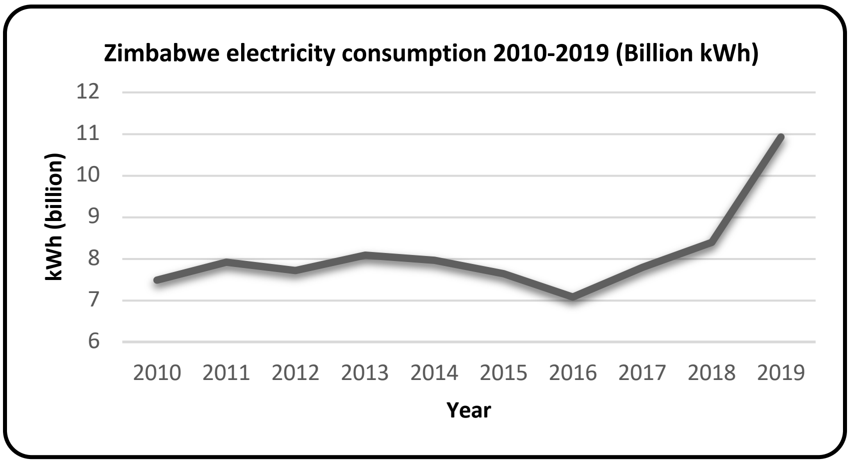


Figure 2-7: *Zimbabwe electricity consumption (2010 – 2019) (Source: USEIA)*

2.2.5 Zimbabwe electricity generation

Total electricity generated in all the years since 2001 is displayed in Figure 2-8 according to (U.S. Energy Information Administration, 2021). The data shows that there is no consistency in electricity generation. For over thirty years, the country had never surpassed 10 billion kWh mark until 2019. There is almost a high likelihood that the fluctuations will continue while simultaneously, population, demand and consumption keep rising (The World Bank, 2022).

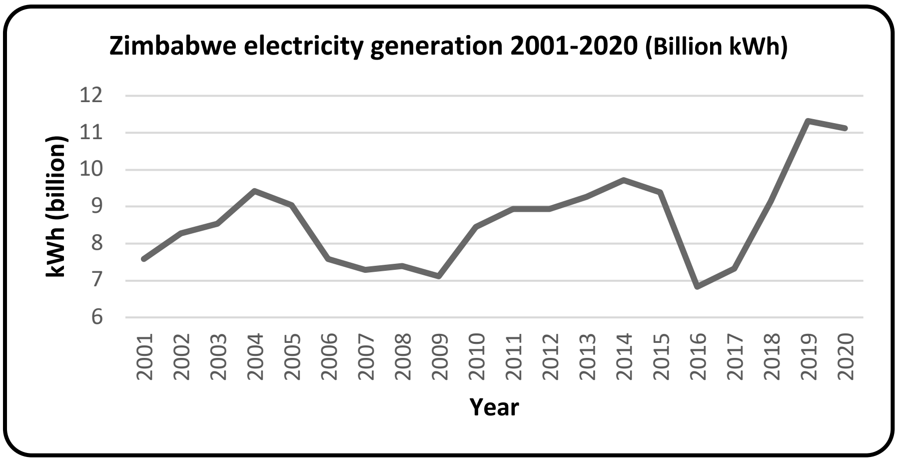


Figure 2-8: *Zimbabwe electricity generation (2001 – 2020) (Source: USEIA)*

2.2.6 Zimbabwe fuel prices

A fuel increase over the years explains the data price hikes as well as project the possibility of extension. The world markets do not show any decrease of fuel in the future. As shown in Figure 2-9 (The World Bank, 2021) and (ZERA, 2022), the surge in 2022 prices show how unsustainable it is to be dependent on fossils especially fuel that is imported.

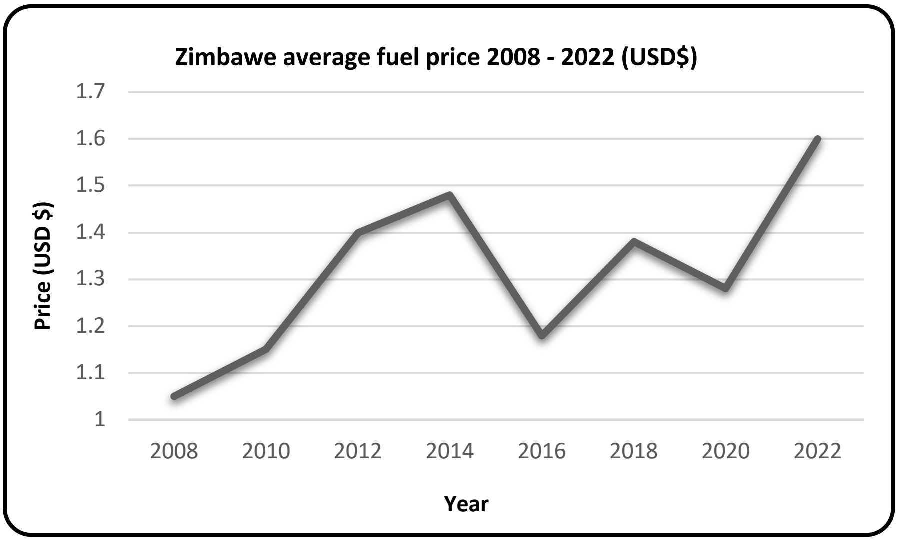


Figure 2-9: *Zimbabwe average fuel pump price*

2.2.7 Zimbabwe Lithium Potential

Zimbabwe is one of the top ten producers of lithium globally (Statista, 2021). Zimbabwe holds a significant percentage (1.0 % | 220,000 tonnes) of Lithium reserve in the whole world as shown in Figure 2-11. There is a huge potential for Zimbabwe to integrate renewable energy in telecommunications and other sectors as well. This is because one of the important components for the development of battery energy storage systems is abundantly available.

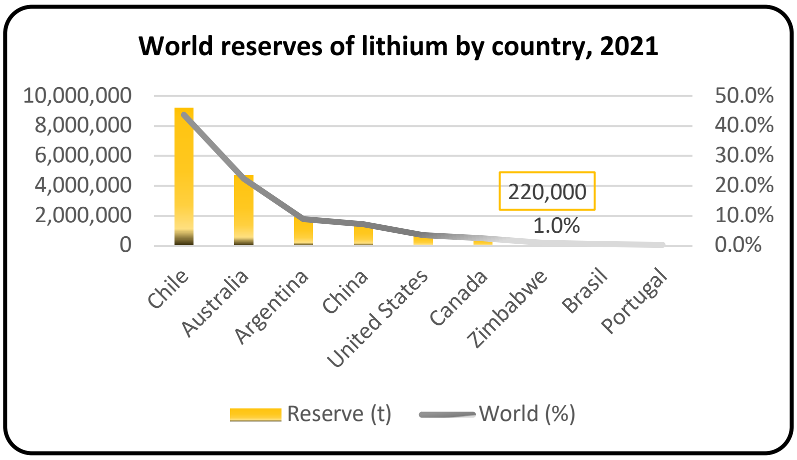


Figure 2-10: *World reserves of lithium by country, 2021*

2.3 Telecommunication Base Stations Status

Understanding continuous development in the industry, the projections in this paper would be obsolete in the future if we don't consider them. An economic analysis for the existing system will not give a clear picture if the ISPs decide to upgrade into 5G, which is a most likely scenario within the next ten years. Hence, the deployment of Solar PV systems has to both replace the generators and at the same time prepare for the reception of 5G by having installed flexible systems that provide sufficient power and modularity that help expand those power systems.

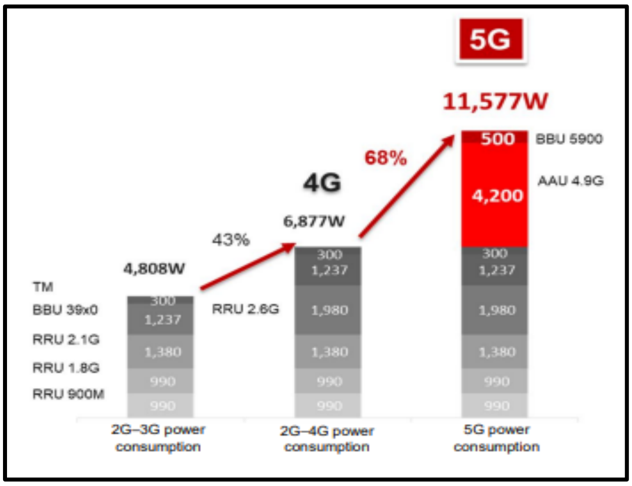


Figure 2-11: *Typical maximum power consumption of a 5G site*

As stipulated by Huawei in their 5G Power whitepaper, the power consumption of 5G drastically increases in a base station with at least five bands by a value of 68 percent as shown in Figure 2-12 below (Huawei Technologies, 2019).

2.3.1 Average Energy Consumption of the Telecommunication Towers

From their power rating analysis (Fortune Business Insights, 2022) discover that most generators installed as back up or prime power range between 10 kVA – 50 kVA due to their reliability and the ability to provide uninterrupted power. The average size backup generator for a telecommunication tower is around 30 kVA. According to a feasibility study by (GSMA, 2010) the average tower rating is between 4kW – 7.5kW. However, this figure will increase to cater for 5G as stipulated in Figure 2-12.

2.3.2 Cost Comparison for running Generator/Solar PV incl. maintenance

Data by (The Solar Hub, 2020) gives a comparison of maintenance of diesel fuel generators to that of Solar PV. As shown in Figure 2-13, costs saved with solar after 25 years amount to $ 190,019.00.

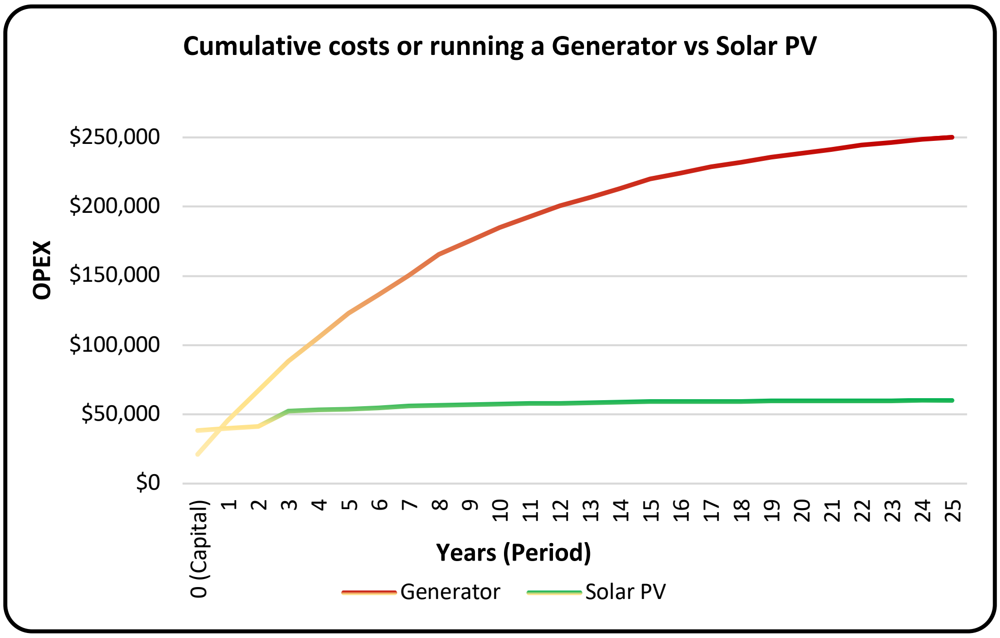


Figure 2-12: *Cumulative cost or running Generator vs Solar PV*

Telecommunication towers that are run purely on generators are run inefficiently at only 20-25 percent of their load; which means increased maintenance frequency and high fuel consumption. A diesel genset typically accounts for 35 percent of the total operating cost of a wireless base station (BTS), including skyrocketing fuel and expensive on-site maintenance costs (BHB, 2013).

Preventive maintained backup generator sets can last for 20 years or more, of which value can reduce if the maintenance criteria is not preventative (Big Rentz, 2021).

Maintenance intervals for generators can average around 1000 hrs. (Himoinsa, 2021). Other maintenance schedules can be quarterly or semi-annually for those at 50 hours or less of backup power annually. However, in off-grids and bad-grids, they may operate 24/7 or more than eight hours a day respectively. Generators operating 24 hours/day will require replacement or complete overhaul approximately every 18 months (GSMA, 2012).

On the contrary, Solar PV systems usually require very little maintenance and the cost is usually very low. Preventive maintenance is key to the running of a solar PV systems. Certain modules require maintenance performed at predetermined intervals to reduce the probability of failure and Solar PV panel degradation. Processes like general solar panel cleaning, dust removal etc are condition based, between two and four times per year, (Solar Reviews, 2022) while other hardcore maintenance like circuit wiring and routing connections, battery tests and infrared camera inspection on electrical protection system can be semi-annually or annually as long as performance is monitored to not change.

2.3.3 Cost of CO_2 Emission

A measure expressed as a dollar value of economic harm by emitting one tonne of CO_2 (EDF, 2022).This is a way of redirecting the cost of damage done on the environment back to the emitters either through **Emission Trading Systems** (Emission limits) or **Carbon Taxes** (Tax rate on emission). According to Zimbabwe Revenue Authority (ZIMRA, 2022) "*Carbon Tax is payable in foreign currency at the rate of US$0.03 (3 cents) per litre of petroleum and diesel products or 5% of cost, insurance and freight value (as defined in the Customs and Excise Act [Chapter 23:02]), whichever is greater.*"

CO_2 Emission: Diesel Generator

This is obtained by multiplying the diesel generator hourly consumption and the CO_2 rate per one litre of diesel which is approximated at 2.4 kg (Carbon Independent, 2008).

2.3.4 Levelized Cost of Energy (LCOE)

LCOE determines how much money must be made per unit of electricity (kWh) to recoup the lifetime costs of the system. It compares lifetime costs of various energy generation systems to measure their overall competitiveness. This measure takes into consideration the Initial or Capital costs of installing a generation system, operational and maintenance costs incurred in running the system, and disposition costs at the end of the system's lifecycle.

2.4 Solar Power as Alternative Energy Source

Currently, the telecommunication industry relies mainly on two convectional power sources, namely, electricity from the grid and stand-alone diesel generators. Grid electricity comes from thermal power and hydroelectric power. Thermal power station emissions lead to global warming, air pollution and climate change. As well, generators cause noise pollution and vibrations where they are installed.

However, the aforementioned effects can be shunned by employing renewable energy. Renewable energy is energy from a source that naturally replenish within the human timescale. The sun which all renewable energies are dependent on, is a source of energy that does not deplete. This source is abundant in Zimbabwe (5.7 kWh/m2 per day) as show in Figure 2-15 by (Solargis, 2022). Further, the idea employed in this research is to make sure the ISPs themselves own and maintain their own renewable energy supply systems unlike paying external suppliers.

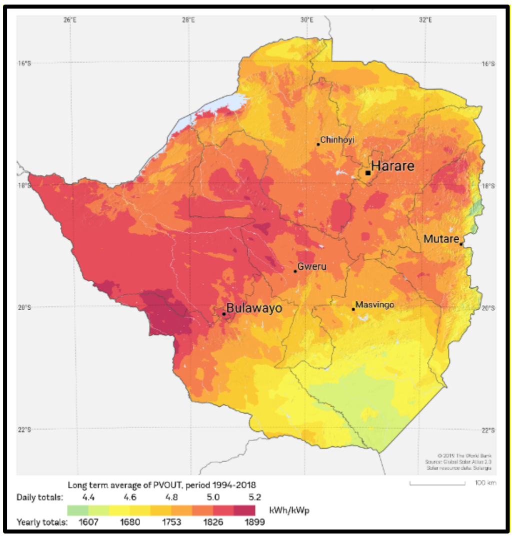


Figure 2-13: *Zimbabwe Photovoltaic Power Potential (Source: ESMAP/Word Bank)*

2.4.1 Telecommunication Base Station PV Supply System

The system consists of the photovoltaic modules, array brackets, sink boxes, charge and discharge controllers, battery packs, inverters, etc., (Bete Telecom Cabinet, 2022).

Components generally use single-crystal silicon or polysilicon batteries, each battery output voltage is about 0.5V, the general components use 72 solar cells in series, so in order to get 43.2 to 56.4V voltage range, two components need to be used in series. Power levels try to select larger production specifications, such as 165W, 170W and 175W and other specifications.

Figure 2-14: *Telecommunication Base Station PV Supply System*

For independent photovoltaic systems, in order to reduce battery usage and system costs, the maximum solar irradiation is required in winter, so the inclination of the components needs to be set to be 10 to 20 degrees larger than the local latitude for maximum collection in the area (Solargis, 2022).

A series of batteries exist for power storage and continues to supply the required energy to the load during the night and cloudy day when there is little to no charge coming from the solar panels. Battery packs are determined by the load capacity, the number of days of self-sufficiency during the night and cloudy days, as well as the depth of discharge.

2.4.2 Solar PV

A photovoltaic (PV) cell is an electronic material or device that converts light energy (photons) into electronic (or electrical) voltage and current. The term ‘Photovoltaic’ is a combination of the two words ‘photo’ for ‘light’ and ‘voltaic’ meaning electricity. Regardless of its high initial cost, Solar PV is the biggest alternative both modularly and extensively a source of energy to power the telecommunication industry.

Figure 2-15: *Solar Photovoltaic*

2.4.3 Batteries

Because of fluctuations in most renewable energy sources like solar, the storage of the harnessed energy for later use imperative. This allows these energy mixes to balance their supply and demand. Whether from re-appropriation of car batteries or specifically producing battery energy storage systems like stationery energy storage infrastructure.

A Battery Energy Storage System (BESS) is a technology developed for storing electric charge through the manufacture of batteries, or used appropriated lithium-ion electric vehicle batteries (Renault Group, 2021).

When selecting batteries for Solar Systems, the run time is more important than instantaneous power bursts, hence usage of batteries with higher energy density is advantages. The reasoning being that, PV systems with higher energy density can be less costly mainly during transportation. The energy density is a function of the weight of the battery, and the volumetric energy density (in Whr/litre^3) is a function of volume of battery. A battery with a higher energy density will be lighter than a similar capacity battery with a lower energy density (Sino Voltaics, 2022).

There are quite a number of batteries with distinctions in materials from which the anode and cathode are made and the type of electrolyte. The most common types of solar batteries are categorised into lead-acid batteries and lithium batteries. Figure 2-18 below shows the breakdown of batteries (Shukir, 2022).

