



University of Wales Trinity Saint David
School of Engineering

An Assessment of Renewable Energy System Deployment in the Average Rural Namibian
Village

Nathan Skyrme
Energy and Environmental Engineering, BEng
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Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Nathan Skyrme

Date: 12th April 2024

Abstract

The issue of climate change is currently one of the most major concerns globally. In order to address this issue a transition away from traditional fossil fuel energy sources must be made. Additionally, there exists the global challenge of tackling wide scale poverty, particularly in third world regions. The aims of this paper are to provide a research basis and propose a suitable solution recommendation that will be able to reduce the effects of these problems. As the research finds, successfully meeting global climate and poverty goals, requires targets to be made down on the community level, in order to facilitate the effective implementation of real solutions. The focus area of this project is Namibia, due to the nation's imbalance of energy access between urban and rural inhabitants (78% and 36% respectively), and abundance of RES potential. Data relating to the country's resources, meteorology, and communities, was collected to enable the creation of a village model, which allowed the analysis of the most optimal RES system to provide electrification. It was estimated that a daily energy requirement of 251.46-kWh would need to be met. Culminating in the recommendation of a 58kW SPV system with a 12kW lithium-ion battery storage, at an estimated cost of £64,182.

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Nomenclature

SPV - Solar Photovoltaic

ST - Solar Thermal

RES - Renewable Energy System

CSP – Concentrated Solar Power

W - Watt

MW – Mega-watt

kW – Kilo-watt

kWh – Killo-watt hour

m – Metre

1 Introduction

1.1 Global Temperature

As record-high temperatures continue to rise, it is becoming increasingly paramount to tackle the deadly effects of climate change immediately. Since 1880, there has been a discernible rise in the average global temperature, amounting to a minimum of 1.1° Celcius (1.9° Fahrenheit). The predominant increase in temperature has primarily transpired subsequent to 1975, *fig.1.*, exhibiting a rate of approximately +0.15 to +0.20°C per decade (NASA, 2023). Across Africa warming has risen at a rate of +0.2°C/decade between 1961-1990 and rose to +0.3°C/decade during the period 1991-2022, suffering a disproportionately higher rate of warming compared to global increase. This has led to severely affected economies, food security and ecosystems (WMO, 2022).

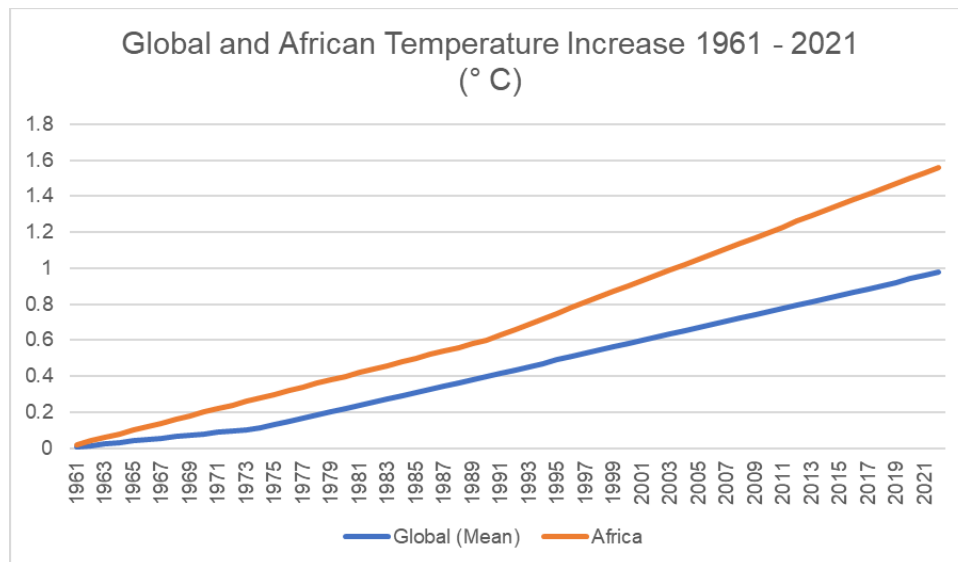


Figure 1 - A graph showing the Global and African Mean Temperature Increase during the years 1961 through 2021 – (NASA, 2023) (WMO, 2022) (Lindsey et al., 2023)

The unfortunate reality is that the nations who produce the most greenhouse gas emissions often do not see the full repercussions of their actions. Rather, it is the poorer developing nations, who are already largely exploited by the developed world for their resources, who must bear the harshest consequences of climate change.

1.2 Sub-Saharan Africa and Energy

The Sub-Saharan region of Africa, *fig.2.*, is home to 1.21 billion people (nearly 1/5 of the global population) (The World Bank, 2022), yet despite this, the region accounts for less than 4% of global energy consumption (IEA, 2019) and has emitted no more than 3% of the world's energy-related CO₂ emissions to date (IEA, 2022). This clear disparity in the level of electricity access is only further backed up by data from (The World Bank, 2021) estimating a 50.6% rate of electricity access.

To combat this global inequality, international cooperation with regional governments across third-world nations will be necessary (UNDP, 2015) (UN, 2023). Rich nations have continually profited from the indirect destruction of these countries since the beginning of the industrial revolution and will need to directly enable the reversal and reconstruction of their natural environments (WWF, 2015). Therefore, extensive research and analysis of the climate and environment will need to be undertaken in order to propose and deploy suitable and effective solutions and applicative technologies.



Figure 2 - Map of the African Continent which highlights the Sub-Saharan nations – (UN, 2013)

1.3 Namibia

1.3.1 Namibian Electrification

Electricity access rates within Sub-Saharan regions can seem more promising on the surface, but in reality, there exists a significant disparity between the access levels of residents living in urban and rural areas. In Namibia, the total electrification rate is 57%, but when broken down between urban and rural areas, the electrification rate is 78% and 36%,

respectively (CIA, 2022) (BSD, 2022). This discrepancy highlights the unequal distribution of electricity infrastructure and resources between urban and rural areas in Namibia. The lower electrification rate in rural areas suggests a need for targeted efforts to improve access and bridge the gap between urban and rural communities. Closing this gap will aid in alleviating economic and social strains on urban infrastructure (WWF, 2015), as residents of rural areas relocate on mass at a current annual rate of 3.2% (The World Bank, 2022).

Preventing the exodus of rural inhabitants to urban communities will require a vast overhaul of and improvement to the living conditions that they currently occupy. If satisfactory standards of living are met, both urban and rural communities will be able to flourish, as opposed to both becoming overburdened with unstable population growth and decline. Households in rural communities are kept in perpetual poverty by widespread unemployment (20.8%) (The World Bank, 2022), thereby creating a lack of the income needed to escape the poverty cycle. Raising the standard of living will require external help to remove the restrictive barriers to development, which these communities would otherwise be unable to overcome (UNDP, 2015)

1.3.2 Development Potential

Electricity access is a key development gateway, without which a modern quality of life cannot be attained (The World Bank, 2023). The provision of electricity is fundamentally vital for the effective operation of crucial rural establishments, including educational institutions, healthcare facilities, and medical centres (Karekezi et al., 2002). All of which are critically underdeveloped yet absolutely necessary for the accelerated development of rural Namibia (Gyamfi et al., 2015). Providing clean energy, will not only release pressure on and bolster these essential services, but will allow the deployment of key infrastructure not currently available (lighting, telecommunications, internet, etc.) in the process creating pathways to employment and increased social development.

Namibia provides a perfect case for the implementation of Renewable Energy Systems (RES), owing to its abundance of underutilised natural resources (Deichman et al., 2011), that could easily be transformed into meaningful energy production (Oertzen, 2012). However, despite increasing efforts, this development has not seen the rapid expansions projected by previous Namibian Government policies. This is mostly the fault of the low population density in rural areas (CIA, 2022) (UNDP, 2015), compounded with the inability of rural inhabitants to contribute towards the investments needed for electrification (UNDP, 2015) (Amesho et al., 2019). Further, investment costs are significantly raised by the

sporadic scattering of settlements across the vast rural plains of the country (UNDP, 2015), increasing the difficulty of connecting communities to the national grid (Hoeck et al., 2022).

1.4 Resolution

Therefore, it is imperative to devise and implement solutions and technologies that can provide Namibian communities with the essential electricity and infrastructure required to alleviate their persistent poverty, which they are unlikely to overcome alone. In order to initiate this undertaking, it is important to develop a foundational understanding of the barriers to electrification in rural Namibia, with the aim of enhancing energy accessibility in these regions. Developing this comprehension serves as a strong basis for addressing the implementation of these technologies into communities, which have unique requirements for which to account.

2 Aims and Objectives

The primary aim of this investigation is to examine the problem of electricity access in rural areas of Namibia, and thereby investigate and provide an assessment of appropriate measures to address the issue. The study will involve an evaluation of the current situation, followed by the development and presentation of a potential solution that may efficiently provide energy to an average rural village. This aim will be accomplished by:

1. Conducting research and investigation addressing the current issue of access to electrification and the barriers to development. Including the collection of data pertaining to the potential for renewable energy generation, including factors such as weather patterns, solar radiation levels, and wind speeds, alongside data concerning rural communities in Namibia, such as population density, employment rates, and living conditions.
2. Creating a research-based model village, which can be used to estimate energy demand whilst making reasonable assumptions. Enabling the critical evaluation of resource availability based on the research findings, in line with the model village created.
3. Evaluating a range of potentially viable renewable energy systems, making considerations such as required generation capacity, cost and viability. Culminating in the recommendation and specification of the most optimal system for the village.
4. Drawing conclusions on research and development findings, justifying reasons for the system design proposed. Providing recommendations based on the analysis for further work and the practical implementation of the system.

The project timing plan can be found in Appendix A.