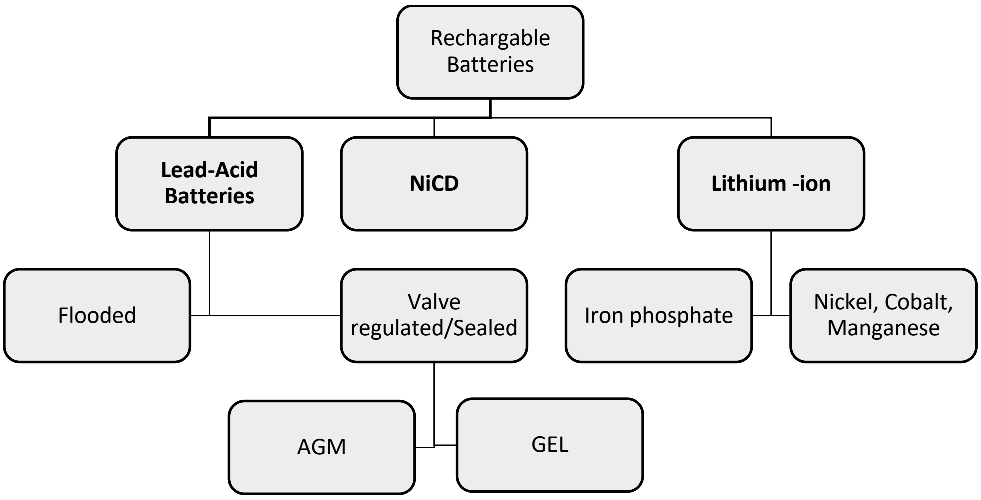


Figure 2-16: *Types of Batteries*

Further comparisons are made in Figure 2-19 below of the two leading battery types used for Solar Systems. The comparison uses, Depth of Discharge (DOD) – The, Round Trip – Percentage of energy that can be used to that it took to fully charge the battery, Maintenance – Cost and routines to keep the battery up, Battery life – Time before a need to replace the battery completely, Charge Cycles – Number of times a battery can go from full charged to discharged in its lifecycle, Capacity – Amount of charge that can be hold after charge, and Size per kWh – The weigh per kWh of batteries, for ease of transportation and storage (Solar Reviews, 2022), (Ultralife Corporation, 2022) and (IRG, 2022).

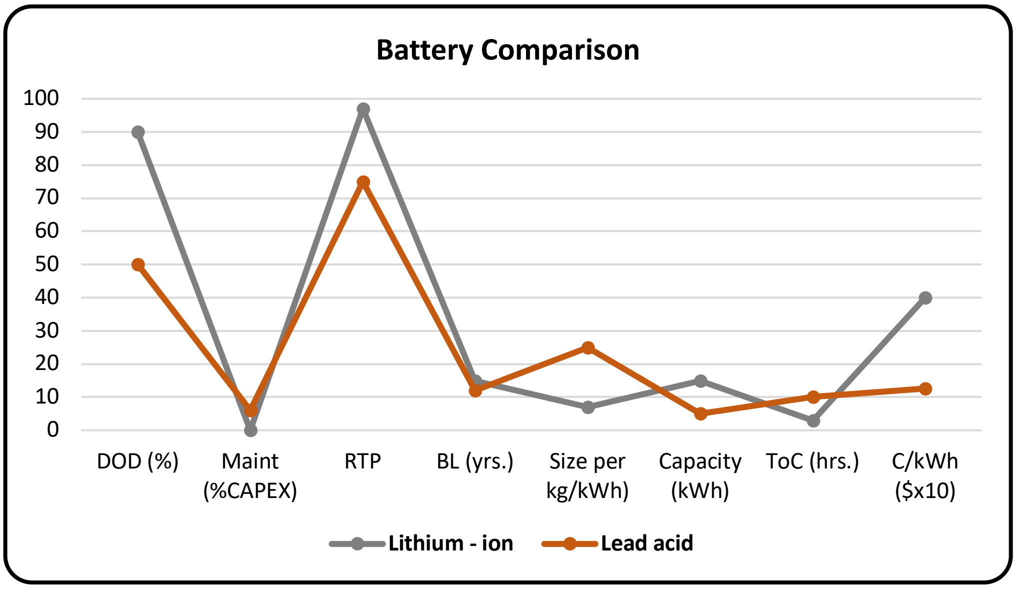


Figure 2-17: *Battery Comparison*

This study focused on the use of Lithium batteries. This is because of the resource availability as discussed in 2.2.7, a resource that is readily available in Zimbabwe. This makes the deployment of solar more favourable in the future if Zimbabwe embarks on manufacturing of lithium batteries because;

1. Lithium is becoming the preferred choice for batteries is green solutions.
2. Zimbabwe is one of the big producers of lithium, this will reduce production cost of batteries, Solar PV installations as well as future maintenance – sustainability.
3. The peak sun hours in Zimbabwe average 5 hours a day. Having lithium batteries means the system can be fully charged in a small period of time within the peak sun hours.

2.4.4 Criteria for Solar Installation

To understand Solar PV, it is important to know the parameters that need to be fulfilled for a successful installation in which irradiance matter as well as topography or geographical outlook. It can be seen from Figure 2-15, that Zimbabwe has a high solar irradiation.

2.4.4.1 Irradiance

The most basic factor for developing a solar PV project is the availability of high average annual Global Horizontal Irradiation (GHI).

The higher the solar insolation, the greater the energy yield per installed development (while there is no min GHI that is required, locations exceeding 5 kWh/m2 /day are considered with sufficient insolation) (Jacobson et al. 2016). Zimbabwe has an opportunity abound in solar energy which has a capacity of 5.7 kWh/m2 per day.

This can be confirmed by data from Global Solar Atlas (2022), the defined area of study which exist in the region demarcated in the Figure 2-18.

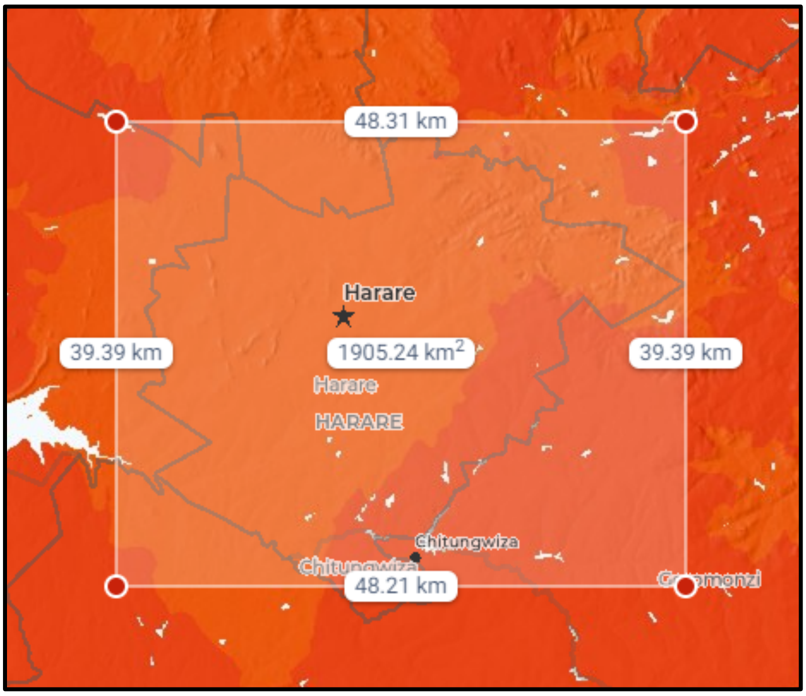


Figure 2-18: *Harare Solar Irradiation*

The area demarcated in Figure 2-18 has an estimated data shown in Table 2-1.

Table 2-1: *Solar PV Irradiation Map Data (Source: SolarGIS)*

Description		Range		
Specific photovoltaic power output	**PVOUT**	4.86	4.98	kWh/kWp
Direct normal irradiation	**DNI**	5.78	6.03	kWh/m^2
Global Horizontal irradiation	**GHI**	5.74	5.87	kWh/m^2
Diffuse horizontal irradiation	**DIF**	1.86	1.93	kWh/m^2
Global tilted irradiation	**GTI**	6.11	6.24	kWh/m^2
Optimum tilt of PV modules	**OPTA**	21	22	°
Air temperature	**TEMP**	17.9	19.7	°C
Terrain elevation	**ELE**	1261	1608	m^2

Harare (the city in which the study area is located) monthly PV performance data is given in Figure 2-21 for Jan – Dec. In the best months of the year, irradiance can reach up to 7kWh/m^2/day. AC and DC array output for the whole year ranges above 400 W.

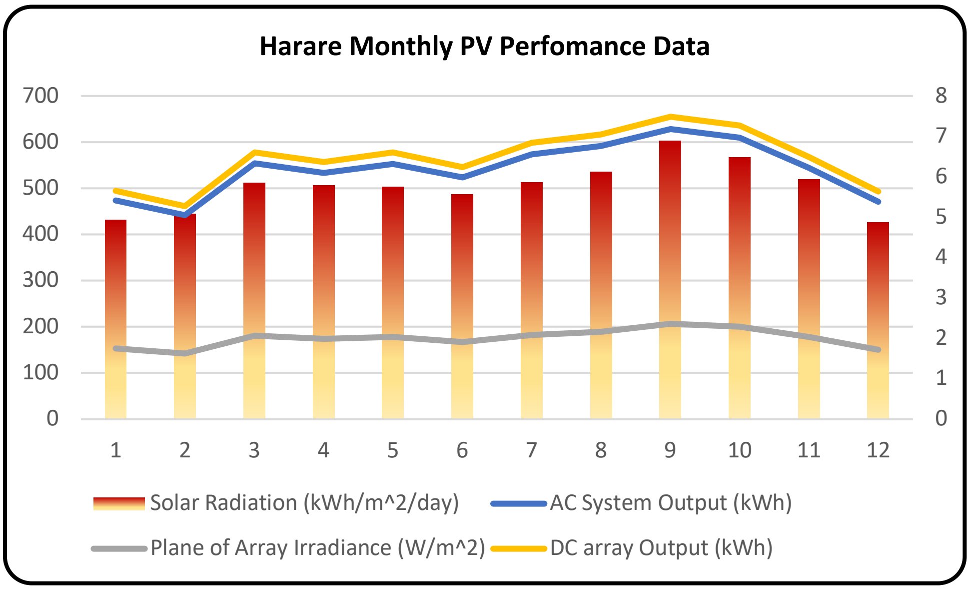


Figure 2-19: *Harare Solar PV monthly performance data (Source: SolarGIS)*

2.4.4.2 Topography

The solar panels should be on flat north facing slopes to ensure greater solar radiation and power production (that make it close to 90 degrees the angle of maximum collection) due to the location of the sun installations (International Finance Corporation 2012; McKinney 2014). According to ZTE (2009), Solar PV modules need to be placed at an angle of 10-20 degrees higher than the latitude of the site of installation for maximum solar radiation in winter. This is made to reduce the number of batteries and more importantly the overall installation and operation costs. Taken in consideration, the values in Table 2-1 above are a closer estimate to solar installation in the area highlighted.

2.4.5 Solar PV designs for Telecommunication Towers

There are four types of electrical designs for Solar PV systems for possible integration into telecoms base station. Those connected to the power utility grid with no back up batteries, systems that interact with the utility power grid and include battery backup, standalone systems, and hybrid standalone systems.

1. **Grid-Tied Solar Systems**

These are systems that connect directly to the already available electrical power grid.

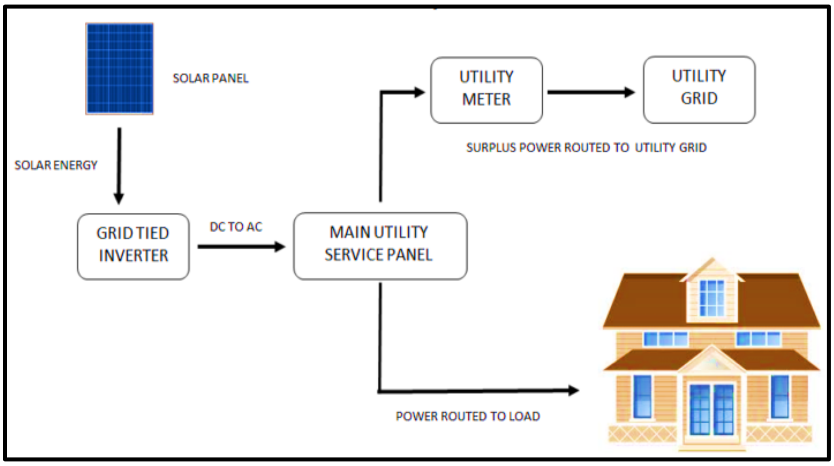


Figure 2-20: *Grid-Tied Solar Systems [Source: (Mesar Energy, 2019)]*

The configuration in Figure 2-22 shows the grid tied solar system. They only operate when utility is available and shut down in the event of an outage, up until the utility power is restored.

2. **Grid-Tied Systems with Battery Back-Up**

They have batteries connected to the system to keep critical load circuits operating when there is a power outage. During load shedding or power outages, the unit disconnects from the utility and powers specific circuit. They can also use power directly from the PV cells during the time when there is enough solar resource.

This research will make use of this system because of underlying benefits of extended power supply due to battery, net metering, to reduce bills by selling back power to the grid and increased reliability. The system is shown in Figure 2-23 below.

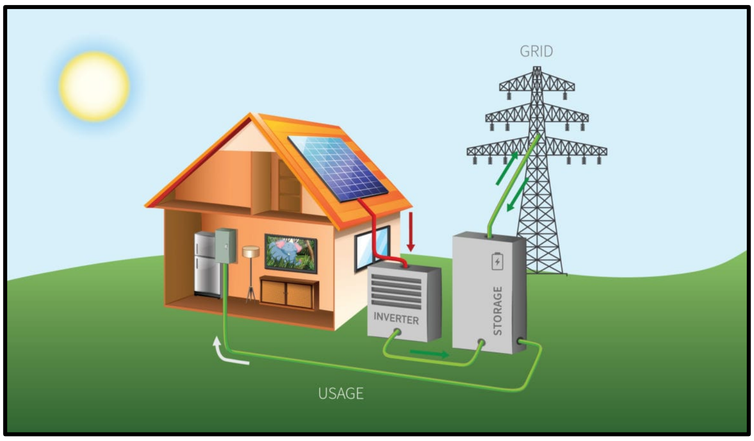


Figure 2-21: *Grid-Tied Systems with Battery Back-Up [Source: (AM Solar, 2021)]*

3. **Off-Grid Solar Systems (Stand Alone Systems)**

These systems are completely isolated from the grid. They are made from the combination of batteries, inverter, switches, and solar array as illustrated in Figure 2-24. Power flows from PV cells through the charge controller to either the battery for storage or directly through the inverter to convert from DC to AC and then to the load.

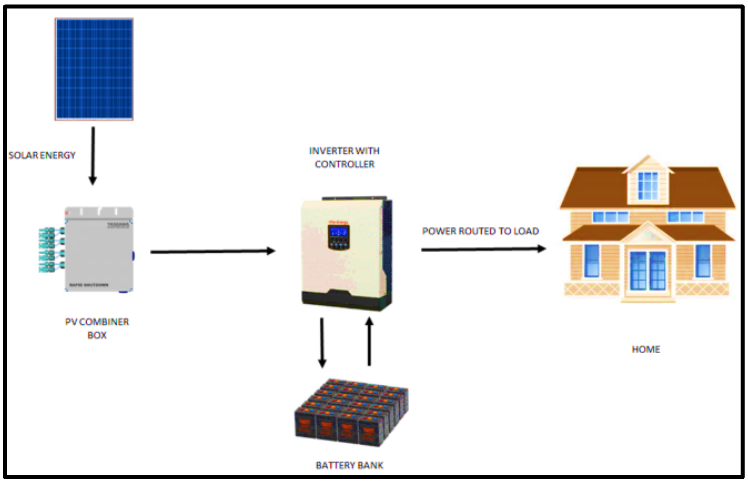


Figure 2-22: *Off-Grid Solar Systems [Source: (Mesar Energy, 2019)]*

4. **Hybrid Solar Systems**

These are systems that feed in multiple power sources. They may use power from other renewable energy sources like wind energy, hydro, and convectional sources like diesel, thermal power etc. The configuration is shown in Figure 2-25.

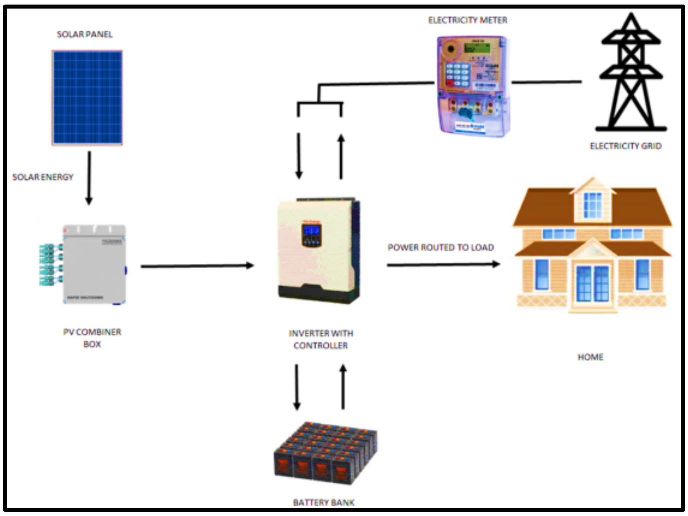


Figure 2-23: *Hybrid Solar Systems [Source: (Mesar Energy, 2019)]*

2.5 Sustainability Pillars

As a business, any investment should bring a return. However, modern Industrialisation brings more focus on products, services and processes that are environmentally conscious. That hence, according to Investopedia (2021) businesses cannot afford to profit at any cost – Economical Sustainability. In this study, the main objective is to provide an approach that not only reduce OPEX but that which facilitate the environment's ability to cater for people's present need but not compromising those of future generations – Environmental Sustainability. In any case, the Telecommunication industry is an enabler to provision of a near need, Internet, which in itself improves people's quality of life. Doing that at the provision at least land use and less emissions that compromise people's lives – Social Sustainability (Botelho, Ointo, Lourenco-Gomes, Valente, & Sousa, 2016). Solar PV systems can produce higher energy per year with enough irradiance – Technical capability.

2.6 HOMER Pro

HOMER (Hybrid Optimization Model for Multiple Energy Resources) is a design, simulation and optimisation software for building cost effective hybrid microgrid and grid-connected systems that combine traditionally generated and renewable power as well as storage, and load management (Homer Energy, 2022).

In simulation, HOMER Pro creates from input parameters, viable systems for all possible combinations of energy sources in a design. A number of systems in some cases even hundreds or thousands can be simulated all of which on the basis of required system capacity.

In optimisation, HOMER Pro closely examines the system combinations and sort systems according to the designer's preferred variable. It can optimise for example for the lowest net present cost if that is the designer's main target. The software's interface is shown in Figure 2-26.

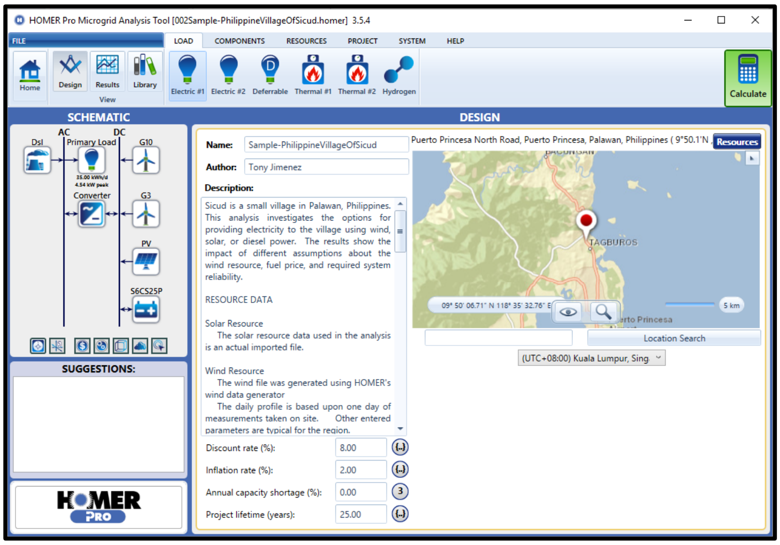


Figure 2-24: *HOMER Pro interface; Source: (Homer Energy, 2022)*

2.7 Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP) is a multi-criteria decision-making framework which produce priority scales through pairwise comparisons (Saaty R. W., 1987) and (Saaty T. L., 2008). Analytic Hierarchy Process (AHP) follows a number of steps (Define the problem and criteria, establish priority amongst criteria using pairwise comparison, consistency checks through established equations and obtaining the relative weights.