3 Literature Review

All resource availability outlined below, where possible is based on the metrics of the Epinga village in Northern-Central Namibian region of Ohangwena.

3.1 Current Energy Supply

There is very significant untapped potential for RES in Namibia (Oertzen, 2012), as shown in *fig.4*. Of all Sub-Saharan countries, Namibia has the highest unutilised RES potential (Deichman et al., 2011), *fig.3*. To some extent this is being recognised and is reflected in Namibia's installed generation capacity, 82% of which is comprised of RES (NIPDB, 2022), *fig.5*. However, far more needs to be done in order to decrease Namibia's dependence on imports. While RES contributes to the majority of Namibia's installed generation capacity, 82% (NIPDB, 2022), it only amounts for 11% of consumption (IEA, 2022). Moreover, Namibia is currently over reliant on the Ruacana hydroelectric power plant (Amupolo et al., 2022) (ECB, 2020), the only hydroelectric power plant in Namibia (Database.Earth, 2024), which generates 95.7% of Namibia's total 374-MW hydroelectric generation capacity (Power Technology, 2021), meaning that it accounts for 48.8% of Namibia's total installed generation capacity (NIPDB, 2022). Previously it has seen generation capacity drop below demand, owing to prolonged periods of drought, leaving many without power (Reuters, 2020). Namibia's drought prone nature makes this event likely to repeat, especially in the face of continuing climate change. Therefore, it is imperative to expand Namibia's RES portfolio and employ a wider variety of renewable generators, strengthening supply security.

Improving electricity access in rural Namibian communities will require the strategic deployment of RES technologies, alongside a shift from a reliance on oil, which constitutes roughly 70% of Namibia's total energy supply (IEA, 2022). At present, there is a heavy dependence upon imports from the Southern African Power Pool (Amesho et al., 2019), with 60% of Namibia's total energy supply coming directly from it (BSD, 2022) (Amupolo et al., 2022). Currently, Namibia lacks the necessary installed generation capacity to achieve self-sufficiency (BSD, 2022). Effective RES deployment will in of itself reduce this dependence, boosting the availability of domestic energy which presently forms merely 40% of energy consumption (BSD, 2022). Securing Namibia's energy future calls for the long-term calculated integration of RES into the nation's generation capacity due to the unstable depleting supply of fossil fuel resources (Martins et al., 2019).

Namibia's current generation capacity is promisingly green. Operating at an installed capacity of 680-MW, broken down as follows: Hydro (347-MW), Solar (163-MW), Coal (122-

MW), Thermal (41-MW), Wind (7-MW), *fig.5*. (NIPDB, 2022). This encouraging generation mix further strengthens the case for increased deployment of RES technologies, especially when considering that the majority of Namibian energy consumption is made up of a combination of oil, biofuels and waste (~89%), *fig.6.*, (IEA, 2022).

Solar irradiation rates in Namibia are the second highest in the world (Hoeck et al., 2022), yet in 2020 only amounted to 20% of Namibia's electricity generation, *fig.5*. and around 1% of its electricity consumption, *fig.6.*, (IEA, 2022). Similarly, this issue is also found with wind energy. Despite there being ample national potential for wind production, (UNDP, 2015) (The World Bank, 2023) in 2020 it totalled only 1% of energy production and consumption (IEA, 2022) (Bloomberg, 2020). Previous successes of these technologies, both in and out of Namibia have demonstrated their capacity for effectively supplying rural communities at limited costs (Karekezi et al., 2002) (Mohammed et al., 2013). This is just a small example of the large potential going unused in Namibia.

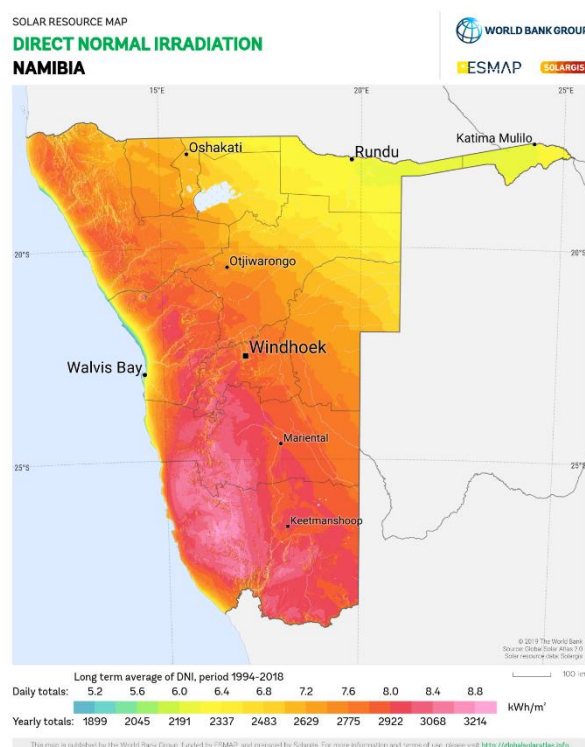


Figure 3 - Map displaying the average direct normal irradiation in Namibia during the year 2018 – (The World Bank Group, 2018)

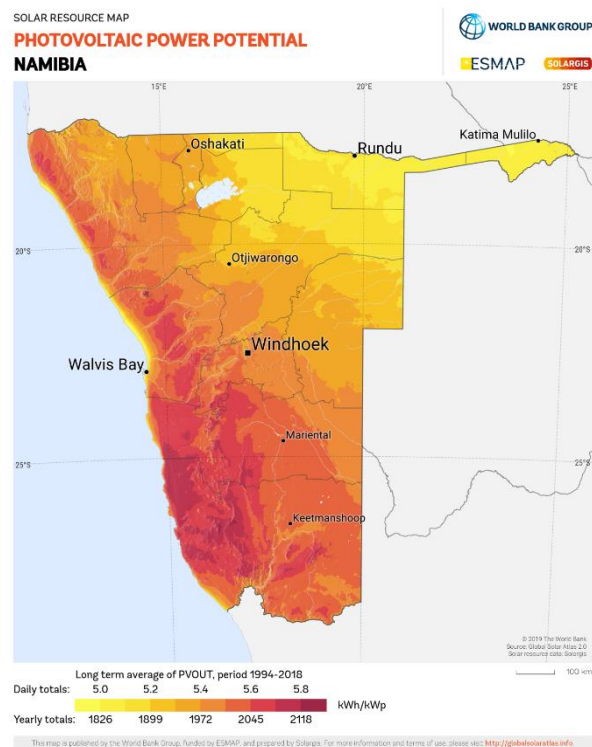


Figure 4 - Map displaying the photovoltaic power potential in Namibia – (The World Bank Group, 2018)

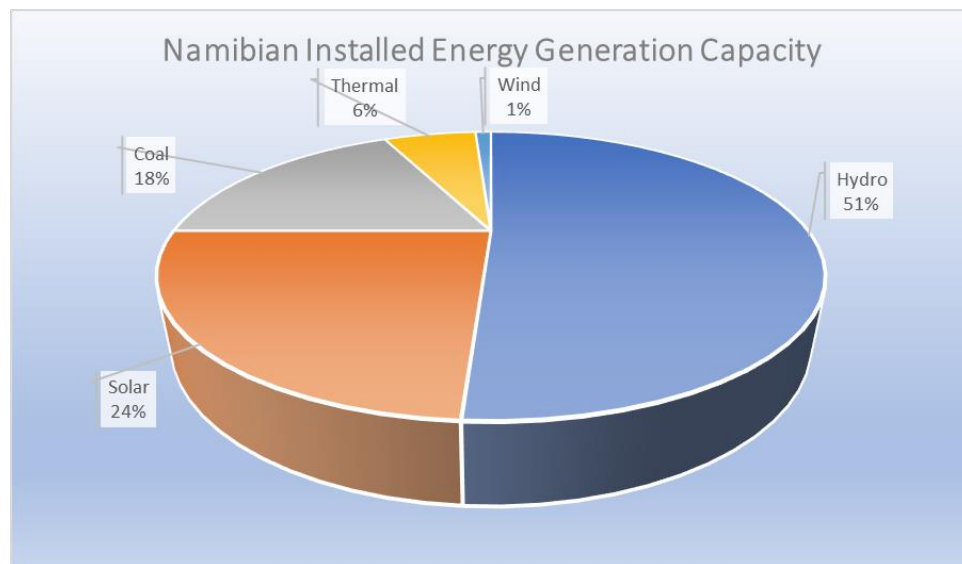


Figure 5 - Chart displaying the Installed Energy Generation Capacity of Namibia – (NIPDB, 2022)