AHP has been used to compare energy systems and energy planning projects. Mwanza and Ulgen (2020) used AHP to determine sustainable electricity generation fuel mix for Zambia, Stein (2013) applied AHP to develop a model for decision makers for selecting electric energy production technologies and Vasileiou et al., (2017) identified suitable sites for wind-wave hybrid offshore energy system development in Greece using AHP.

2.8 Summary

This chapter has put together data to show enough resource availability in-terms of irradiance and lithium for battery the two fundamental ingredients for Solar PV in the area. This means both the energy demand in telecommunication base stations and internet demand can be fully met. As well, feasibility studies and simulations in previous research show that the feat was achieved in other areas as proven by their work, shared here within.

CHAPTER 3: RESEARCH METHODOLOGY

3.0 Introduction

This section describes the procedures that were adopted to achieve the objectives. In this section the operational definition for the variables used are specified in detail, along with the type of variables and the method for measuring these variables. In addition, the section also outlines the study design, the techniques and procedures to be used to achieve the proposed objectives.

Post homer pro section analyse the simulation results; How the respective systems compare against each other on each of the sustainability pillars as well as technical capability. This data was used to create ranking criteria for pairwise comparison in Analytic Hierarchy Process (AHP). Lastly, AHP was conducted to select the optimal alternative energy system to power telecommunication base stations.

3.1 Research Design

For the framework to be applicable elsewhere, there was need to assess at a cost perspective the economic feasibility of different approaches that can be applied in the study area through its availability. The optimal energy system is determined through a number of processes, Figure 3-1. Firstly, based on the available energy resources in the study area, possible configurations are derived. Secondly, these systems were then simulated through a load in HOMER Pro. Lastly, the simulated data was passed through a multi criteria decision making process to decide the optimal system.

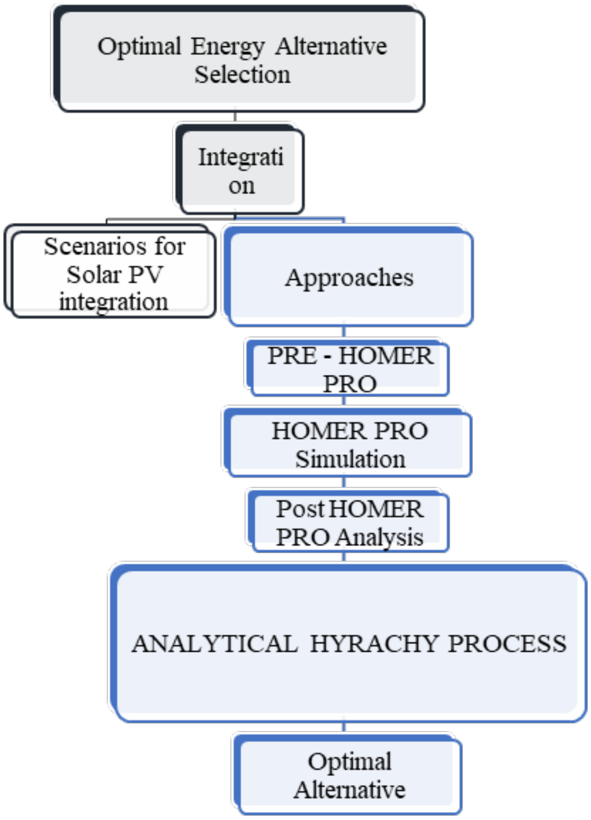


Figure 3-1: *The research framework*

3.2 Study area

Budiriro is a high-density suburb in the southwestern area (map shown in Appendix D) of Harare in Zimbabwe. There are about 30,000 houses, two clinics, five elementary schools and one High school (Dodge, 2011).

3.3 Research Data Collection

Data collection is divided into two parts, primary and secondary data. Primary data is first-hand data with originality that is traceable to its source. Most importantly data is directly related to the issue or problem. Secondary data is data collected in the past by other researchers for specific use. Data may not be directly linked to the study at hand (Sapsford & Victor, 2006).

3.3.1 Secondary Data

Secondary sources that are not first-hand, i.e., that cannot be traced back to its source by directly linked. This data allows the researcher to visualize the type of problem faced by past researchers, regulation boards and the ministry.

i. **Journals and Conference papers**

A set of previous work that firstly strengthen the hypothesis for deploying Solar PV based on areas with success previous success of adoption. Secondly, models; Equations for Solar PV sizing, Models for Analytic Hierarchy Process (AHP).

ii. **Internet**

Data for use in simulation processes in HOMER Pro are collected from online libraries for different types of system simulations. For Solar PV systems, monthly values for GHI – collected from National Renewable Energy Laboratory (NREL), and Temperature – collected from NASA Surface meteorology and Solar Energy database.

3.3.2 Primary Data

The study area has base stations for all three top internet providers namely Econet Wireless, NetOne Cellular and Telecel Zimbabwe. A Questionnaire was prepared, Appendix A, which ISPs answered based on their operations. Table 3-1 shows the distribution on the base stations/ telecommunication towers, estimated range of number of users per day, peak operating hours, estimated generators specifications and estimated daily consumption in kWh.

Table 3-1: *Data from ISPs*

Data	ISPs (All)
Total No. of towers	11
No. of User Carried per tower	20 – 5,000
Peak operating period	24 hrs
Generator specifications	18 kVA – 30 kVA
Daily energy consumption	~60 – 168 kWh

Relevant data from third-party organisations linked to the study was also collected. This data includes, fuel prices and emission data – from Zimbabwe Energy Regulatory Authority (ZERA), grid availability electricity price – electricity tariffs from Zimbabwe Electricity Transmission and Distribution Company (ZETDC)

3.4 Scenarios for Integration

The integration of Solar PV on the existing telecommunication towers can be managed in three different ways i.e., Base stations built on/near residential houses, Base Stations built near Clinics/Shop/Municipality/Communities and beyond the scope of this research, Base stations built in isolated areas (proposed in recommendations). The solutions are discussed in this section to recommend a way for Solar PV integration into energy systems for base stations and measures for security. The integration methods suggested are not solely intended to benefit the telecommunication companies, but both parties through shared electricity, be it individual households, shops, clinics, or municipalities on which the Solar PVs are installed.

3.4.1 Scenario 1 – Base Stations built on/near residential houses

These base stations built on pockets or spaces intentionally left by municipality or next to households or on households' land through agreement. An example in Figure 3-3. Households that agree to install the Solar PVs on their roof will share power with telecommunication companies absolutely paying nothing since the maintenance will be done by these telecommunication companies. Moreover, apart from this offer being enticing to these households, they will guard the facilities with their lives since they are benefiting. ISPs will reduce cost on security personnel as is the case of generators.

Figure 3-2: *Telecommunication Towers built near houses*

3.4.2 Scenario 2 – Base Stations built near Clinics/Shops/Municipal Centres

Base Stations that are built closer to municipal premises like offices, solar powered boreholes as seen in Figure 3-4. and community halls. These have easy integration since there is a lot of free unutilized area of space both on empty roofs and ground. Solar panels enough to power the community hall and the telecommunication towers can be installed.

The particular place as seen in Figure 3-4, the panels are for solar powered boreholes, the maintenance is subsidized by people who pay a small fee to use the water facilities. However, if ISPs invest in those, they would firstly increase the capacity of the water facility; secondly reduce the cost of generation; and most importantly increase maximum power of the solar facility which they can tap into for the telecommunication towers in turn giving back to the community by increase water facilities.

In terms of security; The Halls will house the auxiliary equipment that facilitates the usage of Solar PV like batteries, charge controllers and switches. These can be secured safely inside. As well, since these places are guarded, they are immune to tempering and theft.

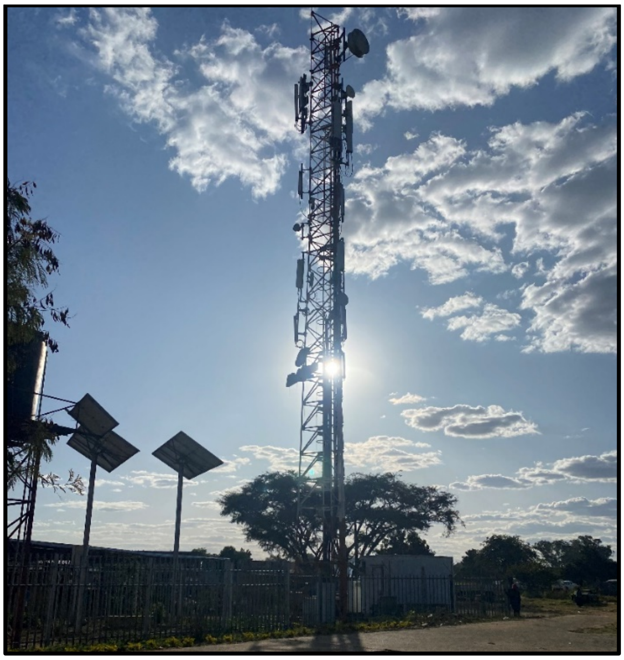


Figure 3-3: *Telecommunication Towers built near municipal facilities*

3.5 Approaches to Base Stations Power Systems and Solar Integration

There are a few combinations of approaches that can be used to provide power for based stations including the integration of Solar PV. For a broader perspective, there is need to analyse how the systems without Solar PV, would perform as well as their environmental impacts so as to prove the importance of Solar PV deployment in this industry. The different energy systems (configurations) considered are; Existing system (Grid + Generators), Generators only, Generators + Solar PV, Solar PV only, Solar PV + Grid and Grid only.

In the aforementioned approaches, the system setup will consist of power supply (either Solar PV with panels with backup storage in form of batteries/ Diesel gensets/Grid/), charge controllers, inverters, and the load (telecommunication tower).

3.5.1 Approach 0 (A0) – Grid + Generators (Existing System)

The existing system has base stations powered with the Grid (National Grid – Hydro Power + Thermal Power) as the main power source and backup generators that kick in during grid outages. The system configuration is shown in Figure 3-4.

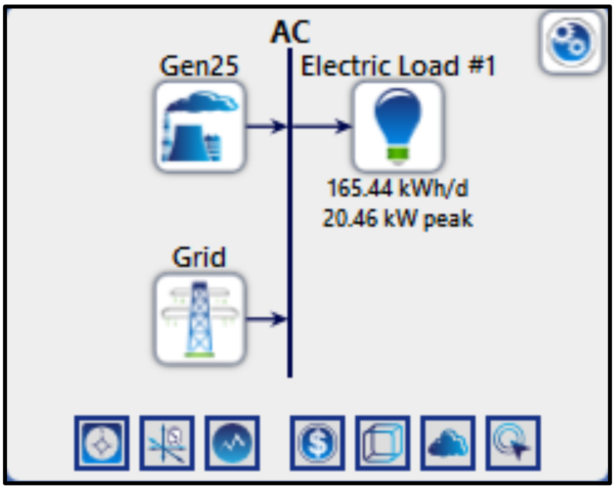


Figure 3-4: *Grid + Generator system configuration*

Input data for simulation will have a weighting put on the grid. The study area has power outages from an average of eight hours as given in the power schedules from ZETDC in Appendix C. In some cases, grid outages can get up to 19 hours in some days. Hence the input data gave a maximum of 40 percent grid availability per day and the rest was powered by the generator. A 25-kW generator was used in the study with fuel price set at the existing average at USD $1.74 per litre at the time of simulation, with grid unit power at 0.11 per kWh (ZERA, 2022). GHG emissions were calculated based on operation time and percentage efficiency of generators taken to be 25 percent. The system used a maximum of 40 percent of thermal power portion for electricity (Zimbabwe Power Company, 2021). This was used to calculate the GHG emissions by the grid. Pros and Cons for the energy system are presented in Table 3-2.

Table 3-2: *Grid with Generators (Existing System)*

Pros	Cons
Backup power availability during grid outages.	Little to no control of power supplied on the grid.
More control of backup power.	Extended load shedding in grid means extended use in generators.
Readily available schedules.	Extended use of generators leads to increased GHG emissions.
No additional infrastructure.	High maintenance cost of generators during power outages.

3.5.2 Approach 1 (A1) – Generator only

Usage of a generator only systems mean running them 24/7 as the sole power source for the telecommunication towers. This means for continuous power there should be an installed redundancy, extra generators to substitute the others during maintenance. This system has a higher OPEX and GHG emissions. Figure 3-5 shows the energy system configuration.

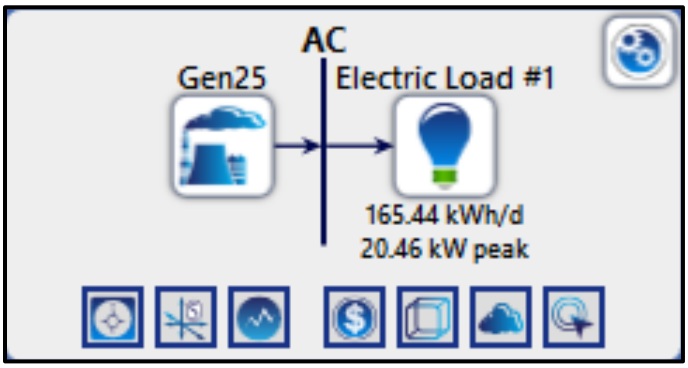


Figure 3-5: *Generator only system configuration*

For simulation, grid availability is zero and 100 percent generator. A 25-kW generator was used in the study with fuel price set at the existing average at USD $1.74 per litre at the time of simulation (ZERA, 2022). GHG emission were calculated based on operation time and percentage efficiency of generators taken to be 25 percent. Pros and Cons for this type of energy system are presented in Table 3-3.

Table 3-3: *Generators only*

Pros	Cons
Independent power source.	Relatively high OPEX
Reduced service downtime if more generators are used as redundancy.	Prone to breakdowns; Increases Service downtime.
Reliable energy supply at all times.	High GHG emissions.
Localised control of power supply utility.	Significant distractive vibrations.
Easy to bring online faster after breakdown.	Additional cost of fuel transportation.

3.5.3 Approach 2 (A2) – Generator + Solar PV

This approach makes use of Solar PV with Generator(s) as backup. It regards solar power as fluctuating means because of inconsistent sunlight availability due to drastic weather changes. This system has a fairly significant prioritisation of generators, hence more emissions though significantly lower to that of Generator only systems.

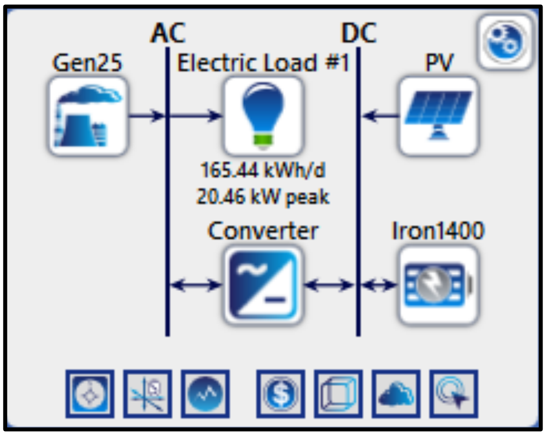


Figure 3-6: *Generator + Solar PV system configuration*

Availability of 60 percent generator and 40 percent availability for Solar PV was used. A 25-kW generator was used in the study with fuel price set at the existing average at USD $1.74 per litre at the time of simulation (ZERA, 2022). The system size for the Solar PV and battery bank sizes are given in 3.6.1 and 3.6.2 respectively. GHG emissions were calculated based on operation time and percentage efficiency of generators taken to be 25 percent. Pros and Cons are presented in Table 3-4.

Table 3-4: *Generator + Solar PV*

Pros	Cons
Reduced GHG emissions by Solar.	Significantly high maintenance costs.
Availability of double backup power from generators and battery.	Possibility of downtime during cloudy days and night when solar power is out.
Excess generator power can be stored in batteries.	Significant GHG emissions from generators.

3.5.4 Approach 3 (A3) – Solar PV only

In this approach, the base stations go totally off-grid and rely solely on solar power 24 hours a day every day. Though this the ideal approach to eliminate a huge chunk of operational costs, depending on the location of the base station, it would need a lot of space to install the solar panels.

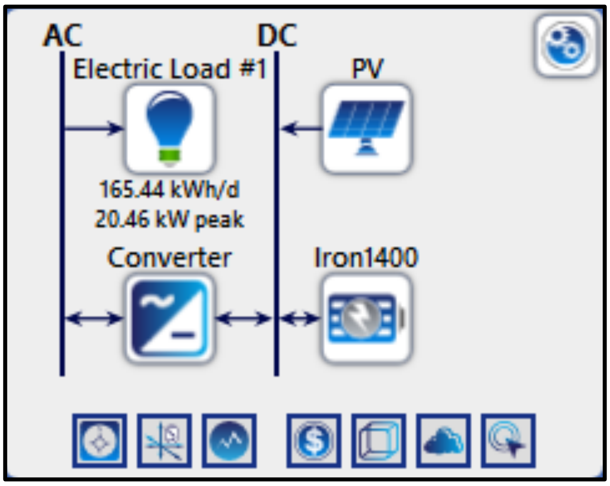


Figure 3-7: *Solar PV only system configuration*

This system uses 100 percent of Solar PV power. The system size for the Solar PV and battery bank sizes are given in 3.6.1 and 3.6.2 respectively. Pros and Cons for this type of energy system are presented in Table 3-5.

Table 3-5: *Solar PV only*

Pros	Cons
Relatively lower OPEX	Relatively high CAPEX
Backup battery power during cloudy and night times.	Increase in power mean increase in solar panels and battery storage.
Low to zero GHG emissions	No little to no power collection at night and cloudy days.
Sustainable source of power.	Power limit due to space unavailability.

3.5.5 Approach 4 (A4) – Grid + Solar PV

In this approach, Solar PV substitute generators. This essentially means that, solar PV will work during grid power outages as well as during peak hours when power is expensive. The average sun hours in the area are five hours (Solargis, 2022), hence the need for a complementary battery pack to increase the reliability of the system during night hours and cloudy days. Grid power have a relatively low LCOE to supplement higher CAPEX associated with Solar PV.

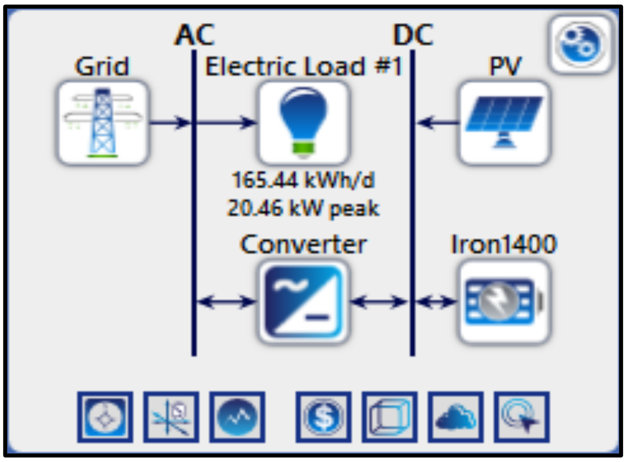


Figure 3-8: *Grid + Solar PV system configuration*

The study area has power outages from an average of eight hours as given in the power schedules from ZETDC in Appendix C. In some cases, grid outages can get up to 19 hours in some days. Hence the input data gave a maximum of 40 percent grid availability per day and the rest will be powered by the Solar PV. The system size for the Solar PV and battery bank sizes are given in 3.6.1 and 3.6.2 respectively, with grid unit power at 0.11 per kWh (ZERA, 2022). The system used a maximum of 40 percent of thermal power portion for electricity (Zimbabwe Power Company, 2021). This was used to calculate the GHG emission by the grid. The system can also be set in such a way that even if grid power is available, solar power can kick in times during which grid power will be expensive to reduce operational costs. Pros and Cons for this type of energy system are presented in Table 3-6.

Table 3-6: *Grid + Solar PV*

Pros	Cons
Availability of backup power in solar battery.	Limited power backup due to limited charge stored in solar.
Cost reduction by substituting grid power with solar during peak hours.	Reliability is low during long outage hours coupled with cloudy days.
Backup batteries can be charged by the grid during off-peak hours when power is cheap.	No control over the grid and weather conditions.
Relatively low OPEX	Relatively high CAPEX

3.5.6 Approach 5 (A5) – Grid only

This system means being totally dependent on the local power supply. However, the power outages make this system become difficult to implement. With the national grid having lower supply and high demand with power outages as much as 19 hours per day average in the study area, its reliability makes this option improbable in practice. The configuration is given in Figure 3-9.

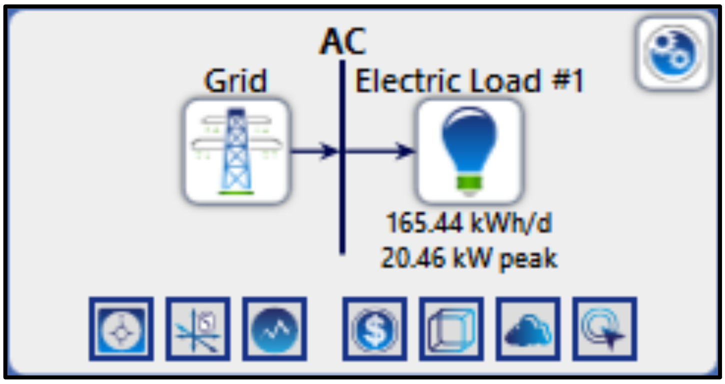


Figure 3-9: *Grid only system configuration*

The grid, if available would provide a 100 percent of the power with grid unit power at 0.11 per kWh (ZERA, 2022). The system used a maximum of 40 percent of thermal power portion for electricity (Zimbabwe Power Company, 2021). This was used to calculate the GHG emission by the grid. Pros and Cons for this type of energy system are presented in Table 3-7.

Table 3-7: *Grid only*

Pros	Cons
The ISP's only focus on maintaining their communications infrastructure	No control over the energy supply. The power supply determines power schedules.
Zero maintenance cost on power by ISPs	Reliability is certainly not guaranteed.
Lower CAPEX on power connection	GHG emissions from convectional sources.

3.6 Input Data for Simulation – Pre Homer Pro

Before simulation of the proposed approaches, there is base data required for input to the simulation software. This data includes, generator size, grid power provided, PV system size and the battery. A weighting is put on the input parameters based on monthly usage, grid availability and system operation hours.

3.6.1 Solar PV System Sizing

Calculating daily energy use

Energy daily use is approximated from data collected. The data collected has a weekly use of approximately 1000 kWh per month per base station.

$$Daily\ energy\ use = \frac{weekly\ use}{days\ in\ a\ week} = \frac{1000}{7} = 142\ kWh/dy \tag{3.1}$$

Calculating Power Output required by the Solar PV system.

From the data collected of the study area, the approximate daily hours of full sun are around 5 hrs/dy., (Solargis, 2022).

$$Power\ Output = \frac{Daily\ energy\ use}{Daily\ hours\ of\ full\ sun} = \frac{142\frac{kWh}{dy}}{5\frac{hrs}{dy}} = 28.4\ kW \tag{3.2}$$

Calculating PV system size

This study makes use of a 0.8 derating factor. The system size is obtained by dividing the power output by the derating factor.

$$Solar\ PV\ system\ size = \frac{Power\ output}{Derate\ factor} = \frac{28.4\ kW}{0.8} = 35.5\ kW \tag{3.3}$$

A 35.5 kW system will be used as the input system in the simulation of approaches with a Solar PV system.

3.6.2 Battery Bank Sizing

For the battery bank system, it should last the system at least a full day up to three days before the next full charge. Hence the battery should sustain operation for up to the time when the grid is available again. The state of charge used will be 20 percent. Since Solar PV power availability is purely dependant on weather which cannot be controlled by any human means. It is not wise to put a 100 percent dependence on it. Hence the calculated power bank will give the required autonomy to deal with the grid outages and cases of maintenance.

Battery bank size

$$Daily\ use = 0.4 \times 142\ kWh = 56.8\ kWh \tag{3.4}$$

$$Battery\ bank\ size = Daily\ use \times \frac{Days\ of\ autonomy}{(1 - state\ of\ charge)} \tag{3.5}$$

$$= 56.8\ kWh \times \frac{1}{(1-0.2)} = 71\ kWh$$

This 71 kWh is the amount of energy our battery bank needs to hold in total when fully charged.

Amp hours required

Assuming a 48 V battery pack,

$$Amp\ hours = 1{,}000\ \times \frac{Energy\ storage}{Battery\ voltage} = \frac{71\ kWh}{48\ V} = 1{,}479.167\ @\ 48V \tag{3.6}$$

A simple battery nomenclature,

By connecting batteries in series: System voltage increases, amp hour remains the same. By connecting the batteries in parallel: System voltage remains the same, amp hour doubles. The amp hour calculated above is just a base figure, the system can be expanded by investing in a number of batteries to increase autonomy.

3.6.3 Generator Size

From data once used for base stations design and that from the study area collected. We can approximate an average of 30 kVA backup generator. Also, a power factor of 0.85.

$$Generator\ Size = \frac{Generator\ rating}{power\ factor} = \frac{30\ kVA}{0.85} = 25.5\ kW \tag{3.7}$$

3.6.4 Grid Considerations

The simulation has to have a weighted Grid data. There has to be a limit on the grid capacity so that the system doesn’t optimise towards the grid which might have a relatively cheap power and lower Capital costs. However, the weighting on the grid is fairly applied because of its low reliability due to loadshedding. The maximum capacity is weighted at 3,000 kWh per month based on the average grid outages. The summary is shown in Table 3-8.

Table 3-8: *Summary of Simulation input data*

Description	Value
Solar PV system size	35.5 kW
Battery Bank size	1,479.167 Ah @ 48 V
Generator	25 kW/ 30kVA @ 0.85 *pf*
Grid	3,000 kWh/month availability

3.6.5 Load Profile

Data collected in the study area was used to determine HOMER Pro synthetic load to create the load profile for the simulation. The study area is located in the southern hemisphere usually with a peak month in January. This same data creates a de-map, a colour coded profile of approximated yearly electric load, essential in the simulation process. The load profile determined in HOMER PRO is a community type of load with an average of 165 kWh per day of consumption. This is a bit more than the average BTS consumption with 4kW rating working 24 hours a day. However, with the advent of 5G networks, within the next 10 – 25 years during which this paper is simulating its data on, there is more likelihood that ISP's will have moved to 5G systems. As reported earlier in Figure 2-11 , 5G will need about 68 percent more power that 4G hence could take the average daily loads above 165 kWh.

From Figure 3-10, the profile shows higher consumption during the day, surge during night time and drop early morning hours. This is because between midnight and early in the morning around 0500 hrs, are sleeping hours, hence low internet usage. A surge of data traffic occurs between 1700 hrs and 2100 hrs because many people have left their work places, school etc and have free time to check up on news and chat on those social apps before they retire to bed.

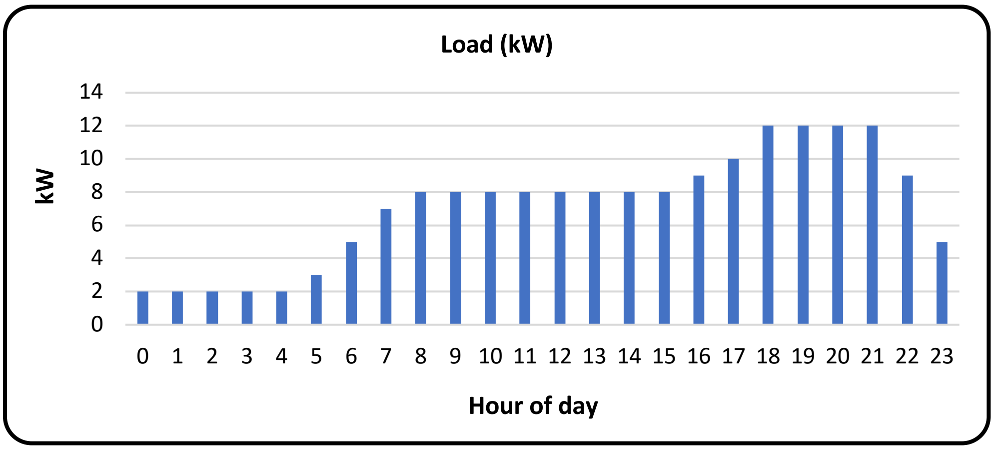


Figure 3-10: *Load profile for simulation*

3.7 Analytic Hierarchy Process

Analytic Hierarchy Process (AHP) is a multi-criteria decision-making framework which produce priority scales through pairwise comparisons (Saaty R. W., 1987) and (Saaty T. L., 2008). AHP start with a focus, which is the main goal – in this case, selecting the optimal energy supply system to power telecommunication base stations, then second level, the main criteria with which the main goal is based and lastly, the sub criteria.

The analysis for this research has criteria based on the sustainability pillars, Economic, Environmental and Social, as well as technical capability, expanded into 15 sub criteria on which a pairwise comparison was performed. The pairwise comparisons were based on both actual measurements, the output HOMER Pro simulation data and a scale derived from relative strength of individual sub criteria standing. Figure 3-16 shows the hierarchy Diagram for selecting the optimal alternative power source for base stations.

Analytic Hierarchy Process (AHP) follows a number of steps which are outlined below and in illustrated in Figure 3-11,

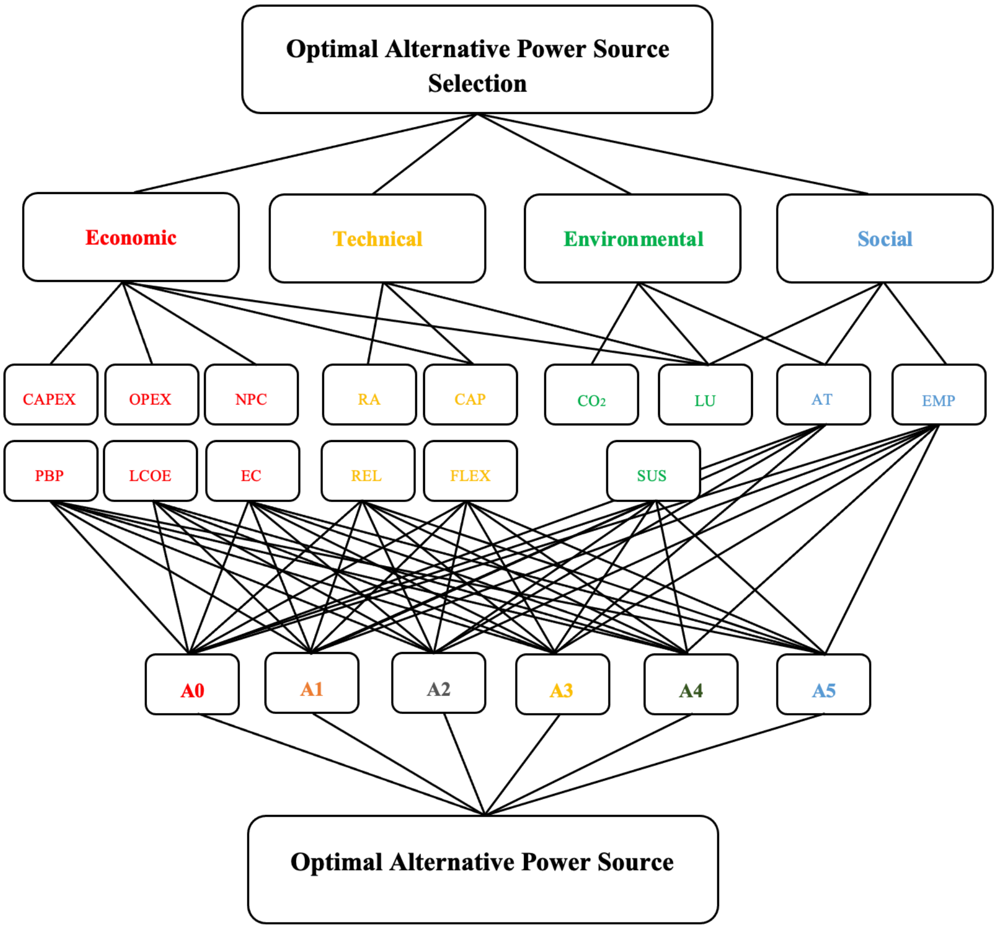


Figure 3-11: *Analytic Hierarchy for selecting optimal alternative power source. [A0 – Generator & Grid System; A1 – Generator only System; A2 – Generator & Solar PV System; A3 – Solar PV only System; A4 – Solar PV & Grid System; A5 – Grid only System]*

3.7.1 AHP – Step 1: Sub Criteria Classification

The output simulation results from HOMER PRO are categorised into sustainability pillars **Economical**; Capital Expenditure (CAPEX), Operating Expenditure (OPEX), Net Present Cost (NPC), Levelised Cost of Energy (LCOE), Emission Cost (EC) — **Environmental**; Emission (CO_2), Land Use (LU), Sustainability (SUS) – **Social**; Acceptability (AT), Employment Creation (EMP) as well as **Technical Capability**; Resource Availability (RA), Capacity (CAP), Reliability (REL), Flexibility (FLEX).

3.7.2 AHP – Step 2: Pairwise Comparison

In this process, criteria and/or sub-criteria are compared individually to one another. These criteria/sub-criteria are ranked against each other based on actual data or assigned preferred values based on AHP fundamental scale shown in Table 3-2 (Saaty R. W., 1987) and (Saaty T. L., 2008).

Table 3-9: *AHP Fundamental Scale for Pair – Wise Comparisons*

AHP Fundamental Scale for Pair-wise Comparisons		
Impact intensity	**Description**	**Definition**
1	Equal Importance	Two criteria contribute equally towards the goal
3	Slightly More Importance	One criteria contribute slightly more than the other criteria towards the goal
5	Strongly More Importance	One criteria strongly contribute more over the other criteria towards the goal
7	Very Strongly Importance	One criteria very strongly contribute more over the other criteria towards the goal
9	Extremely More Importance	One criteria has the highest contribution towards the goal than the other criteria
Intensities of 2,4,6, & 8 are used for intermediate values, while intensities 1.1, 1.2, 3.1,3.2...5.15.2,...,7.1, 7.2,..., etc. are used for criteria that are very close in importance towards a goal.		

After preference values are assigned to individual criteria to be compared, the pairwise comparison is made based on the ***n-by-n*** matrix shown in Equation (3.8),

$$\boldsymbol{A} = \begin{bmatrix} \mathbf{1} & \boldsymbol{a_{12}} & \dots & \boldsymbol{a_{1n}} \\ \mathbf{1}/\boldsymbol{a_{21}} & \mathbf{1} & \dots & \boldsymbol{a_{2n}} \\ . & . & \mathbf{1} & . \\ \mathbf{1}/\boldsymbol{a_{n1}} & \mathbf{1}/\boldsymbol{a_{n2}} & \dots & \mathbf{1} \end{bmatrix} \tag{3.8}$$

In this case, pairwise comparison was performed per each approach (A0 – A5). Before the result of the pair-wise comparison can be accepted, a consistency must be checked. This consistency is checked based on the following Equation (3.9),

$$\boldsymbol{CI} = \frac{\boldsymbol{\lambda_{max}} - \boldsymbol{n}}{\boldsymbol{n} - \mathbf{1}} \tag{3.9}$$

Where *n* is the number of criteria and λ_{max} is the principal eigen value estimated from a summation of products between each element of Eigen vector and sum of columns of the reciprocal matrix. This process follows Equation (3.10),

$$\boldsymbol{\lambda_{max}} = \sum_{i=1}^{n} \boldsymbol{\lambda_{\max p} w_I} = \sum_{i=1}^{n} \sum_{j=1}^{n} \boldsymbol{a_{ij} w_{ij}} \tag{3.10}$$

According to (Saaty T. L., 2008) the pair-wise comparison can maintain consistency only when consistency index (C.I.) is equal to or less than **0.10** calculated based on (3.11) for an average random consistency index (R.I) of n-values given in Table 3-11.

$$\boldsymbol{C.R.} = \frac{\boldsymbol{C.I.}}{\boldsymbol{R.I.}} \tag{3.11}$$

Where C.R. is consistency ratio by (Saaty T. L., 2008). All of the pair-wise comparisons for all systems maintained a consistency less than the threshold.

Table 3-10: *Random Consistency Index (R.I.)*

Random Consistency Index (R.I.)															
n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49	1.52	1.54	1.56	1.58	1.59

3.7.3 AHP – Step 3: Pair-Wise Performance Comparison

This step involves getting single value scores of each sub criteria in a pair-wise comparison performed, which are 15 in this study. This was done for all six approaches proposed (A0 – A5). This is done by getting the average of the normalised relative weights pair-wise of each of the individual pair-wise. To obtain normalized relative weights for each paired matrix values, the reciprocal matrix from paired comparison matrix were summed up in each column of the reciprocal matrix and each element of the reciprocal matrix divided with the sum of its column. The average weighted scores from each sub criteria for each approach (A0 – A5) are shown in Table 3-12.

__Table 3-11:__ Weighted criteria score for all sustainability pillars as well as technical capability

Approaches	Economical						Technical				Environmental			Social	
	CAPEX	OPEX	NPC	PBP	LCOE	EC	RA	CAP	REL	FLEX	CO2	LU	SUS	AT	EMP
A0	0.007	0.006	0.006	0.007	0.007	0.007	0.010	0.010	0.011	0.011	0.013	0.016	0.014	0.021	0.022
A1	0.008	0.006	0.005	0.008	0.007	0.006	0.010	0.011	0.011	0.011	0.011	0.016	0.014	0.021	0.028
A2	0.007	0.006	0.006	0.007	0.007	0.007	0.011	0.011	0.011	0.011	0.014	0.013	0.014	0.021	0.024
A3	0.006	0.009	0.009	0.007	0.005	0.008	0.011	0.009	0.011	0.010	0.017	0.011	0.014	0.021	0.019
A4	0.007	0.008	0.007	0.006	0.008	0.007	0.011	0.011	0.011	0.010	0.014	0.012	0.014	0.021	0.017
A5	0.008	0.007	0.008	0.006	0.008	0.007	0.010	0.009	0.009	0.010	0.015	0.016	0.014	0.020	0.015

3.7.4 AHP – Step 4: Alternative Prioritization

In the final step, the behaviour of these six approaches is analysed by changing priority weights on the main criteria i.e., the sustainability pillars as well as technical capability. By defining a sustainability performance ranking of 1-6 the system with the highest ranking i.e., highest percentage (total percentage across all sustainability pillars) in the sustainability performance is the best system.