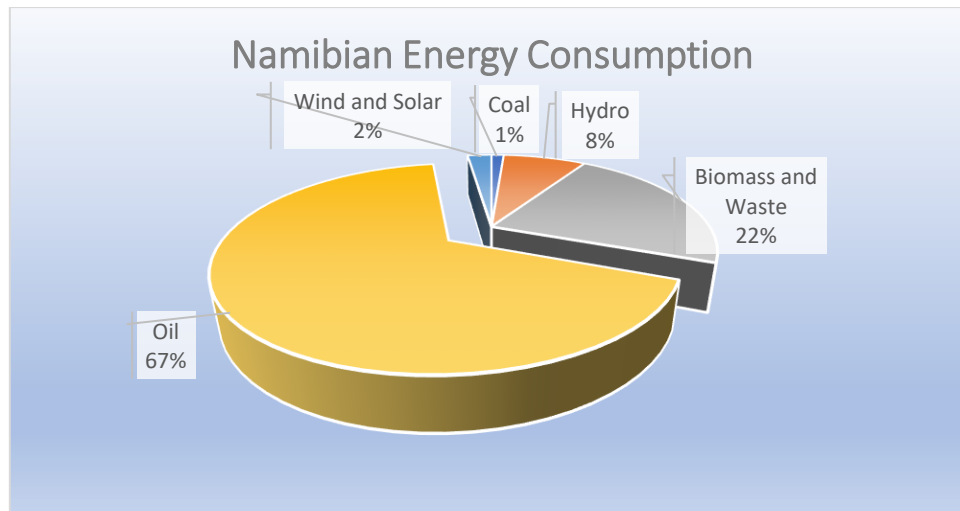


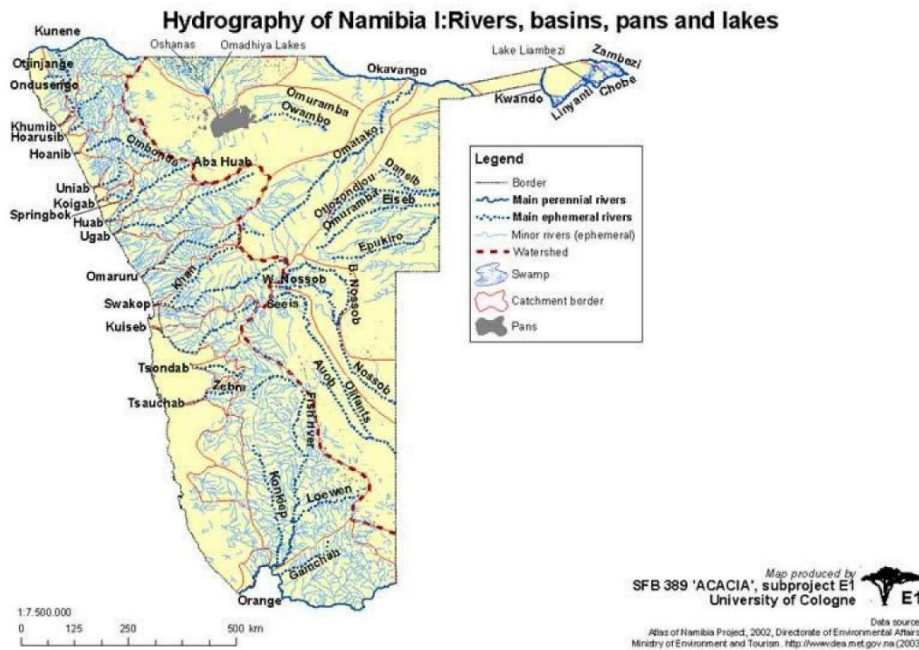
Figure 6 - Graph displaying the source mix of Namibia's Energy Consumption – (IEA, 2022)

3.2 Hydroelectricity

Hydroelectricity Requirements: In order for a hydroelectric system to be a feasible choice, the village must be located near a flowing water source that has a substantial amount of falling water. The optimal location for these systems are regions characterised by mountainous or steep terrain (U.S. Department of Energy, 2024).

Although hydroelectricity accounts for 51% of Namibia's overall generation capacity (NIPDB, 2022), it may not be considered a universally suitable RES for rural settlements.

Hydroelectricity is a more viable source of power at the national level, where power can be exported from larger systems in the most optimal areas (Bakken et al., 2014). Although occasional drought-related challenges, can still cause huge problems even when supplied via the national grid (Zhao et al., 2023). Certain rural communities may potentially derive advantages from implementing a run of river system, which have a higher level of reliability (Gilkes, 2023). However, it is generally not suitable to extend the run of river approach to a wider context due to various factors. Specifically, most communities, particularly those in the Ohangwena region, *fig.7 & 8.*, are unlikely to be situated in close proximity to a river (Maps Namibia, 2002). Furthermore, even for those communities that are located near a river, it may be determined that the river itself is unsuitable for the construction of such a system.



Namibia's rangelands, impacting more than 60% of the area. According to a study conducted by (Oertzen, 2020), the projected potential of bush biomass is roughly 450 million metric tonnes. In 2020, approximately 2 million tonnes of bush biomass were utilised (Oertzen, 2020). However, limited evidence exists to support its feasibility as a viable energy source for rural villages.

While small-scale biofuel production is feasible (De Paola et al., 2021) (Muller, 2008), the growth rate of invader bush is slow, requiring 7-15 years for regrowth once removed (Namibian Hardwood, 2022). Consequently, once the immediate supply of invader bush surrounding the village is depleted, obtaining additional supply for conversion will become progressively more challenging, alongside the risk to local biodiversity, especially if the village was responsible for harvesting the crop (Suckling et al., 2022). There is the potential for the provision of converted fuel to the village (Janota et al., 2023), however, this will not provide the population with their own power generators and will instead make them reliant on external sources of energy, leaving them susceptible to supply vulnerabilities and energy insecurity. Consequently, the production of biofuel from invasive bush, like hydropower, is better suited for large-scale plants rather than local community projects (Maltitz et al., 2011).

Without undergoing conversion into biofuel, burning bush biomass alone is insufficient in providing adequate energy and fails to address the current health concerns associated with the utilisation of existing waste and biomass resources (Chen et al., 2017). Moreover, there exists a dearth of comprehensive development and study pertaining to the utilisation of encroachment and invader bush as a viable energy source, hence impeding the estimation of associated costs and generation capacity. This source is potentially better suited for a large-scale power plant configuration at the national level, especially when considering factors such as the availability of storage space for fuel and the practicality of harvesting (Forest Research, 2024). Given that encroachment and invader bush are Namibia's most prevalent biomass source, it is reasonable to deduce that alternative biomass sources may not be suitable for further consideration.

Further there exists the issue of how land would be utilised in the instance of developing biofuel as a resource within the village. The majority of land use within Namibia is used for agricultural purposes, as rural inhabitants in particular, are heavily reliant on subsistence agriculture to sustain their communities (Zeidler, 2008). Therefore, the growth of biofuel crop within the village area, is likely to consume and remove vast amounts of land that the community are dependent upon, and consequently cause a scarcity of crops. It has been seen previously in Brazil, that converting agricultural land for biofuel production, has led to food supply insecurity (Cudlinova et al., 2020) (Sakai et al., 2020).

3.4 Solar

Solar Requirements: The primary determinant impacting the feasibility of Solar is the availability of sunshine (Energy Savings Trust, 2024).

There exists a substantial and consistent availability of solar irradiation throughout the entire year in Namibia. The quantification of this irradiation can be determined according to *figs 3 & 4.*, from (The World Bank Group, 2018). Additionally, by utilising the solar atlas developed by (The World Bank, 2023), more localised data can be obtained, *fig.9*. Both sources utilise data obtained directly from the World Bank, therefore it would be wiser to rely on data from the solar atlas, as the solar atlas is a real-time satellite source, enabling it to offer more current information. An analysis using a model from the Atlas, calculated based on the metrics of the Epinga village that an SPV system can generate a yearly direct normal irradiation of 2374.2 kilowatt-hours per square metre (kWh/m²), resulting in a specific photovoltaic power production of 1882.3 kilowatt-hours per kilowatt-peak (kWh/kWp).

In comparison to a relatively modest average installed capacity of 4-kWp for home SPV system in the United Kingdom (Tritech Energy, 2021), the atlas power output model predicts an annual energy output of 2428.8-kWh/m². The solar panel output estimation model developed by (The World Bank, 2023) incorporates the influence of air temperature and the reduction in PV cell efficiency (Ecoflow, 2023), which is induced by heat at a 10% rate of decline when ambient temperature increases by 25 (Eicke et al., 2022). Consequently, this results in a higher level of precision and a more compelling argument for the implementation of SPV in the village. Given the accuracy of these estimations, there exists a substantial capacity to design PV into the village system.

The optimal system configuration may be a mini-grid, a standalone system, or a hybrid combination of the two. Based on the analysis of a PV system, it can be reasonably inferred that there exists enough promise to justify additional research and consideration.

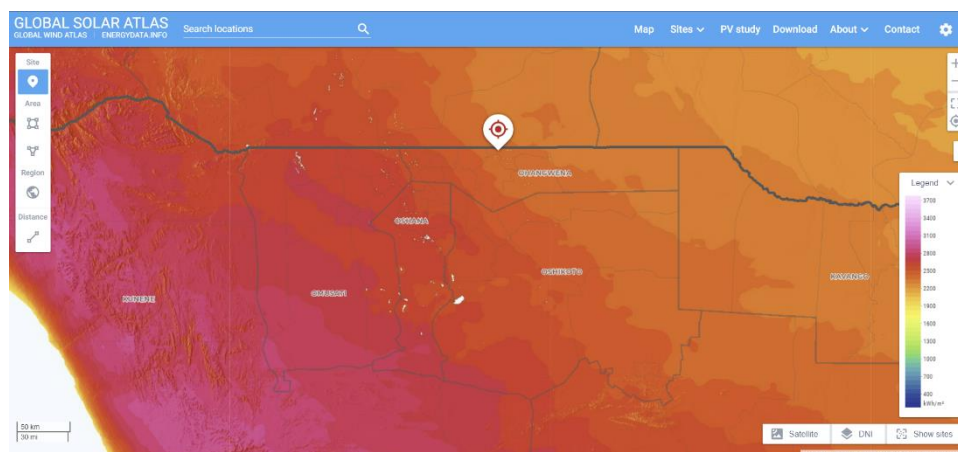


Figure 9 - Direction normal irradiation in Northern Namibia – (The World Bank, 2023)

3.5 Wind

Wind Requirements: In order for wind to be a feasible energy source, there must be a significant annual availability of wind. Alongside an adequate site with unobstructed 360-degree access to prevailing wind, required for the construction of the system. Additionally, the site must be able to accommodate a system that is 30 feet taller than any obstructions within a 300-foot radius (U.S. Department of Energy, 2024).