3.8 Summary

This chapter looked at the methodology from data collected, evaluation of proposed approaches, simulation of approaches in HOMER Pro and their results, the overall steps in Analytic Hierarchy Process to evaluate the proposed approaches. The results of the approaches are discussed in RESULTS AND DISCUSSIONS.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.0 Introduction

The proposed approaches for the integration of solar systems into the telecommunications were analysed through Analytic Hierarchy Process. Data from a total of 15 sub criteria was tabulated in a pair-wise comparison to derive their contribution to the selection of the required solution. In return, sustainability pillars, Economical, Environmental and Social, as well as technical capability, were prioritised individually (while keeping the other three constant) across all six approaches to observe their behaviour there by giving out the final perspective. It is noted that, though the final result has almost the same shape, there are slight distinctions to different prioritisation of pillars.

This chapter presents and discusses results, and the overall findings of the research that has been conducted. At the end, the research proposes the selected optimal alternative energy supply system to power telecommunications base stations overall.

4.1 Simulation Results – Post HOMER-Pro Analysis

HOMER PRO 3.5.4 by Homer Energy (2022) was used in this study to simulate the different proposed approaches. The output results are analysed in this section grouped into respective sustainability pillars as well as technical capability.

4.1.1 Economic Analysis

The simulation of approaches in HOMER Pro gave results of a number of economic measures of viability of hybrid systems. These include but not limited to Initial Capital, Net Present Cost (NPC), Operating cost (in \$/year), LCOE, O&M of genset systems (in \$/year) and equivalent Cost of Emission (which is computed from local taxes in a country).

Solar PV systems have generally high initial costs over ten percent more than fossil fuel-based systems with generators. Grid only systems have the least initial capital costs, but a relatively higher operating costs around 108 percent per year more than grid coupled with solar. Whereas diesel generators only systems have operating costs between 697 – 1,559 percent per year more than grid only systems and grid + solar systems respectively. In essence, generator only systems will spend between $1,158,025.00 – $1,244,275.00 in its entire lifetime in operation cost only than the two latter systems which more than ten times more than the initial cost of Solar PV installation. This is shown in Figure 4-1.

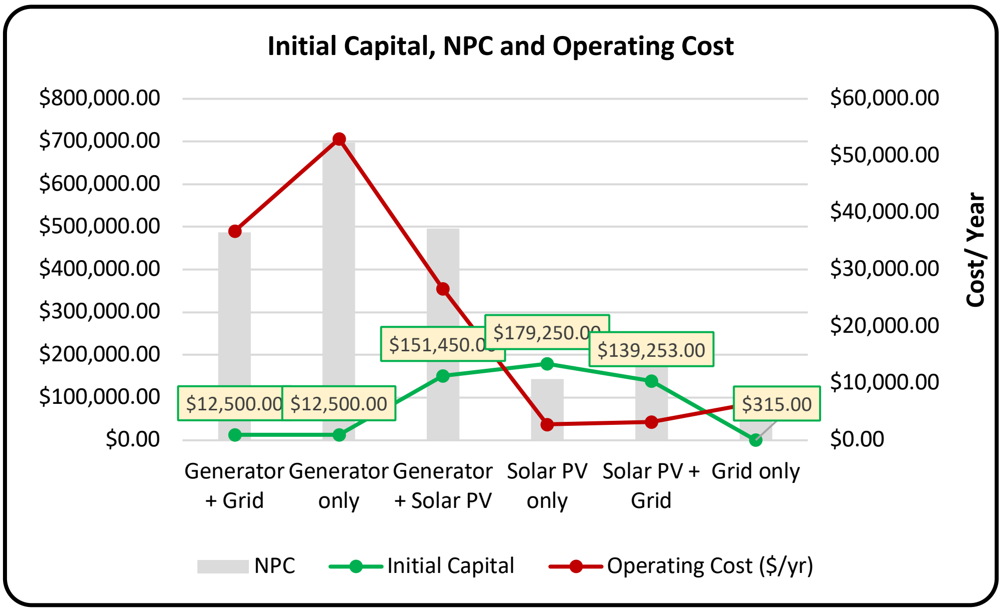


Figure 4-1: *Initial Capital, NPC and Operating Cost*

Because of drastic measures to prevent exacerbating the effects of climate change, taxes are set upon fossil fuel burnt or CO_2 released into the atmosphere. Apart from the extra cost of maintenance, generator only systems have 618 and 278 percent more extra cost paid in emissions than grid + solar PV systems and grid only systems respectively, as shown in Figure 4-2. Generator-based systems have generally lower LCOE than purely solar PV only system ($2,40). Grid + solar PV system ($0.20) and grid only system ($0.11) has the lowest electricity cost per unit. The existing system (grid + generator) has 190 percent more cost per unit of electricity than grid + solar system.

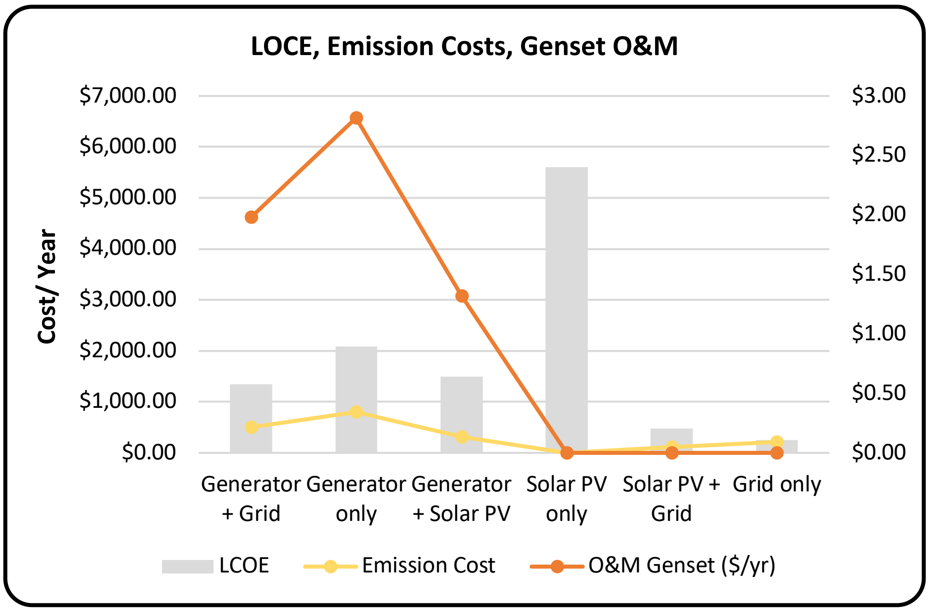


Figure 4-2: *Genset O&M, Emission Cost and LCOE*

4.1.2 Technical Analysis

Solar PV + grid system has 37 percent more energy per year than the existing system (generator + grid) based on the weighted input figures in the simulation results shown in Figure 4-3. This means that at a LCOE of $0.20 per kWh, ISPs can sell the extra power back to the grid or share with home owners to subsidise their land use as a rental for the spaces used and still have enough to run their base stations.

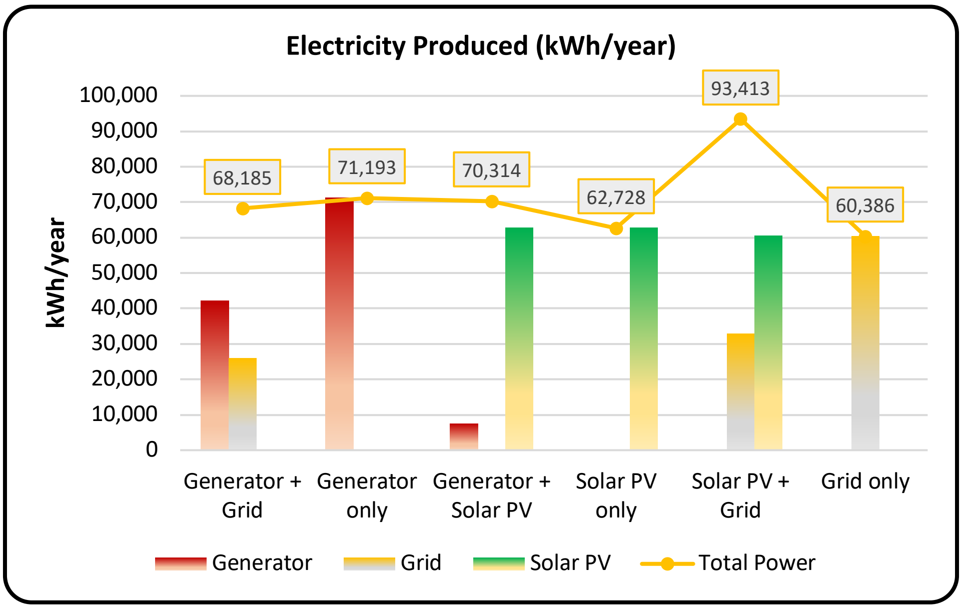


Figure 4-3: *Electricity production per year of different approaches*

4.1.3 Environmental Analysis

According to a simulation on PV Watt web Solar PV Calculator (PVWatts Calculator, 2022), a 100 m^2 of roof space can produce up to 30 kWh of energy per year. This approximate to 3.5 m^2 per kWh of energy space. The Figure 4-4 below gives an overview of land use with Solar PV Systems having around 200 m^2/kW. The same figure compares the amount of CO_2 released by the individual approaches. The existing system (Grid + Generator System) has 359 percent emissions in tonnes per year more than that of Grid + Solar PV System.

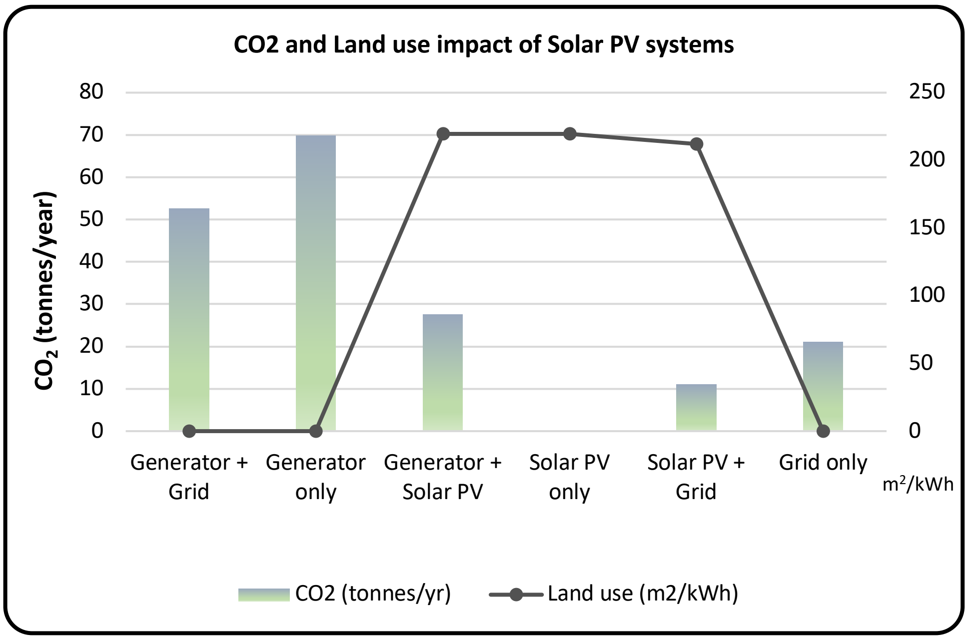


Figure 4-4: *CO_2 and Land use of Approaches*

4.2 AHP Equal - Overall Priority

In this iteration, all sustainability pillars as well as technical capability, carried the same weighting. Figure 4-5 above shows the exact raw result from Analytic Hierarchy Process. It can be seen that Grid only (A5) and Grid + Solar PV (A4) systems are preferred systems in this priority followed by Solar only (A3) and lastly generator-based systems.

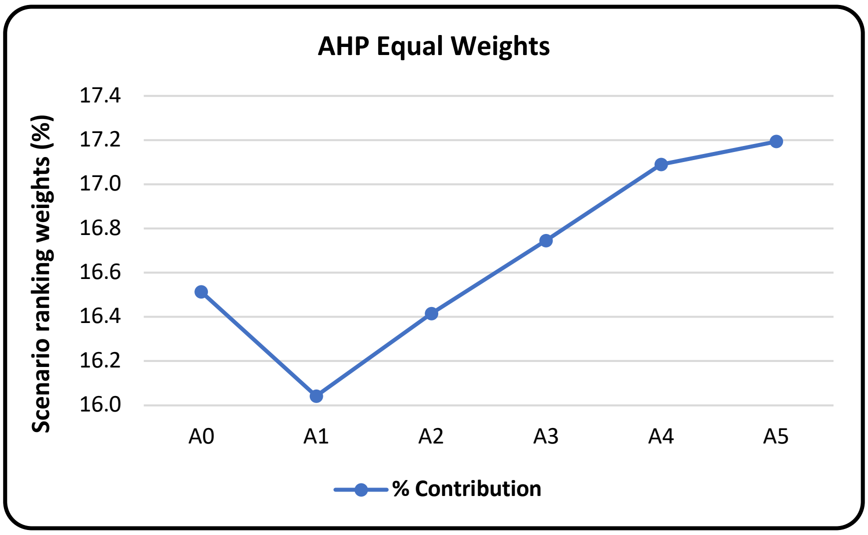


Figure 4-5: *Analytical Hierarchy Process (Economical 25%, Technical 25%, Environmental 25% and Social 25%) [A0 – Grid + Generator System; A1 – Generator only System; A2 – Generator + Solar PV System; A3 – Solar PV only System; A4 – Grid + Solar PV System; A5 – Grid only System]*

4.3 AHP Economical Priority

In the iteration that prioritises the economics of such systems, there is a drop between Solar PV only systems but a huge jump on the Grid + Solar PV systems on preference levels. As shown Figure 4-6 in the same two systems, Grid only and Grid + Solar PV still dominate followed by Solar only and Grid + Generator.

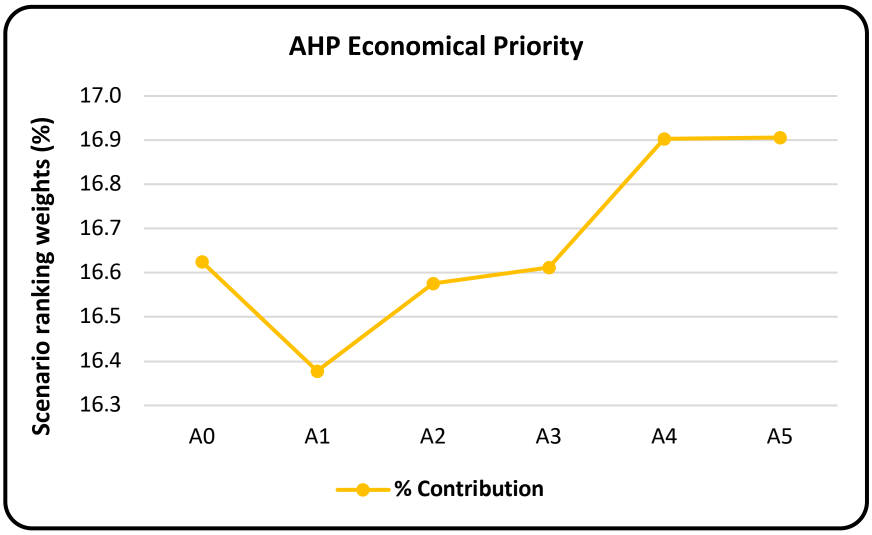


Figure 4-6: *Analytical Hierarchy Process (Economical 40%, Technical 20%, Environmental 20% and Social 20%) [A0 – Grid + Generator System; A1 – Generator only System; A2 – Generator + Solar PV System; A3 – Solar PV only System; A4 – Grid + Solar PV System; A5 – Grid only System]*

4.4 AHP Technical Priority

Technically, the same systems in Grid only and Grid + Solar PV are still preferred options when compared to the other four systems from the results in Figure 4-7.

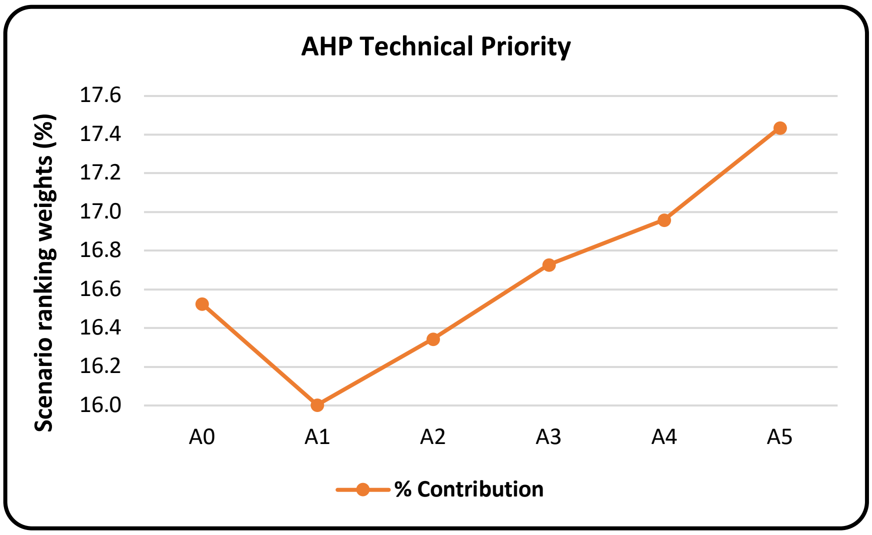


Figure 4-7: *Analytical Hierarchy Process (Economical 20%, Technical 40%, Environmental 20% and Social 20%) [A0 – Generator & Grid System; A1 – Generator only System; A2 – Generator & Solar PV System; A3 – Solar PV only System; A4 – Solar PV & Grid System; A5 – Grid only System]*

4.5 AHP Environmental Priority

Grid + Solar PV system has the highest environmental sustainability as in Figure 4-8.

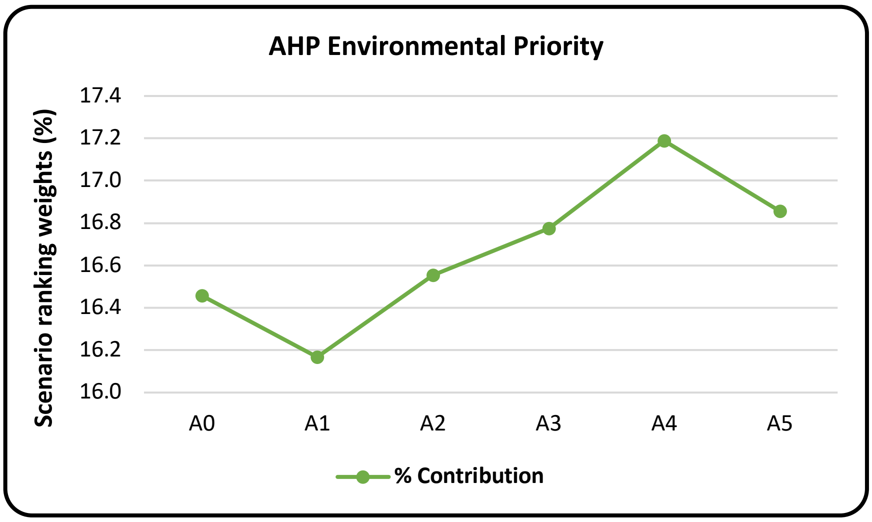


Figure 4-8: *Analytical Hierarchy Process (Economical 20%, Technical 20%, Environmental 40% and Social 20%) [A0 – Generator & Grid System; A1 – Generator only System; A2 – Generator & Solar PV System; A3 – Solar PV only System; A4 – Solar PV & Grid System; A5 – Grid only System]*

Grid only system is higher than Solar only system for the possible reason that the major contributor to the Zimbabwean power grid is hydro power, hence the system maximised more on hydro power.