The wind availability can be determined using the metrics for the Epinga village. This can be found by utilising the Wind Atlas provided in reference (The World Bank, 2023), as shown in *fig.10.*, and employing the Epinga village's geographical coordinates as a reference point. As incorporated in the model there is a consistent average wind speed of 5.24 m/s throughout the entire year. The majority of wind activity is observed between the hours of midnight and 11:00 in the morning. The monthly data obtained from the Wind Speed Index reveals a notable increase in productivity, starting at 0.82 in March and reaching its highest point of 1.35 in July. Subsequently, there is a gradual decline in productivity, culminating in its lowest recorded value of 0.75 in November. For six-months of the year, the productivity index is above 1.0, indicating a high and steady level of productivity. Moreover, for ten months, the index remains above 0.80, signifying a sustained level of productivity. However, a slight decline is observed in November and December, with the index decreasing to 0.75 and 0.76, respectively.

Evidently there exists a substantial abundance of wind, rendering it a feasible resource for this rural area. During half of the year, wind productivity significantly exceeds the annual average, except for two months characterised by substantial declines. During the months of November and December, there remains a considerable amount of sunlight, despite the

decrease in output observed during the summer months. Hence, it may be contended that solar systems have the potential to compensate for this decline in productivity during this period.

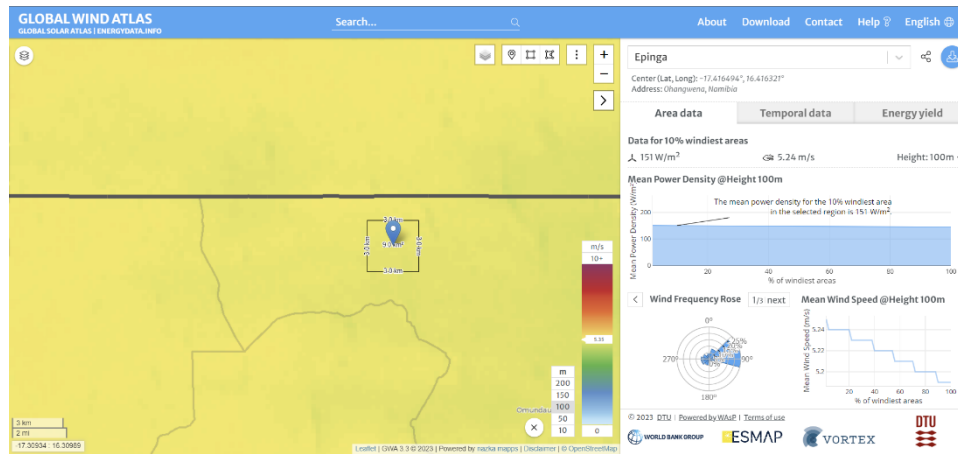


Figure 10 - Map showing wind speed in the Ohangwena region and the Epinga village – (The World Bank, 2023)

3.6 Grid

The main issue that surrounds the problem of electricity access is the inability to access grid connection, which has not been expanded to most rural settlements. The most obvious answer to this would be to simply extend the grid connection, however this ignores entirely the cost-benefit of doing this. The nearest available connection to the Epinga Village is approximately 55-miles away (The World Bank, 2018) (Mapbox, 2023) (Google, 2024), the cost to install a connection of this length could be around £1.5m per mile (DeSantis et al., 2021). Although the Epinga village is used, the general principle is intended to extend far beyond it. The Epinga village is actually in a far more favourable position than most, as most rural villages are far further from grid connection than this, situated upwards of 100-miles away. Furthermore, installing grid connection neglects the fact that the connection will only be beneficial to a small portion of the population, and that they will be unlikely to be able to afford to pay the cost of the energy even if given grid access. Additionally, if these grid installation costs were not evenly distributed across the entire country but were instead charged at an unsubsidised rate, the cost of energy would be astronomical, and if these costs were to be distributed evenly and subsidised to the village by charging a fixed standing charge across Namibia, it would significantly affect the cost for the average Namibian, worsening energy poverty.

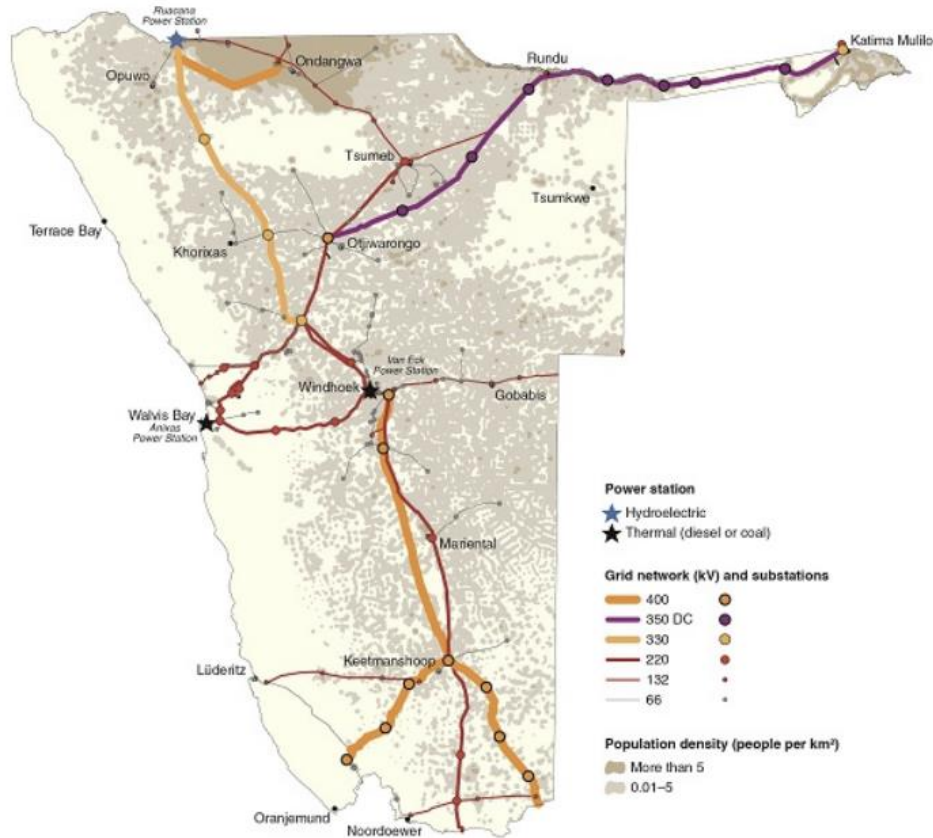


Figure 12 - Map of Namibian power stations, transmission lines and main substations – (Jaro Consultancy, 2016)

3.7 Mini-Grid and Standalone Systems

While an ideal scenario would see these rural communities connected to the central grid, achieving this in the short-term will be simply too costly, time-consuming and arduous to effectively deliver power to most inhabitants, especially when compared to the alternative off-grid options (Dagnachew et al., 2017) (Zeyringer et al., 2015) (BSD, 2022) (Marino et al., 2020). Some sources such as (Zeyringer et al., 2015) suggest that the quality of electricity provided by grid connection and standalone/mini-grid systems can vary considerably region-to-region, but this is dependent on individual factors, and one cannot be considered objectively better than the other. Although as stated by (Mohammed et al., 2013), even if the electricity quality were found to be lower, alternative systems may still be considerable in the meantime, due to grid-connection timescales, which if long, can leave inhabitants remaining without electricity and in poverty potentially indefinitely. Additionally, power grid connection does not directly discourage the use of fossil fuels as an energy source (Deichman et al., 2011), which will not aid in the overarching goal of combatting climate change.

3.7.1 Mini-Grid

Mini-Grids are defined as a collection of small-scale electricity generators, which can include storage systems, which are connected to an energy distribution network. The network delivers electricity to small, local groups of customers and functions independently from the centralised national grid (AFDB, 2024). Mini-grids are employed for generating electricity on a tiny scale, with capacities ranging from a Pico system of less than 1 kilowatt to a multiple megawatt system (Numminen et al., 2018).

3.7.2 Standalone

Standalone systems are defined as systems that consist of one or more energy generators, often PV and wind. The generators utilise a charge controller to transfer an electric current into battery storage. An inverter is then used to convert the energy from DC to AC to be delivered to the end user (FF Solar, 2024).

3.8 Previous Projects

Several studies and initiatives have achieved positive outcomes in implementing and evaluating the efficacy of RES in Sub-Saharan Africa, in fact the nations of Ghana, Kenya and Rwanda, are on track to achieve 100% electrification by 2030 (IEA, 2022). This is a sharp rise considering previous access levels, in 2013, ~25% of Kenyans had electricity access, and by 2019, this had risen substantially to ~75%.

Kenya sourced 81% of its electricity generation from low carbon sources in 2021. 50% of which originated from Kenya's vast geothermal capacity (Rapid Transition Alliance, 2022). This shows that the most straightforward approach to achieving electrification, as demonstrated by the success of other Sub-Saharan countries, is to fully leverage the country's primary abundant resources.

To successfully attain electrification goals, specific targets and methods were implemented, which effectively targeted specific regions (The Ministry of Energy, 2018). A significant challenge encountered in the process of electrifying these countries is the lack of specific plans tailored to individual communities or regions (The World Bank, 2022). To replicate Kenya's success and ensure efficient power delivery, it is imperative to adopt a highly targeted approach and establish frameworks that can be implemented at the community level.

3.9 Energy Systems

Based on the analysis of resource availability, it can be concluded that the suitable sources for power generation in the village include solar photovoltaic, solar thermal, and wind. The most suitable system for power generation will depend on specific factors. There is no one-size-fits-all solution for applying these systems to real villages. However, the most appropriate type will be applied to the generic village model created.

3.9.1 Solar PV

An SPV generator is an electricity producing device that transforms sunlight into usable electrical energy (U.S. Department for Energy, 2022). SPV systems can be implemented in various configurations, these being Pico systems, solar-home systems, and solar mini-grids (Feron, 2016).

Pico Systems: are systems that are below 1-kW and are typically used for individual appliances, such as, radio, lighting or calculators (Feron, 2016) (Numminen et al., 2018).

Solar Home Systems: are systems which are used for an individual household (Feron, 2016).

Solar Mini-Grids: systems which generate and distribute electricity across the entire target area (Feron, 2016).

Solar panels typically come in three sizes: 60-cell, 72-cell, and 96-cell panels (Airis Energy, 2021) (Skills Training Group, 2023). The size and quantity of panels utilised in a system, will primarily rely on the required system output (Skills Training Group, 2023).

A SPV system can be either roof or ground mounted (Awan et al., 2020). Ground mounted systems are often more costly than roof mounted systems (around 25-35% more expensive), although they can be more advantageous due to higher potential energy production and more optimal positioning with easier access for routine maintenance (Watt Logic, 2022) (Lebreton, 2023).

The electricity generation output from SPV systems will be contingent upon the expected levels of direct irradiation in the specific location in which they are installed (Market Watch, 2024). Nevertheless, the resulting output can be negatively affected and reduced by various conditions, including but not limited to shade, dust, humidity, and temperature, each of which will need to be addressed in order to attain an optimal power output (Rahman et al., 2023).

The main obstacles that SPV systems will encounter in Namibia are the elevated temperatures and dust accumulation, attributed to Namibia's Savannah habitat and consistently high temperatures throughout the year (Shikangalah, 2020) (Meteoblue, 2023).

Dust can have a substantial impact on the efficiency of a SPV system, potentially reducing it by up to 50% when accumulated (Sulaiman et al., 2011). The most effective approach to address this issue is by regular cleaning of the panels, which is the simplest and sole viable solution to this problem (Abuzaid et al., 2022).

Regarding the influence of temperature, the existing infrastructure in rural communities offers few possibilities for addressing this issue. Cooling systems are commonly employed, but they rely on a consistent and uninterrupted water supply (Dwivedi et al., 2020), which is not assured, particularly given Namibia's susceptibility to drought (Zhao et al., 2023). The absence of a viable remedy for the elevated temperature could have a substantial impact on the efficiency and power generation of the systems. According to estimates, the efficiency of systems drops by around 0.4-0.5% for every 1°C increase above 25°C (Palmetto, 2023) (Agyekum et al., 2021). SPV systems are already very inefficient with panels typically being only around 15-20% efficient (Eicke et al., 2022) (IRENA, 2022). On an average day the temperature typically reaches as much as 31°C, however during the summer it can reach as high as 40°C (The World Bank, 2023). Assuming on an average day that the temperature hits 31°C and the system is affected at a maximum rate of 0.5% per 1°C increase with a 15-20% system efficiency, the system efficiency could be reduced to around 12-17%, and on days where the temperature reaches 40°C the system efficiency could be reduced to between 7.5-12.5%.

3.9.2 Solar Thermal

Solar thermal systems (ST) are devices that transform concentrated solar irradiation into heat. ST systems have a much greater efficiency than PV systems (Kumar et al., 2022) (U.S. Energy Information Administration, 2024). There are three classifications of ST generators, these being, low-, medium- and high-temperature collectors. Low- and Medium-temperature collectors are used to heat water or air. While high-temperature collectors, otherwise known as concentrated solar power systems (CSP), are used to convert steam into electricity (Bhatia, 2014).

CSP systems function by converting the steam produced from the heated transfer fluid into electrical energy using a turbine engine. The CSP types include, linear concentrating

systems, solar power towers and solar dish/engine systems (U.S. Energy Information Administration, 2024).

Linear Concentrating Systems: are installations that utilise an array of mirrors to focus and capture sunlight, with a huge tube receiver positioned above them to absorb the concentrated sunlight (U.S. Energy Information Administration, 2024) (U.S. Department of Energy, 2024).

Solar Power Towers: are systems which utilise heliostats, which are mirror systems that detect the movement of the sun and redirect and focus sunlight onto a receiver located at the top of a tower (U.S. Energy Information Administration, 2024).

Disk/Engine Systems: are systems which utilise a mirror-based dish to focus sunlight onto an engine. The dish system has the lowest energy output among the several types of high-temperature collecting systems. Having the ability to produce electricity within the range of 3 to 20 kilowatts (U.S. Department of Energy, 2024).

ST systems can come as either mini-grid or standalone systems and can be ground or roof mounted (Murugan et al., 2022) (Tschopp et al., 2020).

As with SPV, the power output potential of an ST system is mainly contingent upon the direct solar irradiation that it is able to receive (Law et al., 2014). The results of testing completed by (Jio et al., 2015) showed that on clear days in July the system held an average of a 37.55% efficiency, however on cloudy days this could reach as low as 15.47% and on overcast days consistently hit 0% rendering the system inoperable. This study however was performed during periods of peak sunlight during July, which can serve as a solid basis for how effective the technology can be, although it does not accurately reflect its limitations. Additional studies have shown that annual efficiency, depending on the CSP type, can range 13-23% (Bhattacharjee et al., 2020) (Mashrur et al., 2023). Furthermore, during the winter the productivity of a ST system can decrease further and even as the study above has shown reach 0% (Solar Guide, 2024).

As with SPV, ST systems are rendered less efficient the higher the ambient temperature becomes, and larger system sizes are required (Buck et al., 2019) (Channaoui et al., 2016). The system further as shown by the studies discussed above are dependant entirely on the amount of sunlight they receive.

3.9.3 Wind

Wind energy systems are a type of power generation that transforms rotational energy from wind into electrical energy. This process involves the construction of a tower with blades, which is subsequently rotated by wind to activate an engine. This allows for the conversion of the kinetic energy from the rotating motion into electrical energy (U.S. Department of Energy, 2018).

The primary impact on the potential power output of a wind system will be the availability, direction and speed of wind (Bashir, 2021), which is clearly abundant in Namibia as discussed in section 3.5. However, the system output is also heavily affected by the radius of the turbine blade and air density (European Wind Energy Association, 2016).

Wind energy systems typically fall within the range of 20W – 100kW power output (U.S. Department of Energy, 2024) (U.S. Energy Information Association, 2023) with an average system being about 35% efficient, although this can be as high as 52% (UIM, 2024).

The major risk to a wind system, particularly in Namibia will be dust particles accumulating on and hitting the system, which both causes breakdown of the system and reduced power output (Khalfallah et al., 2007). An investigation by (Zare et al., 2023) finds that particulate degradation caused a decrease in power output by as much as 4.3%-13.3%. Particulate accumulation can be addressed by regular cleaning and maintenance of the turbines (Khalfallah et al., 2007). Dust impacting the system on the other hand is predominantly combatted by applying protective layers to the turbine during or after the construction in order to strengthen the system against erosion (E.U. Publications Office, 2020) (Dangle, 2023).

3.9.4 Battery Storage

Battery storage is a method used to store energy produced by a system for future use. These systems are especially beneficial for renewable energy sources that have intermittent generating potential, such as wind and solar (National Grid, 2023). For instance, this would enable the collection of sunlight during the day and its utilisation at night, when the generation source is inaccessible (Sanchez et al., 2022). Deployment of battery storage creates greater energy capacity and security (Sayed et al., 2023).

Lithium-ion batteries are currently the dominant form of battery storage used for RES, with an expected lifespan of 5 – 15 years (National Grid, 2024) (Sayed et al., 2023).

The type of battery storage applied will depend upon the type of technology being deployed. In terms of the technologies being considered here, the types of battery storage available will be, thermal and electrical (Sayed et al., 2023).

4 Methodology

4.1 Community Model Creation

The community model is based on real-world data relating to the average Namibian village and its conditions as well as some more region-specific data. Some assumptions have been made, although these should not affect the general principal and outcome of how the RES can best be implemented.

In order to assess the energy production capacity of the region, data such as wind speed, direct normal irradiation, elevation, etc. will use the metrics of the Epinga village (as shown in *fig.13.* & *fig.14.*), although the community data will be based on broader averages.



Figure 13 - Epinga Village on map of Namibia – (Google, 2024)

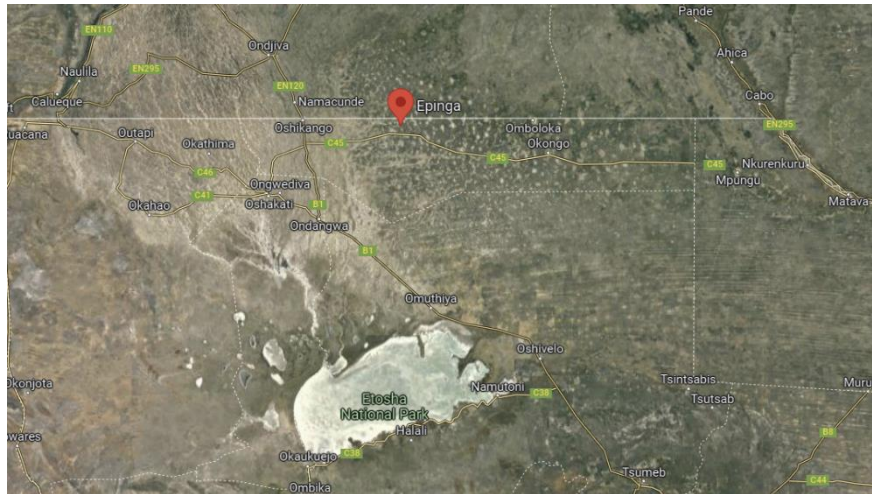


Figure 14 - Epinga Village on map of Northern Namibia – (Google, 2024)

The location of the model is based on a report from (UNDP, 2015) and (CIA, 2022) which states that most of the rural population lives along the central-north, this is evidenced further by geospatial data from (Landscan Global, 2022), *fig.15.*, which shows a concentration in the central-northern area.