4.6 AHP Social Priority

Residential areas (like Budiriro) were already pre-planned to work on grid connected power supply system. Communities have already got used to the setup that bringing any additional systems will cause an outcry. For example, people in Budiriro, those that are closer to Telecommunication base stations always complained on vibrations and noises coming from gensets powering these towers. Grid connected systems will score higher because of lower land use as shown in Figure 4-9. Moreover, large power stations employ more people, which is a huge benefit to the community.

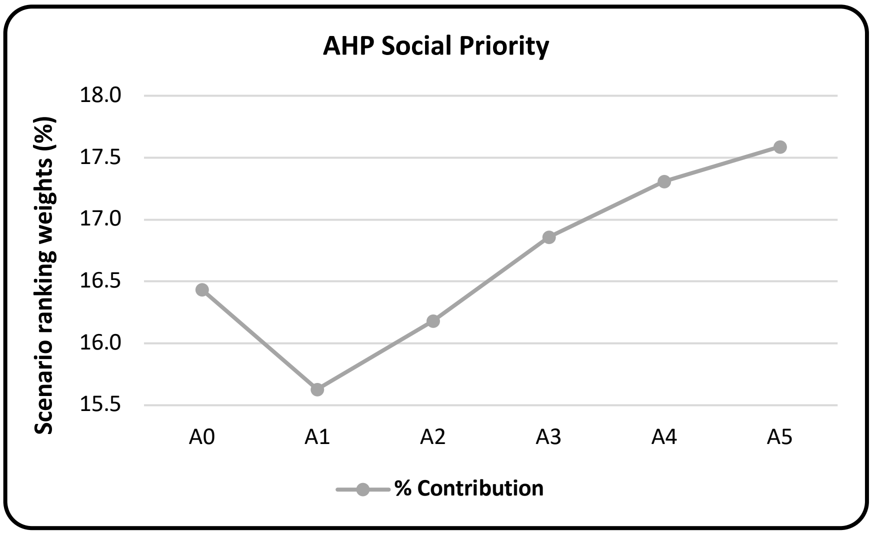


Figure 4-9: *Analytical Hierarchy Process (Economical 20%, Technical 20%, Environmental 20% and Social 40%) [A0 – Generator & Grid System; A1 – Generator only System; A2 – Generator & Solar PV System; A3 – Solar PV only System; A4 – Solar PV & Grid System; A5 – Grid only System]*

4.7 Selected System

From the simulation results as presented in full form in Figure 4-10, it is can noticed that Grid Systems and Solar PV + Grid System seem stand out in many sustainability pillars. In a general sense, hybrid systems with any portion of Solar PV are more preferable in many sustainability pillars as well as technical capability, including equal priority, than those with generators.

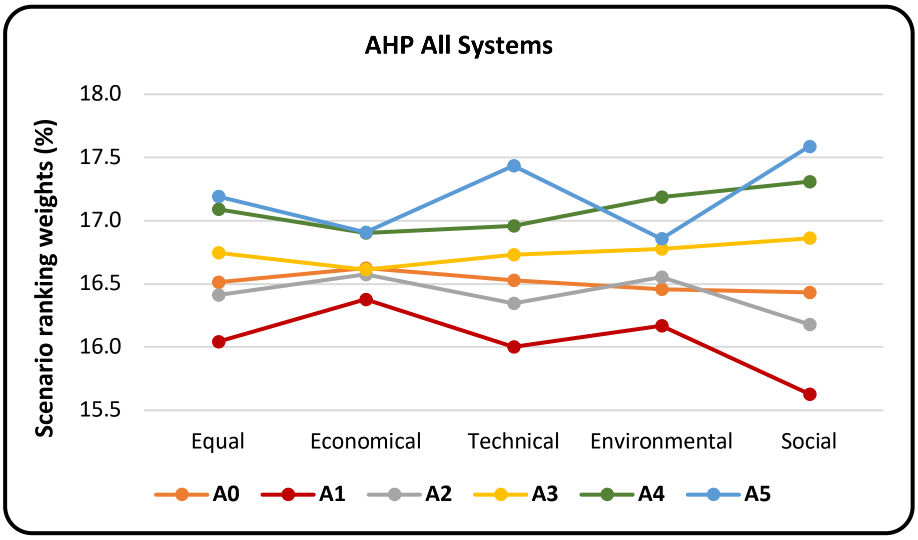


Figure 4-10: *Analytical Hierarchy Process different prioritisations [A0 – Generator & Grid System; A1 – Generator only System; A2 – Generator & Solar PV System; A3 – Solar PV only System; A4 – Solar PV & Grid System; A5 – Grid only System]*

The sustainability performance of all the systems is given in Figure 4-11. All the approaches are ranked based on the total percentage weights across all sustainability pillars, as well, technical capability. Grid only system ranks first, followed by Grid + Solar PV system, with Generators systems ranking lower than systems with Solar PV.

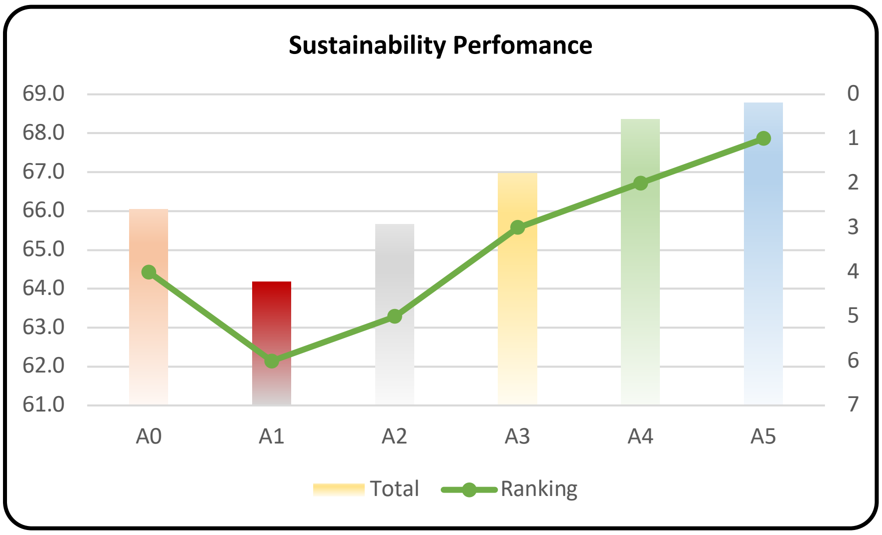


Figure 4-11: *Analytical Hierarchy Process different prioritisations [A0 – Generator & Grid System; A1 – Generator only System; A2 – Generator & Solar PV System; A3 – Solar PV only System; A4 – Solar PV & Grid System; A5 – Grid only System]*

From their sustainability performance it is evident that generator systems are visibly less preferrable, hence, could not be selected as a means of power in the telecommunication industry.

Grid only System in particular, had higher technical preference, and social sustainability. This is mainly because Grid Systems take very minimal land space, produce quiet power in the supplied area as opposed to noisy and vibrating generators. As well, Grid systems means setting up huge companies at macro level in the process, creating employment for the local people. However, their unreliability makes them less preferable. Furthermore, the energy mix in Zimbabwe is currently dominated by hydro. During times of drought or low rainfall, hours of outages drastically increase, up to 24 hours per day in some cases; during that same time, thermal stations, if available, fire up and take the bigger percentage in the energy mix. Though this can supplement the energy demand, firstly – it's not sufficient; secondly – it increases GHG emission. The goal is to reduce and possibly in the near future eliminate fossil fuel use. Reducing dependence on the grid in some other industries, in this case telecommunications, can significantly reduce demand and possibility of emissions by thermal plants as base station power can prioritise using more of Solar PV. Most importantly, grid outages are the reasons for ISPs to turn to generators for back-up power. Hence, to increase reliability of base station power supply by offering redundancy, it therefore leaves Grid + Solar PV system (A4) the optimal alternative power system for powering telecommunications base stations.

Based on the priority results, Grid + Solar PV systems ranks higher on the Economic and Environmental sustainability pillars which are very crucial pillars in modern day business. A system of Grid + Solar PV is not only the best due to redundancy but even feasible as ISP's will only focus on Solar PV installation as the Grid connection already exists. As reported in Figure 4-3, Grid + Solar PV have the highest energy production per year. According to the scenarios in 3.4, residencies or municipal premises on which ISP's can install Solar PV gain free use of power according to this paper's design proposition; A4 – Grid + Solar PV System can produce sufficient power for this model.

4.8 The Optimal Alternative System

From the selected approach A4 – Grid + Solar PV, there are a number of potential benefits if adopted by the ISP's. The breakdown of why Grid + Solar PV are more preferrable is given in Table 4-1.

Table 4-1: *A4 - Grid + Solar PV system | A0 - Grid + Generator*

	System	
	A0 - Existing	**A4** - Proposed
	Grid + Generator	**Grid + Solar PV**
OPEX ($/yr.)	36,769.35	3,192.00
Emission Cost ($/yr.)	111.35	498.51
Energy Produced (kWh/yr.)	68,185	93,413
GHG emissions (tonnes/yr.)	53	11
Initial Capital	12,500.00	139,253.00
NPC	487,836.30	180,518.00
LCOE	0.58	0.20

For energy systems projects, NPC is the best measure of how feasible its implementation is in comparison to others and where a breakdown of sales and net revenue are not given. A system is more preferrable if it minimises NPC. As presented in Figure 4-12 Grid + Solar PV (A4) system offer by 170 percent lower NPC over its entire lifecycle than Grid + Generator (A0) system.

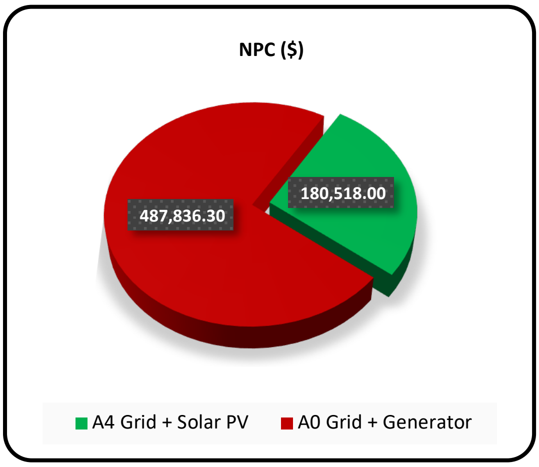


Figure 4-12: *NPC comparison for Grid + Generator | Grid + Solar PV systems*

Solar PV systems have generally a higher CAPEX than Generator based systems. This is proven in Figure 4-13 with Grid + Solar PV (A4) systems 1,014 percent higher initial capital than Grid + Generator (A0). However, if Solar PV systems are well maintained, they stand as a one-time investment in their lifecycle of 25 years, which is more than that of generator systems, 10 years. This essentially means that midway in the lifecycle of Solar PV, there is a new generator installation.

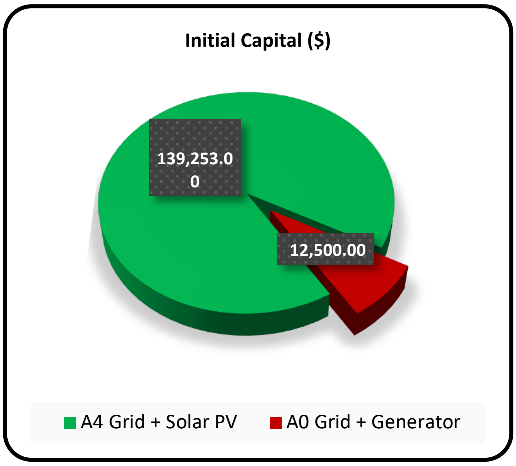


Figure 4-13: *Initial Capital comparison for Grid + Generator | Grid + Solar PV systems*

The reason why the existing system Grid + Generator would cause an increase in data price is because the unit cost of electricity ($0.58 per kWh) is generally higher than the grid ($0.11 per kWh) in the area. By adopting Grid + Solar PV, ISPs reduce the unit cost of electricity by 183% as shown in Figure 4-14 to $0.20 per kWh.

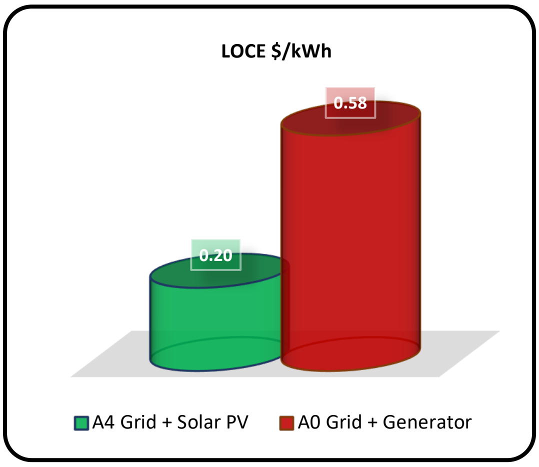


Figure 4-14: *LCOE comparison for Grid + Generator | Grid + Solar PV systems*

Operating expenditure for generator-based systems are huge. Though the initial cost of Solar based systems is high, the cost of running generators only is more than 100 percent initial cost of solar PV systems over the entire life time. Grid + Generator system has 1,052 percent more OPEX per year than the proposed approach. The cost difference is best represented by the distribution in Figure 4-15.

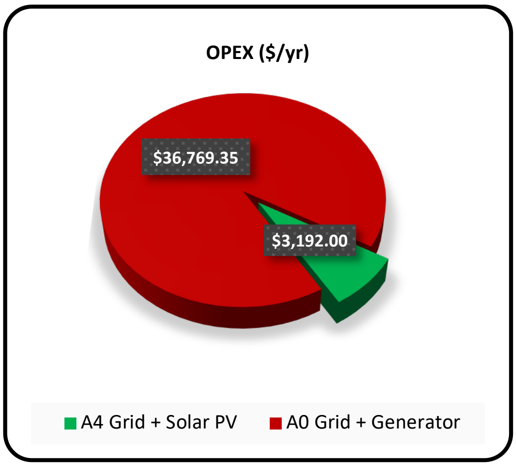


Figure 4-15: *OPEX comparison for Grid + Generator | Grid + Solar PV systems*

Setting a cost on carbon is a measure put by governments to reduce emissions by taxing the emitter. To avoid these taxes ISP's can adopt systems with less GHG emissions. By coupling the grid with Solar PV, telecommunications companies can avoid 348 percent additional cost on emission. The existing system in the study area has a distribution as shown in Figure 4-16 on comparison to the proposed Grid + Solar PV.

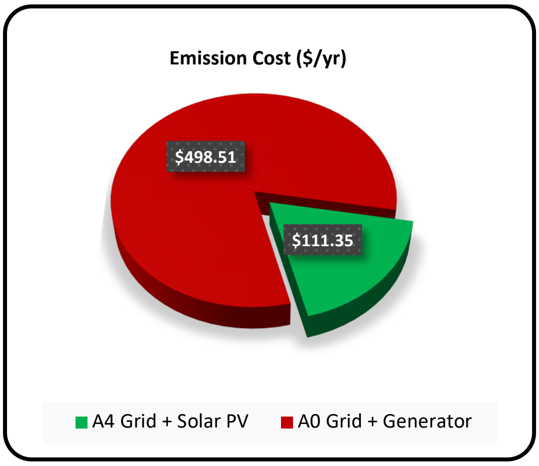


Figure 4-16: *Emission Cost comparison for Grid + Generator | Grid + Solar PV systems*

The existing system (Grid + Generator System) has 359 percent emissions in tonnes per year more than that of Grid + Solar PV System. The distribution is shown in Figure 4-17 for perspective. By adopting the proposed approach there is potential of 41.13 tonnes per year of GHG emissions avoided per base station.

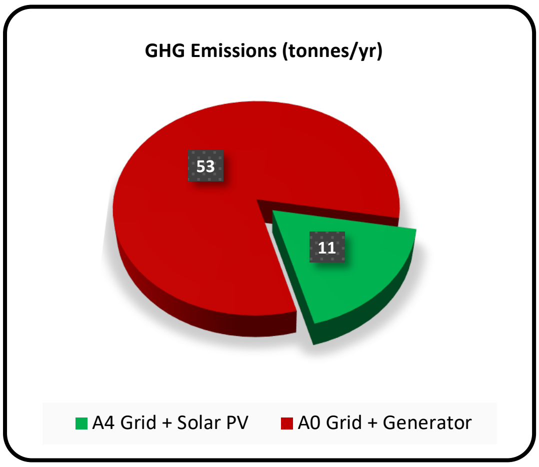


Figure 4-17: *GHG Emissions comparison for Grid + Generator | Grid + Solar PV*

To fully make use of the proposed approach, the installed Solar PV has to provide excess power to share with either the household or municipality on which the Solar PV is installed. At the same power load, the simulation results show that the Grid + Solar PV system can produce 37 percent more energy than the existing system as shown in Figure 4-18.

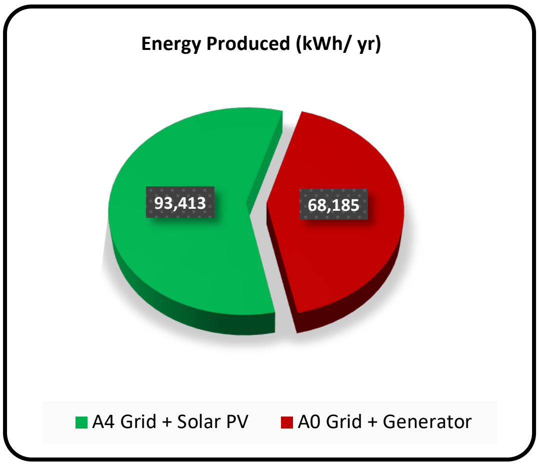


Figure 4-18: *Energy Produced comparison for Grid + Generator | Grid + Solar PV*

4.9 Summary

This chapter looked at the results from Analytic Hierarchy Process. After analysis of all the six proposed approaches, the optimal alternative energy supply system to power telecommunication base stations was selected based on the overall results from simulation to AHP as Grid + Solar PV system to replace the existing system in Grid + Generator.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The research's aim was to find a solution for deploying Solar PV by proposing an optimal alternative energy supply system to power telecommunications base stations based on sustainability pillars; Economical, Environmental and Social, as well as technical capability. Budiriro was used as a Case Study, a reference, to be able to streamline the research outcomes. The study derived six power system configurations from the available possible power sources in the study area. The systems were then simulated in HOMER Pro and from the simulation results, the systems were ranked through Analytic Hierarchy Process (AHP) by performing pairwise comparisons of 15 sub criteria. After considering a number of factors like reliability, power output and mainly sustainability, Grid + Solar PV system came out as the optimal alternative system to power telecommunications base stations in the study area. The results show that the optimal system reduces OPEX by over 1,000 percent offering 37 percent more power and 41.13 tonnes of GHG emissions avoided per year. The solutions given here within can be applied in similar areas with similar demand and most importantly a sufficient solar irradiation, which is the main resource the study focused on.