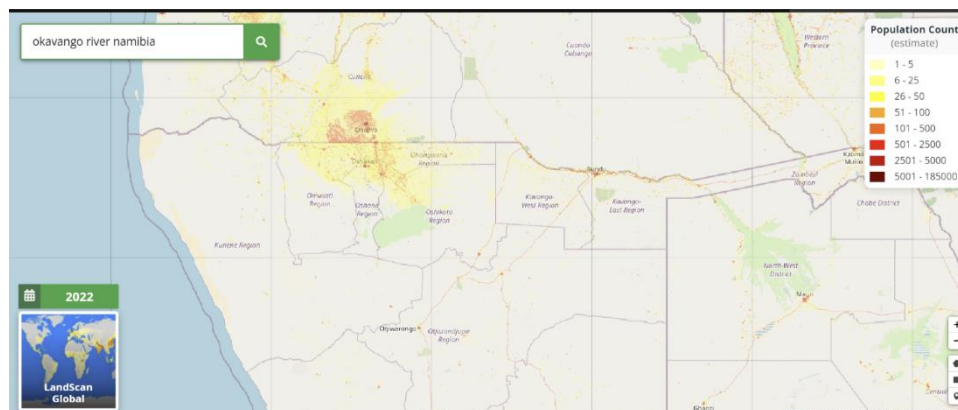


Figure 15 - Population density map of Northern Namibia – (Landscan Global, 2022)

A sample size of 100-inhabitants was chosen as the (Landsan Global, 2022) geospatial data on average displays an approximate population count of between 26 – 100 inhabitants per km² across most of the central-north, particularly as the dispersement tends to the right. There is high rural concentration at the very centre, although as shown in the grid distribution map from (The World Bank 2018), *fig.11.*, this area has grid access and surrounding settlements have lower barriers to grid expansion. An average rural household size of 3.9 was taken from a 2016 report by (The World Bank, 2021) and backed up by 2018 data from

(Batana et al., 2018), while this information is not as current as desired, it can be assumed that due to household size being a typically stable metric, that any change will be negligible, likely only fluctuating between a few decimal places in the 6-year period.

The land type and biome of the Epinga village has been determined using *fig.16 & fig.17.*, from (Shikangalah, 2020).

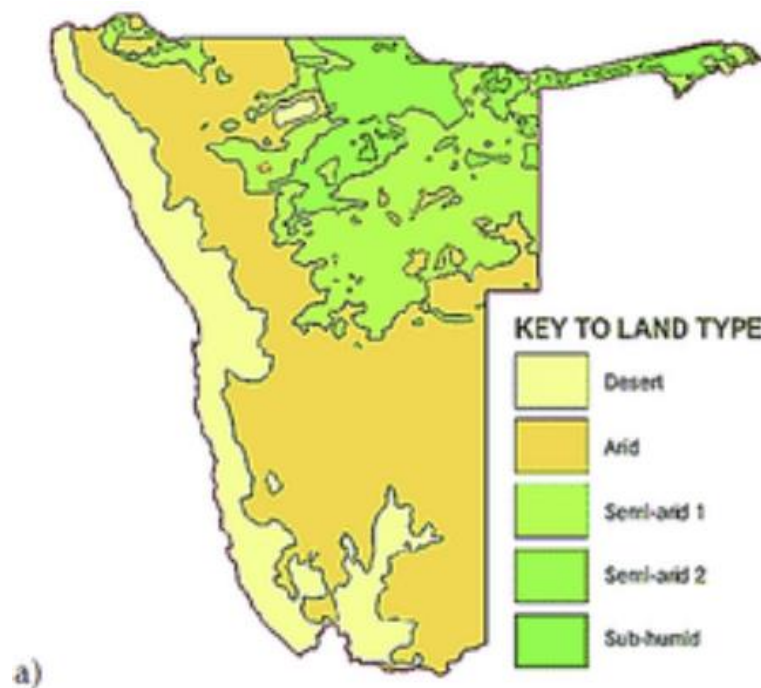


Figure 16 – Map of Namibian land type – (Shikangalah, 2020)

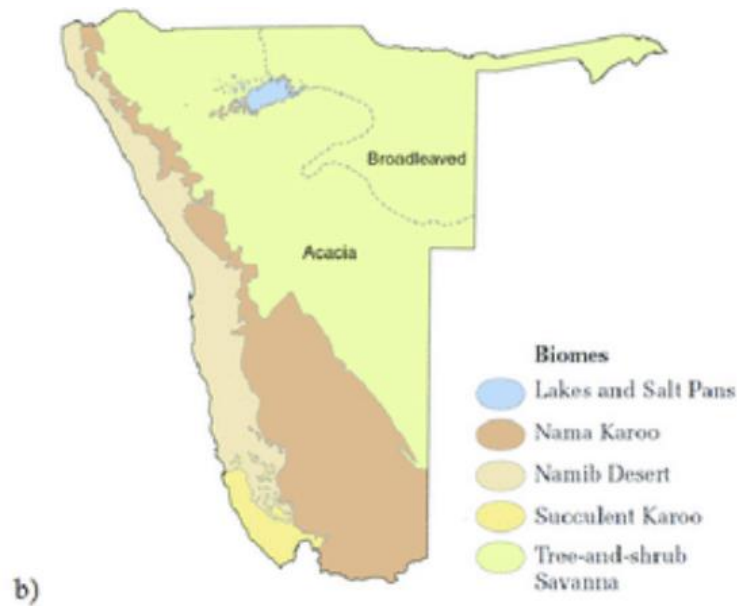


Figure 17 - Map of Namibian biome type – (Shikangalah, 2020)

Current energy fulfilment is a concern of many reports (UNDP, 2015) (Copinschi, 2022) (Mandelli et al., 2014) which highlight the health effects of biomass use as a rural resource, and additionally the degradation of woodland stemming from unrenewable harvesting methods, hence its application to the model.

The potential applications of electricity should ideally expand beyond home usage and encompass many everyday work tasks. For example, certain residential applications, such as lighting, may also prove advantageous in occupational settings. Therefore, it is important to evaluate the industrial application of electrification (Hoeck et al., 2022). The employment rates in the Ohangwena region are significantly low, as evidenced by only 11.5% of the population being engaged in formal employment. The remaining 88.5% of the population comprises individuals who are informally employed (11.6%), vulnerably employed (39.6%), or unemployed (33.3%) (Jaro Consultancy, 2016). However, it should be noted that census statistics may overlook those who are engaged in some type of labour, even if they are not classified as "employed" in the traditional sense (Jaro Consultancy, 2016). The primary mode of labour in these regions is subsistence agriculture, a sector that would greatly benefit from the implementation of RES. Additional significant forms of work include familial caring and trade/production (Jaro Consultancy, 2016), both of which are facilitated by the advantages brought forth by residential electrification.

Average length of day and sunlight has been sourced from (ClimaTemps, 2014) and verified against more up to date information from (Met Office, 2023), using the Namibian capital

Windhoek as the base. The seasonal months were sourced from (Vreugde Guest Farm, 2020) and (Safari Consultants, 2024).

Weather and temperature were determined using historical weather data from (Meteoblue, 2023), *fig.18*, for the year 2022, the data set uses Epinga as its base. In applying this data to the model, it has been assumed that similar patterns occur each year, and that it was not an anomalous year for the weather in 2022.

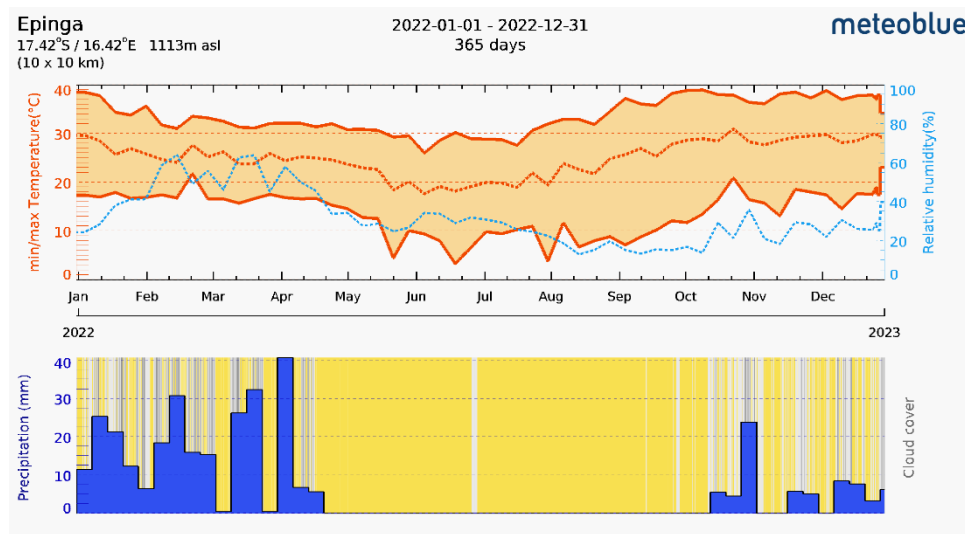


Figure 18 - Temperature and precipitation data for the Epinga village in 2022 – (Meteoblue, 2023)

Wind speed data has been obtained from the Wind Atlas created by (The World Bank, 2023), the data uses the coordinates of the Epinga village as a base, *fig.19*.

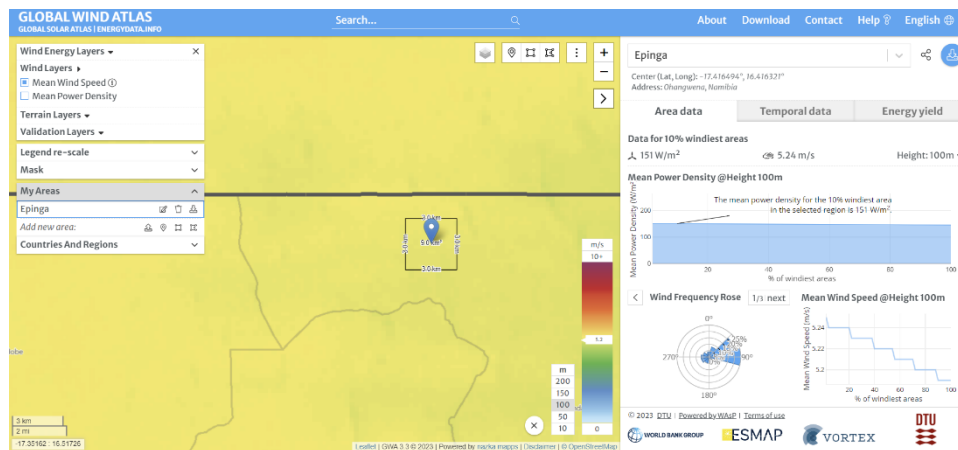


Figure 19 - Wind Atlas with data based on the coordinates of the Epinga Village – (The World Bank, 2023)

4.2 Household and Building Model Creation

4.2.1 Households

A model home consisting of four rooms was created. The home model is largely based on the findings of a study from (Mathee et al., 2021). The research conducted utilises data samples collected from two rural communities in South Africa. Although this study does not specifically focus on Namibia, it is reasonable to infer that given the geographical proximity and comparable levels of poverty between the two nations, it is justifiable to use certain aspects of this data.

The homes examined in the study sometimes had a greater number of internal rooms compared to the model, ranging from 2 – 6 rooms, with a median of four. Likewise, there was typically a median of one external room, which encompassed either a bathroom, bedroom, or kitchen. It would be unjustifiable to make the assumption that a rural household possesses exterior rooms only based on the findings of this study, given that the Jouberton village did not exhibit this characteristic, having a median of zero external rooms. Given this, it is plausible that there could be an overestimation of electricity demand if external rooms are assumed, which could result in escalated expenses and the implementation of generator systems that exceed the necessary capacity.

The inclusion of pit latrines was considered as a method to evaluate potential enhancements to sanitation within the village. According to the research conducted by (Mathee et al., 2021), a significant proportion (45%) of households only have access to restrooms that are located outside of their homes. However, the report does not provide clarification concerning the privacy of these external toilets for the occupants of the households. Hence, in order to

enhance the model's simplicity, the households within the model lack any indoor toilet amenities. Although they include a basic bathroom as only 10% of these were found to be external to homes, implying that bathrooms and toilets have separate rooms in rural communities. The objective of this is to simplify the analysis process by focusing just on electrification, rather than introducing complexities associated with studying toilets inside a residential setting. The intention is to minimise costs and potential issues when assessing the impact of electrification. Additionally, it is worth noting that pit latrines are the most prevalent form of toilet facility in rural areas (Nakagiri et al., 2015).

Study findings revealed that 95% of the homes were built using brick and mortar, while 81% had corrugated metal roofs (Mathee et al., 2021). Consequently, these materials have been applied to the model homes.

4.2.2 Primary School

Namibia holds a commendable level of primary school enrolment, boasting an impressive rate of 97% enrolment (The World Bank, 2018). Hence, it is reasonable to incorporate a primary school into the model. The primary school in the village does not possess a huge capacity due to the small population size of the village, which stands at only 100 residents. The presence of insufficient personnel in rural primary schools serves as a reflection of the prevalent problem of understaffing, wherein there is a scarcity of teachers (Iilonga, 2016). Further, there is typically a large problem with underfunding from the state making acquiring additional staff more unlikely (Du Plessis et al., 2019).

4.2.3 Medical Facility

The healthcare system in the Ohangwena region of Namibia is currently facing significant challenges, particularly in terms of its doctor-patient ratio, which stands at a concerning figure of 22,144 patients per doctor (Van Rooy et al., 2015). Generally, most of the population (76%) live within a 10km distance of a healthcare facility (Christians, 2020), although this does not necessarily mean rural inhabitants have adequate or even any access, as this statistic is likely skewed by those living in and around urban areas. Despite the limited availability of healthcare facilities in the region, a healthcare facility has been incorporated into the model to evaluate the potential impact of energy generation on its operations. The implications of the research can be extrapolated to encompass the entirety of Namibia, without requiring special regional considerations.

4.2.4 Church

A church was added to the model in response to Namibia's Christian population, which constitutes 97.5% of the total population (CIA, 2022). Epinga, which has been used as a base for much of the village data, was a former Anglican mission (Timm, 1996), making it likely a rural village such as this would have reasonable church capacity. This church serves as a significant communal centre and provides further opportunity to analyse the advantages of electrification. Considering the dynamic character of the church, it is crucial to establish appropriate contingency to account for the variability of weekly meetings and events.

4.3 Electricity Demand Calculation

In order to ascertain the electricity demand inside the village, it will be necessary to establish a set of assumptions pertaining to the desired utilisation of electrical power. Some data such as peak demand may be averaged from national data, by comparison to electrified urban and rural communities. The consideration of contingency is necessary to accommodate population growth and facilitate community development. Additionally, there exists the potential risk of an abrupt and unnatural surge in community growth due to migration from neighbouring localities seeking access to the electricity supply. Assumptions will be required with respect to the categorisation of appliances and the anticipated length of their usage. It is advisable to also take into account the energy efficiency of appliances, as unless they are directly provided to the community through external sources such as charitable organisations, it is probable that this equipment will be second-hand and outdated in terms of energy efficiency (WWF, 2015) (Dagnachew et al., 2017).

The approach for calculating energy use is based on (Hankins, 1991).

4.3.1 Household Electricity Demand

Furthermore, for the purpose of additional simplification, it is assumed that all homes are identical in nature and possess comparable electrical requirements. In practise, it is challenging to correctly predict the varied electrical demands of an actual village. Therefore, it is more suitable to employ an assumed average requirement, as attempting to estimate the precise needs of individual hypothetical households would be impractical. While acknowledging the existence of some variance among homes, the model simplifies the analysis by assuming uniformity across all homes.

4.3.2 Household Applications

It has been assumed that the primary uses of electricity in the village will be; lightbulbs, an outdoor lamp, a desk lamp, an electronic fan, a fridge-freezer, a cooker, and a radio. The appliances have been partially based on data from (AFRE, 2024).

The applications considered for demand estimation are those that are necessary for enhancing the overall standard of living, as opposed to applications that primarily provide recreational value, such as a television. The model assumes that there is an absence of sufficient groundwater infrastructure, as it frequently coincides with the availability of electricity (Chakravorty, 2022). Therefore, the model does not encompass applications such as central heating and washing machines. It could be argued that this consideration should be incorporated into the contingency. Nevertheless, there is insufficient empirical evidence to suggest that the implementation of the system will guarantee its availability. The primary emphasis of this study lies in evaluating the immediate and quantifiable advantages of RES, as opposed to speculative long-term benefits.

Obtaining historical data on the efficiency of old appliances proved to be rather challenging while doing estimates. Consequently, the energy efficiency metric was derived from a combination of the lowest-rated and cheapest equipment currently available at Currys. When contemplating the implementation of this project, it is important to take into account the time required for its execution in the village. This is because the existing products currently accessible would gradually become obsolete, hence increasing the likelihood that those analysed would align more closely with the appliances owned by the community. There also exists a significant likelihood that the currently available items may already be old and lacking in efficiency, similar to those that the community would utilise.

Lighting

Data from the study (Dominguez et al., 2021) was used to estimate the efficiency and duration of lightbulb use. Further it was assumed, for simplicity, that there is only one ceiling fixed lightbulb per room. In regard to the desk lamp, it has been simply assumed that since a large portion of labour in the village will be production based, textiles, etc. that there will be a need for a desk lamp, it has further been assumed that between cooking and familial caregiving responsibilities, that the homemaker will operate on roughly an 8-hour working day. Data from (International Labour Organisation, 2023) found that 53% of textile workers work for at least 8 hours a day, verifying this assumption. The desk lamp efficiency has been derived from (Dominguez et al., 2021).

Electric Heater and Fan

For heating and cooling, the temperature data included in the model from references (Meteoblue, 2023) and (Met Office, 2023) suggests that an electric fan will be desired during the daytime hours of 11:00-18:00. It may be reasonably inferred that a significant number of households residing in rural communities engage in various activities within their premises throughout the majority of the day, thus necessitating the use of a fan during these hours.

An electric heater was considered for the model, however it was so grossly inefficient as a heating method, it was decided against. Based on findings from (Currys, 2024) it would take 18-kWh per-home daily to use for heating.

The fan efficiency is derived from (Currys, 2024).

Radio

Given the low power consumption of a radio, it has been assumed that it may run continuously throughout the day. Consequently, any potential overestimation of power usage is expected to have minimal impact. The energy efficiency was derived from a UK Government published report (Department for Culture, Media and Sport, 2013).

Cooking

From study (Jagoe et al., 2020), it has been shown that women spend an average of 285-minutes per-day cooking when given electric stoves. The energy efficiency of the oven-and-hob cooker was derived from (Currys, 2024).

Fridge-Freezer

The duration of the fridge freezers use is 24-hours as it is a continually powered device. The energy efficiency was derived from (Currys, 2024).

4.3.3 Primary School Applications

When evaluating the energy demand of the primary school, two crucial assumptions have been made that will impact the computations. One notable aspect is that the educational

institution observes approximately 60 days of holiday throughout the year, resulting in the annual electricity consumption calculations being limited to 305 operational days.

Additionally, it is worth noting that certain equipment, such as the fridge-freezer, exhibit higher levels of efficiency due to the anticipated allocation of government funds.

The fundamental appliances that are presumed necessary for schools are those that enhance the quality of education while recognising the constraints associated with limited access to energy. The educational institution will possess sufficient capacity to accommodate lighting, computer systems, electrical fans, and catering equipment.