The research was made on the assumptions that, for a lifecycle of Solar PV of 25 years, there will be a lot of changes in the telecommunications industry. ISPs are going to definitely invest on 5G and or 6G systems, with the former going to drastically increase base station power, as given in literature, by 68 percent. The systems here in this study was modelled for an upper value, i.e., 7.5 kW capacity base stations of which not all of the stations in the study area are. However, for sustainability and relevance of this study, it was important to forecast a model that will not become obsolete halfway the lifecycle of Solar PV systems which have a higher CAPEX, if ISPs decide to invest.

Though the proposed system (Grid + Solar PV) has a higher CAPEX, the existing system's (Grid + Generator) higher OPEX becomes more costly in the long run. As well, fuel prices are detected by global markets as opposed to Solar PV of which the main resource, solar irradiance, is readily available in the study area. This hence offers a little more control on the factors that help decision making of the business.

The study fulfilled the findings and reported results of its specific objectives;

i. *To investigate the existing energy supply systems for telecommunication base stations in the study area.*

In 2.2.1.1 and 3.3 the research established the existence of a power supply system consisting of the national grid and backup generators, referred in this study as the existing system. This system consists of generators of capacity an upwards of 30 kVA, operating during grid power outages up to 19 hours per day.

ii. *To investigate the feasibility of integrating Solar PV in telecommunication base stations in the study area.*

The study area as discussed in 2.4 has abundant resources to establish solar power generation. The main resources for Solar PV are enough irradiance and capacity for power storage. Data from literature reviews the feasibility of harnessing solar power as presented by the irradiance in Harare – (5.7 kWh/m2 per day), the city in which the study area is located. For storage, the abundance of lithium (reserves approximated to 220,000 tonnes) in the country will increase leverage in deploying Solar PV systems if Zimbabwe invest in the manufacture of lithium batteries.

iii. *To propose energy supply system approaches for telecommunication base stations in the study area.*

The study proposed possible energy systems that can be applied based on available resources in the area of study. These systems could make use of the grid, fuel generators and Solar PV. By evaluating these power sources and possible redundancies as given in 3.5, the optimal alternative was proposed on the basis of how it compared to other alternative power sources in the same area looking at a number of criteria.

iv. *To assess the performance of proposed energy supply systems using HOMER Pro based on Sustainability Pillars; Economical, Environmental and Social, as well as technical capability.*

Using HOMER Pro, an industry standard to evaluate distributed generation, and national grid, performance of the proposed power systems was evaluated. A number of results of their performances established based on sustainability pillars, as well as technical capability, as given in 4.1.

v. *To determine an optimal energy supply system alternative to power telecommunications base stations in the study area from available energy sources using Analytic Hierarchy Process (AHP).*

To make the final decision on the best optimal alternative power system, power systems from the simulation in HOMER Pro had to be further ranked by weighting a number of criteria. Using AHP, a decision-making tool, the research established that, based on sustainability pillars; Economical, Environmental and Social, as well as technical capability, the best optimal alternative power source is a combination of power from the grid, with a Solar PV system.

There is no doubt that net zero is achievable as laying off of fossil fuels will not decrease our ability to meet our present energy needs as well as those of future generations. Hence, their adoption present and future is imminent.

A shift to Solar PV in telecommunications industry will create a need for Solar PV major components, solar panels, inverters and batteries. Already as proven in this study that there is a huge availability of lithium, means if investment in locally producing lithium batteries advances, it will have a huge impact on the reduction of prices of solar systems components. As usable high value products are manufactured, this creates employment opportunities for the locals. Contrary to raw material exportation, an increase in foreign currency from these high value products export can be realised.

5.2 Recommendations

5.2.1 Technical

The simulation results show Solar PV system having more energy produced. Like in many countries e.g., Zambia, where telecommunication towers are maintained by a different company, telecommunication towers are shared between different Service Providers. This means that rather than individual companies producing their own energy, they can all invest also in a shared energy system.

The solutions given here within can be applied in similar areas with similar demand and most importantly a sufficient solar irradiation, which is the main resource the study focused on.

5.2.2 Risk Management

The research proposes a deployment which utilises idle households' or municipalities' roof space to install solar panels which has a fairly low land use, huge benefits of power sharing with households and nearby municipality premises as well as a guaranteed protection of the investment by these local Internet Service Providers. There are risks associated with that. People with houses on which these systems are installed can temper around with these premises. Care has to be taken and contracts should be designed for ISPs to protect the premises as well as to safeguard homeowners from being manipulated. Only the ISPs should have the right to put their hands on the system and their teams will be the sole maintenance providers. The house owner's job is to physically protect the system, and guard from robbery. In case of system fault, the house owner can briefly return to the grid or make use of other sources in a way that doesn't harm the system while reporting.

5.2.3 Further Research

This study can be a starting point for the analysis of other base stations in isolated areas (off-grid) Figure 5-1, in rural areas, most of which have dispersed settlements and mostly powered by generators. In addition, research has to contribute to the safety of systems installed because ISP's have to device risk aversion measures to successfully deploy Solar PV systems in these isolated areas.

Figure 5-1: *Telecommunication towers built in off-grid areas (source: edotcogroup.com)*

REFERENCES

Able Sales. (2019, June 13). *Able Sales: Home/Blog/Diesel Generator Fuel Consumption Chart in Litres*. Retrieved from Able Sales: https://www.ablesales.com.au/blog/diesel-generator-fuel-consumption-chart-in-litres.html

All Africa. (2021, July 9). *All Africa: Zimbabwe: Uproar As Econet Effects 20 Percent Data Prices Increases*. Retrieved from All Africa: https://allafrica.com/stories/202107090480.html

Allison Lantero. (2014, June 17). *Energy.Gov*. Retrieved from Energy.Gov - How Microgrids Work: https://www.energy.gov/articles/how-microgrids-work

Alsharif, M. H., & Kim, J. (2016). Optimal Solar Power System for Remote Telecommunication Base Stations: A Case Study Based on the Characteristics of South Korea's Solar Radiation Exposure. *Sustainability*, 16-17.

AM Solar. (2021, October 22). *AM Solar: Grid-Tied and Hybrid Solar Systems with Battery Backup*. Retrieved from AM Solar: https://amsunsolar.com/solar-blog/uncategorized/grid-tied-and-hybrid-solar-systems-with-battery-backup/

Anodolu Agency. (2021, July 18). *World Africa: Zimbabweans hit by exorbitant internet costs*. Retrieved from World Africa: https://www.aa.com.tr/en/africa/zimbabweans-hit-by-exorbitant-internet-costs/2307947

Bete Telecom Cabinet. (2022, July 25). *Bete Telecom Cabinet: Solar Telecommunications Base Station*. Retrieved from Bete Telecom Cabinet: https://www.bttelecomcabinet.com/services/solar-telecommunications-base-station/

BHB. (2013). *Wireless Base Stations: Meet the cost and carbon challenge.* Lisbon: AEG Power Soutions.

Big Rentz. (2021, April 15). *Big Rentz: Equipment-Generator*. Retrieved from Big Rentz: https://www.bigrentz.com/blog/generator-maintenance-checklist

Botelho, A., Ointo, L. M., Lourenco-Gomes, L., Valente, M., & Sousa, S. (2016). Social sustainability of renewable energy sources in electricity production: An application of the contingent valuation method. *Sustainable Cities and Society*, 429-437.

Carbon Independent. (2008, November 8). *Carbon Independent: Emissions from cars*. Retrieved from Carbon Independent: https://www.carbonindependent.org/17.html

Clifford Power. (2022, June 27). *Clifford Power: Information sheet*. Retrieved from Clifford Power: https://cliffordpower.com/wp-content/uploads/2020/01/IS_61_App_Telcom1.pdf

CNN World. (2019, January 18). *CNN World: Internet shutdowns aren't just Africa's problem. They're happening worldwide*. Retrieved from CNN World: https://edition.cnn.com/2019/01/17/africa/internet-shutdown-zimbabwe-censorship-intl/index.html

Dhivyadeepa, E. (2015). *Sampling Techniques in Educational Research.* Maharashtra: Laxmi Book Publication.

Dinata, M. M., Mardiana, V. A., Mitayani, A., & Nurkahfi, G. N. (2020). Techno-economic analysis of an optimized hybrid energy system implementation using PV-wind turbine-diesel generator at Indonesia’s remote telecommunication base. *IOP Conference Series: Earth and Environmental Science*, 8-9.

EDF. (2022, August 15). *Environmental Defence Fund: The true cost of carbon pollution*. Retrieved from Environmental Defence Fund: https://www.edf.org/true-cost-carbon-pollution#:~:text=The%20social%20cost%20of%20carbon%20is%20a%20measure%20of%20the,per%20ton%20in%20today's%20dollars.

Enerdata. (2020). *Global Energy Statistical Yearbook.* Enerdata.

Fortune Business Insights. (2022, June 22). *Fortune Business Insights: Telecom Generator Market*. Retrieved from Fortune Business Insights: https://www.fortunebusinessinsights.com/telecom-generator-market-104598

Global Solar Atlas. (2022, June 29). *Global Solar Atlas*. Retrieved from Global Solar Atlas: https://globalsolaratlas.info/map?

Goel, S., & Ali, S. M. (2014). Cost Analysis of Solar/Wind/Diesel Hybrid Energy Systems for Telecom Tower by using HOMER. *International Journal of Renewable Energy Research*, 4, 305-311.

Gravetter, F. J., & Forzano, L.-A. B. (2010). *Research Methods for the Behavioral Sciences.* Wadsworth: Cengage Learning.

GSMA. (2010). *Green Power Feasibility Study – Econet Zimbabwe.* London: Green Power for Mobile.

GSMA. (2012). *GSMA: Green Power for Mobile Interactive Replication Guide.* London: GSMA Association. Retrieved from GSMA: https://www.gsma.com/mobilefordevelopment/wp-content/uploads/2012/04/gsmagreenpowerformobilereplicationguide.pdf

GSMA. (2014). *The Global Telecom Tower Esco Market: Overview of the global market for energy to telecom towers in off-grid and bad grid areas.* London: Green Power for Mobile (GPM) & IFC.

GSMA. (2020). *Renewable Energy fo Mobile Towers: Opportunities for low and middle income countries.* London: GSMA Association.

GSMA. (2021, September 28). *GSMA:Over Half World's Population Now Using Mobile Internet*. Retrieved from GSMA: https://www.gsma.com/newsroom/press-release/over-half-worlds-population-now-using-mobile-internet/

GSMA. (2022, July 22). *GSMA Mobile for Development: Renewable Energy Dashboard*. Retrieved from GSMA Mobile for Development: https://www.gsma.com/mobilefordevelopment/renewable-energy-dashboard/

Haldar, S. K. (2018). *ScienceDirect: Topics*. Retrieved from Science Direct: https://www.sciencedirect.com/

Hardesty, Linda. (2020, April 3). *Fierce Wireless: 5G base stations use a lot more energy than 4G base stations: MTN*. Retrieved from Fierce Wireless: https://www.fiercewireless.com/tech/5g-base-stations-use-a-lot-more-energy-than-4g-base-stations-says-mtn#:~:text=shift%20to%205G.-,A%20typical%205G%20base%20station%20consumes%20up%20to%20twice%20or,a%20denser%20layer%20of%20small

Himoinsa. (2021, July 1). *Himoinsa*. Retrieved from Himoinsa: https://www.himoinsa.com/electric-generators/generator-sets-for-telecommunications/generator-sets-for-base-telecommunications-stations/4-14/eng.html

Hogan Lovells. (2021, April 21). *DJSUPRA Legalnews:Does energy hold the key to transforming fortunes in Zimbabwe*. Retrieved from DJSUPRA: https://www.hoganlovells.com/en/blogs/the-a-perspective/does-energy-hold-the-key-to-transforming-fortunes-in-zimbabwe

Homer Energy. (2022). *Homer Energy: Homer Software*. Retrieved from Homer Energy: https://www.homerenergy.com/

Huawei Technologies. (2019). *5G Power Whitepaper.* Huawei Technologies Co., Ltd.

Humar, I., Ge, X., Xiang, L., Jo, M., Chen, M., & Zhang, J. (2011). Rethinking energy efficiency models of cellular networks with embodied energy. *IEEE Network*, 40 - 49.

Internet Packages. (2022, March 24). *Internet Packages: Mozambiques internet packages and data*. Retrieved from Internet Packages: https://internetpkg.com/mozambique-internet-packages/

Investopedia. (2021, June 21). *Investopedia: The 3 Pillars of Corporate Sustainability*. Retrieved from Investopedia: https://www.investopedia.com/articles/investing/100515/three-pillars-corporate-sustainability.asp#:~:text=The%20environmental%20pillar%20often%20gets,have%20a%20positive%20financial%20impact.

IRENA. (2016). *Solar PV in Africa: Costs and Markets.* Bonn: IRENA.

IRG. (2022, July 12). *Infinite Renewables Group: How to choose the best battery for a solar energy system*. Retrieved from Infinite Renewables Group: https://infinity-renewables.com/how-to-choose-the-best-battery-for-a-solar-energy-system/

Lameshow, S. (1988). *Sampling Techniques for Evaluating Health Parameters in Developing Countries.* Washington, D.C.: National Academy Press.

Law Insider. (2022, March 24). *Law Insider: Telecommunication Tower definition*. Retrieved from Law Insider: https://www.lawinsider.com/dictionary/telecommunication-tower

Lorincz, J., Garma, T., & Petrovic, G. (2012). Measurements and Modelling of Base Station Power. *IEEE SoftCOM*, 4285-4286.

Masternaut. (2018, July 03). *Masternaut: How to calculate your fleet's carbon footprint*. Retrieved from Masternaut: https://www.masternaut.com/blog/how-to-calculate-your-fleets-carbon-footprint

Mesar Energy. (2019, January 1). *Mesar Energy: Solar PV System*. Retrieved from Mesar Energy-Towards Sustainable Future: http://www.mesarenergy.com/solar-pv-system/

Ministry of Mines and Mining Development. (2016). *Ministry of Mines and Mining Development: Zimbabwe Geological Survey*. Retrieved from Ministry of Mines and Mining Development: http://www.mines.gov.zw/?q=zgs-all

MISA Zimbabwe. (2021, October 28). *MISA Zimbabwe*. Retrieved from MISA Zimbabwe: https://zimbabwe.misa.org/2021/10/28/increase-in-data-tariffs-impediment-to-access-to-information/

Mordor Intelligence. (2022, June 27). *ZIMBABWE Mordor Intelligence: RENEWABLE ENERGY MARKET - GROWTH, TRENDS, COVID-19 IMPACT, AND FORECASTS (2022 - 2027)*. Retrieved from Mordor Intelligence: https://www.mordorintelligence.com/industry-reports/zimbabwe-renewable-energy-market

Nastu, J. (2021, February 9). *Environmental Leader: Telecoms to Triple Electricity Consumption, Boosting Growth of Distributed Energy Generation*. Retrieved from Environmental Leader: https://www.environmentalleader.com/2021/02/telecoms-to-triple-electricity-consumption-boosting-growth-of-distributed-energy-generation/

Nganga, Michael Waiyaki. (2016, Nov 17). *Understanding Africa's Energy Needs*. Retrieved from World Economic Forum: https://www.weforum.org/

Norfund. (2020, December 15). *Norfund: Breakthrough Renewable Energy Project in Myanmar.* Retrieved from Norfund: https://www.norfund.no/breakthrough-renewable-energy-project-in-myanmar/

Novergy Solar. (2022, July 5). *Novergy - Power Geration for Generations: Do you know how solar can empower the telecom industry*. Retrieved from Novergy - Power Geration for Generations: https://www.novergysolar.com/do-you-know-how-solar-can-empower-the-telecom-industry/

Odoi-Yorke, F., Woenagnon, A., & Kalam, A. (2021). Techno-Economic assessment of Solar PV/Fuel cell hybrid power system for telecom base stations in Ghana. *Cogent Engineering*, 8:1, DOI: 10.1080/2331916.2021.1911285.

Oracle. (2022, January 03). *Oracle*. Retrieved from Oracle - Supply Chain Management - Internet of things: https://www.oracle.com/internet-of-things/what-is-iot/

POTRAZ. (2020). *2020 Information and Communication Technology (ICT) Access by Households and Use by Individuals Survey Report.* Harare: ZimStat & POTRAZ.

PVWatts Calculator. (2022, April 1). *PVWatts Calculator*. Retrieved from PVWatts Calculator: https://pvwatts.nrel.gov/pvwatts.php

Renault Group. (2021, January 7). *Renault Group: ELECTRIC MOBILITY - The future of energy storage: are batteries the answer?* Retrieved from Renault Group: https://www.renaultgroup.com/en/news-on-air/news/the-future-of-energy-storage-are-batteries-the-answer/

Reserve Bank of Zimbabwe. (2022, March 15). *Reserve Bank of Zimbabwe: Daily Exchange Rates*. Retrieved from Reserve Bank of Zimbabwe: https://www.rbz.co.zw/index.php/research/markets/exchange-rates/13-daily-exchange-rates/1134-march-2022

Saaty, R. W. (1987). The Analytic Hierarchy Process - What it is and How it is used. *Mathl Modelling, Vol. 9, No. 3-5*, 161-176.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *Int. J. Services Sciences, Vol. 1, No. 1*, 83-89.

Sapsford, R., & Victor, J. (2006). *Data Collection and Analysis.* London: Sage Publications Ltd.

SEforAll Africa Hub. (2016, October 20). *Home:Country Data/Zimbabwe*. Retrieved from Sustainable Energy for ALL Africa Hub: https://www.se4all-africa.org/seforall-in-africa/country-data/zimbabwe/

Shukir, S. (2022). Solar Energy Batteries-A Critical Review. *Journal of Instrumentation and Innovation Sciences*, 25-30.

Sino Voltaics. (2022, July 5). *Sino Voltaics: Energy Density and Specific Energy of Battery*. Retrieved from Sino Voltaics: https://sinovoltaics.com/learning-center/storage/energy-density-and-specific-energy-of-battery/

Solar Reviews. (2022, April 4). *Solar Reviews: Solar panel maintenance: Everything you need to know*. Retrieved from Solar Reviews: https://www.solarreviews.com/blog/solar-panel-maintenance-everything-you-need-to-know#:~:text=clean%20them%20manually.-,It%20is%20generally%20recommended%20that%20you%20perform%20solar%20panel%20cleaning,doesn't%20require%20much%20work.

Solargis. (2022, June 29). *Solargis: Solar resource maps of Zimbabwe*. Retrieved from Solargis: https://solargis.com/maps-and-gis-data/download/zimbabwe

Solex. (2022, June 2). *Solex: Solar Powered Mobile Tower*. Retrieved from Solex: https://solex.in/solar-powered-mobile-tower/#:~:text=Globally%2C%20telecommunications%20companies%20only%20cover,companies%20had%20renewable%20energy%20targets.

Som, K. R. (1996). *Practical Sampling Techniques.* New York: Marcel Dekker Inc.

Statista. (2021, November 2). *Statista: Average price for mobile data in select African countries 2021*. Retrieved from Statista: https://www.statista.com/statistics/1180939/average-price-for-mobile-data-in-africa/

Statista. (2021, June 21). *Statista: World lithium reserves 2021, by country*. Retrieved from Statista: https://www.statista.com/statistics/268790/countries-with-the-largest-lithium-reserves-worldwide/

Sustainable Energy for All. (2022, February 17). *Sustainable Energy for All/Zimbabwe*. Retrieved from Sustainable Energy for All: https://www.se4all-africa.org/seforall-in-africa/country-data/zimbabwe/

The Solar Hub. (2020, October 25). *The Solar Hub: Cost analysis Solar vs Generator and Solar vs Hybrid*. Retrieved from The Solar Hub: https://thesolarhub.org/resources/cost-analysis-generator-vs-hybrid/

The World Bank. (2021, November 15). *The World Bank*. Retrieved from The World Bank: The World Bank in Zimbabwe: https://www.worldbank.org/en/country/zimbabwe/overview#1

The World Bank. (2022, April 2022 19). *The World Bank: Individuals using internet (% of population) Zimbabwe*. Retrieved from The World Bank: https://data.worldbank.org/indicator/IT.NET.USER.ZS?locations=ZW

Trade Economics. (2022, March 15). *Trade Economics: Zimbabwe Living Wage Individual*. Retrieved from Trade Economics: https://tradingeconomics.com/zimbabwe/living-wage-individual

U.S. Energy Information Administration. (2021, May 24). *U.S. Energy Information Administration: How much coal, natural gas, or petroleum is used to generate a kilowatthour of electricity?*

Retrieved from U.S. Energy Information Administration: https://www.eia.gov/tools/faqs/faq.php?id=667&t=6

Ultralife Corporation. (2022, July 12). *Ultralife: Summary of Li-Ion advantages compared to Lead Acid*. Retrieved from Ultralife: https://www.ultralifecorporation.com/ECommerce/category/applications/energy/energy-storage

UNFCCC. (2016, November 4). *United Nations Climate Change*. Retrieved from United Nations Climate Change: The Paris Agreement: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

United Nations. (2011). *Report of the Special Rapporteur on the promotion and protection of the right to freedom of opinion and expression.* New York City: UN General Asembly.

United Nations. (2019, August). *United Nations: Department of Economic and Social Affairs*. Retrieved from United Nations: https://population.un.org/wpp/Download/Standard/Population/

US. Energy Information Administration. (2022, April 20). *US. Energy Information Administration: Zimbabwe, data*. Retrieved from US. Energy Information Administration: https://www.eia.gov/international/overview/country/ZWE

Vodacom Mocambique. (2022, March 24). *Vodacom: National Rates*. Retrieved from Vodacom: https://www.vm.co.mz/Individual/Pre-pago2/Tarifarios-Roaming/Tarifas-Nacionais

World Economic Forum. (2016). Retrieved from https://www.weforum.org/

World Population Review. (2021, January 7). *World Population Review*. Retrieved from World Population Review - Countries - Zimbabwe Population: https://worldpopulationreview.com/countries/zimbabwe-population

Yaacoub, E., Ghazzai, H., & Alouini, S. M. (2016). Game Theory Framework Applied to Wireless Communication Networks. 35. Retrieved from IGI Global: https://www.igi-global.com/chapter/a-game-theoretic-framework-for-green-hetnets-using-d2d-traffic-offload-and-renewable-energy-powered-base-stations/136646

ZERA. (2022, April 20). *Zimbabwe Energy Regulatory Authority: Home - FUEL PRICES IN ZIMBABWE ZWL AND USD* . Retrieved from Zimbabwe Energy Regulatory Authority: https://www.zera.co.zw/

Zimbabwe Power Company. (2021, November 4). *Zimbabwe Power Company*. Retrieved from Zimbabwe Power Company: https://www.zpc.co.zw/

ZIMRA. (2022, October 2). *Zimbabwe Revenue Authority: Carbon Tax*. Retrieved from Zimbabwe Revenue Authority: https://zimra.co.zw/index.php?option=com_content&view=article&id=1727:understanding-

bad-debt-deductions&catid=5:notice&Itemid=7#:~:text=Carbon%20Tax%20is%20payable%20in,02%5D)%2C%20whichever%20is%20greater.

ZTE. (2009, July 10). *ZTE Technologies: 2009 No.7*. Retrieved from ZTE: https://www.zte.com.cn/global/about/magazine/zte-technologies/2009/7/en_421/173704.html

APPENDICES

Appendix A:

Data Collection Questions

1. **Number of base stations in Budiriro only (Budiriro 1 – 5).**

   …………………………………………………………………………………………

2. **Number of users on each base station at any particular time.**
   a. **Maximum number……………………………………………………………………..**
   b. **Minimum number……………………………………………………………………...**
3. **Power consumption of each base station per day (24 hrs.).**

   …………………………………………………………………………………………

4. **Power Usage of each base station per week;**
   a. **Electricity usage per week (kWh)**

      …………………………………………………...

   b. **Fuel usage per week (Litres)**

      ………………………………………………………...

5. **Average rating of backup generators (Either 18 KVA, 22 kVA, 30 kVA etc.)**

   …………………………………………………………………………………………

6. **Maintenance schedule (Fortnightly, monthly quarterly etc.)**

   …………………………………………………………………………………………

7. **Cost of maintenance of generators.**

……………………………………………………………………………………...................
....

8. Average hours of operation per day (The share ratio in 24 hours).

a. Electricity (hrs.)

……………………………………………………………………….

b. Generators (hrs.)

………………………………………………………………………

9. Future Plans for 5G.

a. Do you have plans to install 5G on Base Stations?

…………………………………………………………………………………
…………

b. In approximately how many years you plan to deploy 5G?

…………………………………………………………………………………
…………………………………………………………………………………
……………………

Appendix B: Approximate Diesel Fuel Consumptions

The Table 3 below gives an approximate diesel fuel consumption, (Able Sales, 2019). Though actual usages may vary due to environment and frequency of service, this table can help compute significant analysis data.

Table 0-1: *Approximate Diesel Fuel Consumption*

	Approximate Diesel Fuel Consumption			
Generator Size	1/4 Load (l/hr.)	1/2 Load (l/hr.)	3/4 Load (l/hr.)	Full Load (l/hr.)
8kW / 10kVA	0.80	1.30	1.80	2.40
10kW / 12kVA	0.90	1.60	2.20	2.90
12kW / 15kVA	1.10	1.90	2.70	3.60
16kW / 20kVA	1.50	2.50	3.60	4.80
20kW / 25kVA	1.80	3.10	4.50	6.00
24kW / 30kVA	2.20	3.70	5.40	7.20
32kW / 40kVA	2.90	5.00	7.20	9.60
40kW / 50kVA	3.60	6.20	9.00	12.00
60kW / 75kVA	5.40	9.40	13.50	18.00
80kW / 100kVA	7.20	12.50	18.00	24.00
120kW / 150kVA	10.80	18.80	27.00	36.00
160kW / 200kVA	14.40	25.00	36.00	48.00
200kW / 250kVA	18.00	31.20	45.00	60.00
280kW / 350kVA	25.20	43.70	63.00	84.00
400kW / 500kVA	36.00	62.40	90.00	120.00

Appendix C: Load-shedding schedules

DAY		MORNING PEAK	EVENING PEAK
MONDAY	*First areas to be affected*	*H2, H4, H5, H6, H7, H8, H10, H14, H15, H16, H18, H21, H23, H24, H27, H28, C1, C4, C5*	*H1, H3, H11, H12, H13, H17, H18, H19, H20, H22, H29, C2, C3*
	Additional areas to be affected	H30, H31, H32	H33, H34, H35
TUESDAY	First areas to be affected	H1, H3, H11, H12, H13, H17, H18, H19, H20, H22, H29, C2, C3	H2, H4, H5, H6, H7, H8, H10, H14, H15, H16, H18, H21, H23, H24, H27, H28, C1, C4, C5
	Additional areas to be affected	H33, H34, H35	H30, H31, H32
WEDNESDAY	First areas to be affected	H2, H4, H5, H6, H7, H8, H10, H14, H15, H16, H18, H21, H23, H24, H27, H28, C1, C4,C5	H1, H3, H11, H12, H13, H17, H18, H19, H20, H22, H29, C2, C3
	Additional areas to be affected	H30, H31, H32	H33, H34, H35
THURSDAY	First areas to be affected	H1, H3, H11, H12, H13, H17, H18, H19, H20, H22, H29, C2, C3	H2, H4, H5, H6, H7, H8, H10, H14, H15, H16, H18, H21, H23, H24, H27, H28, C1, C4, C5
	Additional areas to be affected	H33, H34, H35	H30, H31, H32
FRIDAY	First areas to be affected	H2, H4, H5, H6, H7, H8, H10, H14, H15, H16, H18, H21, H23, H24, H27, H28, C1, C4, C5	H1, H3, H11, H12, H13, H17, H18, H19, H20, H22, H29, C2, C3
	Additional areas to be affected	H30, H31, H32	H33, H34, H35
SATURDAY	First areas to be affected	H1, H3, H11, H12, H13, H14, H17, H18, H19, H20, H22, H29, C2, C3	H2, H4, H5, H6, H7, H8, H10, H14, H15, H16, H18, H21, H23, H24, H27, H28, C1, C4, C5
	Additional areas to be affected	H33, H34, H35	H30, H31, H32
SUNDAY	First areas to be affected	H2, H4, H5, H6, H7, H8, H10, H14, H15, H16, H18, H21, H23, H24, H27, H28, C1, C4, C5	H1, H3, H11, H12, H13, H17, H18, H19, H20, H22, H29, C2, C3
	Additional areas to be affected	H30, H31, H32	H33, H34, H35

Figure 0-1: *ZETDC Harare Load shedding Schedules 2019*

DAY		MORNING PEAK	EVENING PEAK
MONDAY	**First** areas to be affected	H2, H4, H5, H6, H7, H8, H10, H14 H15, H16, H18, H21, H23, H24, H27, H28, C1, C4, C5	H1, H3, H11, H12, H13, H17 , H18, H19, H20, H22 H29, C2, C3
	Industrial areas to be affected	H30, H31, H32	H33, H34, H35
TUESDAY	First areas to be affected	H1, H3, H11, H12, H13, H17, H18, H19, H20, H22, H29, C2, C3	H2, H4, H5, H6, H7, H8, H10, H14, H15, H16, H18, H21, H23, H24, H27, H28, C1, C4, C5
	Industrial areas to be affected	H33, H34, H35	H30, H31, H32
WEDNESDAY	First areas to be affected	H2, H4, H5, H6, H7, H8, H10, H14, H15, H16, H18, H21, H23, H24, H27, H28, C1, C4,C5	H1, H3, H11, H12, H13, H17, H18, H19, H20, H22, H29, C2, C3
	Industrial areas to be affected	H30, H31, H32	H33, H34, H35
THURSDAY	First areas to be affected	H1, H3, H11, H12, H13, H17, H18, H19, H16, H18, H21, H23, H20, H22, H29, C2, C3	H2, H4, H5, H6, H7, H8, H10, H14, H15, H24, H27, H28, C1, C4, C5
	Industrial areas to be affected	H33, H34, H35	H30, H31, H32
FRIDAY	First areas to be affected	H2, H4, H5, H6, H7, H8, H10, H14, H15, H16, H18, H21, H23, H24, H27, H28, C1, C4, C5	H1, H3, H11, H12, H13, H17, H18, H19, H20, H22, H29, C2, C3
	Industrial areas to be affected	H30, H31, H32	H33, H34, H35
SATURDAY	First areas to be affected	H1, H3, H11, H12, H13, H14, H17, H18, H19, H20, H22, H29, C2, C3	H2, H4, H5, H6, H7, H8, H10, H14, H15, H16, H18, H21, H23, H24, H27, H28, C1, C4, C5
	Industrial areas to be affected	H33, H34, H35	H30, H31, H32
SUNDAY	First areas to be affected	H2, H4, H5, H6, H7, H8, H10, H14, H15, H16, H18, H21, H23, H24, H27 H28, C1, C4, C5	H1, H3, H11, H12, H13, H17, H18, H19, H20, H22, H29, C2, C3
	Industrial areas to be affected	H30, H31, H32	H33, H34, H35
Key: H - Harare **C** - Chitungwiza			

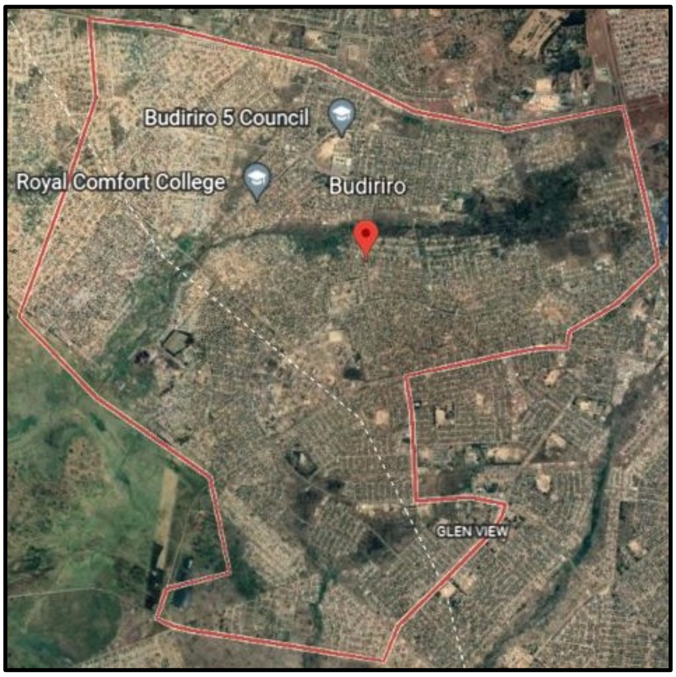
Figure 0-2: *ZETDC Harare Load-Shedding Schedule 2021*

Codes for the schedules above are shown in Figure 0-3 below

SUBURB	CODE
Borrowdale	H7
Borrowdale Brook	H7
Borrowdale N	H27
Bothashof	H7
Budiriro	H23
Carrick	H7
Chadcombe	H14
Chedgelow	H17
Chikurubi	H6
Chiltern Hill	H28

Figure 0-3: *Harare region load-shedding schedules - Area Codes*

Appendix D: Maps



Area of study: Budiriro

Appendix E:

Ethical Clearance

THE UNIVERSITY OF ZAMBIA
DIRECTORATE OF RESEARCH AND GRADUATE STUDIES

Great East Road Campus | P.O. Box 32379 | Lusaka10101 | Tel: +260-211-290 258/291 777 **Fax**: (+260)-211-290 258/253 952 | **E-mail**: director.drgs@unza.zm | Website: www.unza.zm

APPROVAL OF STUDY

IORG No. 0005376
HSSREC IRB No. 00006465

20th June, 2022

REF NO. NASREC-2022-APR-009

Kline Tarcisius Mapfumo
The University of Zambia
School of Engineering
Department of Mechanical Engineering
P.O. Box 32379
LUSAKA

Dear Mr. Mapfumo,

RE: "TECHO-ECONOMIC STUDIES OF INTEGRATION OF SOLAR PV TECHNOLOGY IN TELECOMMUNICATION SECTOR FOR SUSTAINABLE DEVELOPMENT: A CASE STUDY OF BUDIRIRO"

Reference is made to your protocol dated as captioned above. NASREC resolved to approve this study and your participation as Principal Investigator for a period of one year.

REVIEW TYPE	ORDINARY REVIEW	APPROVAL NO. NASREC-2022-APR-007
Approval and Expiry Date	Approval Date: 20th June, 2022	Expiry Date: 19th June, 2023
Protocol Version and Date	Version - Nil.	19th June, 2023
Information Sheet, Consent Forms and Dates	• English.	To be provided
Consent form ID and Date	• Version - Nil	To be provided
Recruitment Materials	• Nil	Nil
Other Study Documents	• Questionnaire.	

Specific conditions will apply to this approval; As Principal Investigator it is your responsibility to ensure that the contents of this letter are adhered to. If these are not adhered to, the approval may be suspended. Should the study be suspended, study sponsors and other regulatory authorities will be informed.

Conditions of Approval

- No participant may be involved in any study procedure prior to the study approval or after the expiration date.

- All unanticipated or Serious Adverse Events (SAEs) must be reported to NASREC within 5 days.

- All protocol modifications must be approved by NASREC prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address.

- All protocol deviations must be reported to NASREC within 5 working days.
- All recruitment materials must be approved by NASREC prior to being used.

- Principal investigators are responsible for initiating Continuing Review proceedings. NASREC will only approve a study for a period of 12 months.

- It is the responsibility of the PI to renew his/her ethics approval through a renewal application to NASREC.

- Where the PI desires to extend the study after expiry of the study period, documents for study extension must be received by NASREC at least 30 days before the expiry date. This is for the purpose of facilitating the review process. Documents received within 30 days after expiry will be labelled "late submissions" and will incur a penalty fee of K500.00. No study shall be renewed whose documents are submitted for renewal 30 days after expiry of the certificate.

- Every 6 (six) months a progress report form supplied by The University of Zambia Natural and Applied Sciences Research Ethics Committee as an IRB must be filled in and submitted to us. There is a penalty of K500.00 for failure to submit the report.

- When closing a project, the PI is responsible for notifying, in writing or using the Research Ethics and Management Online (REMO),both NASREC

- and the National Health Research Authority (NHRA) when ethics certification is no longer required for a project.

- In order to close an approved study, a Closing Report must be submitted in writing or through the REMO system. A Closing Report should be filed when data collection has ended and the study team will no longer be using human participants or animals or secondary data or have any direct or indirect contact with the research participants or animals for the study.

- Filing a closing report (rather than just letting your approval lapse) is important as it assists NASREC in efficiently tracking and reporting on projects. Note that some funding agencies and sponsors require a notice of closure from the IRB which had approved the study and can only be generated after the Closing Report has been filed.

- A reprint of this letter shall be done at a fee.

- All protocol modifications must be approved by NASREC by way of an application for an amendment prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address or methodology and methods. Many modifications entail minimal risk adjustments to a protocol and/or consent form and can be made on an Expedited basis (via the IRB Chair). Some examples are: format changes, correcting spelling errors, adding key personnel, minor changes to questionnaires, recruiting and changes, and so forth. Other, more substantive changes, especially those that may alter the risk-benefit ratio, may require Full Board review. In all cases, except where noted above regarding subject safety, any changes to any protocol document or procedure must first be approved by NASREC before they can be implemented.

Should you have any questions regarding anything indicated in this letter, please do not hesitate to get in touch with us at the above indicated address.

On behalf of NASREC, we would like to wish you all the success as you carry out your study.

Yours faithfully,

Dr. E. M. Mwanaumo

CHAIRPERSON
THE UNIVERSITY OF ZAMBIA NATURAL AND APPLIED SCIENCES RESEARCH ETHICS COMMITTEE - IRB

cc: Director, Directorate of Research and Graduate Studies
Assistant Director (Research), Directorate of Research and Graduate Studies
Assistant Registrar (Research), Directorate of Research and Graduate Studies

Appendix F:

Submission of a Paper

SD Publisher Group

Publisher of peer reviewed international journals, books and monographs

F. No. SDI/ JENRR/40/00045

Dated 10-Mar-2023

Submission Letter_2023_JENRR_97687

To

Dr. Kline Tarcisius Mapfumo

Thank you very much for submitting your valuable paper to our journal. We have started the editorial processing of the manuscript with the following details

Title: Techno-Economic Studies of Integration of Solar PV Technology in Telecommunications Sector for Sustainable Development: A Case Study of Budiriro

Journal: Journal of Energy Research and Reviews

Manuscript Number: 2023/JENRR/97687

Thank you for submitting your paper.

Thanking you,

Dr. M. Basu
Chief Managing Editor

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UK: Third Floor, 207 Regent Street, London, W1B 3HH, UK, Fax: +44 20-3031-1429