There is an assumption that certain appliances will be utilised moderately, whereas others will be utilised during the entirety of the school day. The projected length of the cooker was based on the assumption that households normally prepare two meals per day, however in a school setting, only one meal is likely to be cooked. Therefore, the estimated time for cooking in a school setting is decreased by half of the time spent on food preparation at home. The true time of use for each appliance can only be purely speculative, and extra contingency may be appropriate.

Data regarding the efficiency of appliances was derived from, (Dominguez et al., 2021), (Currys, 2024).

4.3.4 Medical Facility Applications

Firstly, it is assumed that the medical facility is open for 10 hours each day, and due to the dynamic nature of a clinic, each piece of equipment may be required for the entirety of it.

4.3.5 Church Applications

Data regarding the appliances in the church is based survey data collected from Mount Pleasant Baptist Church, Swansea. Due to the similar capacity levels, it was assumed that data such as number of lightbulbs in each section of room, meeting frequency, etc. was comparable and applicable to the model.

Some level of error will be likely present in terms of energy consumption, the large hall at the church surveyed contained 20 lights, however these will not be used much throughout the week and are mainly only used for Sunday services, therefore, to factor this in the lighting has been categorised by room. Even so, there still will likely be some level of error and there may be increased use in the future so it may be argued that allowing for full operational capacity in the event that they were functional daily is more appropriate.

In order to ensure a balanced calculation, it is assumed that the main hall experiences approximately five hours of lightbulb utilisation per day, or one out of two days throughout a two-day period. It is assumed that the pastor's office is potentially utilised throughout the entire day without any time restrictions, whereas the small hall experiences a higher frequency of usage and may be used during full operational hours.

Survey data collected which was applied to the model can be seen in, *table 1*, below. The full survey conducted can be found in Appendix B.

Table 1 - Survey Data used in Model - Mount Pleasant Baptist Church Swansea

ROOM	NO. OF LIGHBULBS PRESENT	AVERAGE DURATION OF DAILY USE (HOURS)	SIZE (m ²)	MAX. CAPACITY
MAIN HALL	20	5	286	400
SMALL HALL	6	8	195.5	100
OFFICE	1	8	15.75	8

When comparing the capacity of the church to the size of the village, it may be considered that the capacity is over the necessary requirements of the village. It should be noted however that within the church surveyed the capacity of the main hall is split between an upper and lower level with equal capacity. These levels utilise the same lights and so in applying a single floor church within the model, the same amount of lighting is required to serve a capacity of 200. According to (Sharma, 2024) the Church Events Manager for Mount Pleasant Baptist Church, the capacity given for the church, is the absolute maximum each room can accommodate rather than an accurate reflection of the number of people who generally occupy a room at any one time. Therefore, it was considered appropriate to use the lighting survey data within the model in order to gain a realistic basis for how many lights a church will typically require.

4.3.6 Safety Factor

To accommodate the various unforeseeable situations that may arise and result in an increase in electricity consumption, a safety margin of 20% was incorporated into the electricity demand. This safety factor will compensate for any potential miscalculation, while

also providing capacity for delivery to other nearby communities and future population expansion.

4.3.7 Room Size

With in the model, terms which can be considered relative and ambiguous are used to describe the size of the rooms in relation to how many lightbulbs they will require. Therefore, it is important to define the size of the rooms mentioned here.

For the households the room size is defined based upon the UK average, while this may not be the most accurate representation, there is little reliable data available that would indicate the approximate average size of the village homes. The household rooms can therefore be defined as, a large room of size $17m^2$, a medium sized room of $13m^2$, and a small sized room of $6m^2$ (Statista, 2024) (Chard, 2024).

The dimensions of the rooms in the Church are based upon data gathered during a site visit to Mount Pleasant Baptist Church, Swansea. The dimensions data of each room was collected by measuring the area in square metres using a measuring tape and verified against available blueprints from (Swansea Council, 2022). From this it was determined that the main hall has a size of $286m^2$, the small hall had a size of $195.5m^2$, and the office had a size of $15.75m^2$.

A discussion with (Rev. Martyn, 2023) of Mount Pleasant Baptist Church, informed that the room used as a basis for the small hall included in the model used to be used as a school room, and from the book 'The Hafod, 1920's – 1950's' (The Hafod History Society, 1996), it was able to be verified that this was the case between 1866 and 1975. It was therefore decided that it was appropriate to assume that the size of the church rooms can be applied to the primary school and further the medical facility, due to the similar daily uses and applications of the rooms.

Therefore, in the model where a room (except in the case of households) is referred to as small, medium, or large, the dimensions are assumed to be the same as those of the church building, with large, being the main hall, medium, being the small hall, and small, being the office.

4.4 Estimated System Cost

To calculate the overall system cost for a ground-mounted 58kW solar system with 12kW battery storage, a combination of factors were considered. These being, the average cost of

similar components and other average cost estimates, of both the components themselves and costs per kW output. It should be noted that an exact cost estimate will be hard to accurately predict, and that the overall system cost is intended to give an idea of the expected cost or range of cost that the system should fall within.

One issue that may present itself in cost calculations, is regionality, between different nations there is often some variability in the cost of technologies and therefore the final cost estimate should be understood as such.

The cost of the SPV system is based on UK Government estimates (GOV UK, 2023), which state median prices for a 10-50kW system of around £1016/kW for the year 2021-2022. This estimate increases costs above the global estimated average of £39,034 for a SPV system cost of £58,928. Although it should be noted that this global average is based on costs for utility-scale SPV.

Data pertaining to the calculation of the SPV system came from (Mandys et al., 2023) (IRENA, 2022) (GOV UK, 2020) (GOV UK, 2023).

The average cost of battery storage is around £437.83/kWh, therefore totalling £5253.96 for a 12kW system. This estimated price is comparable to those by regional UK manufacturers offering lithium-ion battery storage systems (Dragons Breath Solar, 2024) (Eco Wizard, 2024) (Garden Furniture Centre, 2024).

Data pertaining to the calculation of the battery storage came from (IRENA, 2022) (Cole and Karmakar, 2023) (Mongird et al., 2020) (EIA, 2021)

5 Community Model

5.1 Specification

5.1.1 Village Specification

The community is situated in the northern-central Ohangwena region below the northern-central border of Namibia and Angola. There are 100 inhabitants within the village making up 26 households. The village sits on semi-arid land classified as having a tree-and-shrub Savannah biome.

Similar to most rural villages there is no access to electricity and grid connection is unavailable, with expansion unlikely in the near future. Fulfilling basic energy needs (lighting, cooking, etc.) currently requires the use of waste and biomass, which is leading to detrimental health effects (namely to women and children), alongside deforestation due to improper biomass harvesting. As expected, the community does not have proper access to modern services and facilities as a result of non-existent electrification.

The village possesses adequate access to a modest health clinic, a primary school, and a church, all of which are presently lacking access to electrical power.

In the community, the predominant means of labour encompass a blend of subsistence agriculture, familial caregiving, and self-employment, particularly in sectors such as textile production and trade. The majority of residents typically engage in familial employment, fulfilling various subsistence-related responsibilities.

The average length of day is 12-hours, varying moderately season-to-season. The average sunlight hours however are 9-hours and 52-minutes. The peak length of day occurs in December, during Namibia's spring and summer months (October – March), where days last ~13-hours 29-minutes, and the shortest days during the autumn and winter (April – September) lasting ~10-hours 46-minutes. The reverse of the expected trend appears as the longest sunlight hours transpire during the winter and the shortest during the summer, peaking at an average of 11-hours per-day in August and falling to 8-hours 59-minutes in February.

The year-round temperature ranges exhibit consistently elevated levels. The temperature ranges hit their peak values in October, with fluctuations spanning from 12°C to 39°C, while they reach their minimum values in August, oscillating between 4°C and 32°C. Throughout most of the year, the minimum temperatures persist above 10°C, occasionally fluctuating throughout the winter season, yet consistently remaining above 0°C. Even in the most frigid winter months, temperatures can still reach a maximum of 30°C, while during the height of

summer, they can reach up to 40°C. The mean temperature throughout the year has a high degree of stability, typically fluctuating within the range of 18°C to 31°C during the day.

The village experiences bi-annual weather patterns, characterised by a rainy season that mainly occurs throughout the spring and summer months, spanning from around mid-October to mid-April. During the month of May and throughout the winter season, there is a notable decrease in precipitation, reaching almost zero, accompanied by minimal cloud cover. During this particular time frame, solar radiation reaches its maximum intensity.

Wind speed averages 5.24 m/s, remaining consistent throughout all seasons, with a mean power density of 151 W/m² at a hub elevation of 100m. There is a substantial and sufficient source of wind for efficient energy generation.

5.1.2 Household and Building Specification

Homes in the village are very basic, comprising of one large room that the household occupy as a main living and working area, one medium-sized room acting as a kitchen, one medium-sized room as a family bedroom, and one further small room which acts as a bathroom (with no toilet). Homes are constructed of brick and mortar and have corrugated iron roofs. At present, none of the residences are equipped with electrical power.

5.1.3 Primary School

The primary school in the community consists of two medium sized classrooms and a spacious large hall that serves as both an assembly area and a dining hall, which receives large amounts of natural lighting. The school's current workforce comprises 5 personnel, including 2 teachers, a principal, a custodian, and a cleaner/cook.

5.1.4 Medical Facility

The healthcare facility is characterised by a scarcity of resources, including a limited number of medical professionals and constrained availability of pharmaceutical supplies. The facility has limited capacity, necessitating the recruitment of healthcare staff from more highly educated urban regions. The limited availability of rural healthcare facilities means that residents from nearby villages frequently visit the clinic seeking aid. Consequently, this influx of patients places additional strain on the healthcare service, resulting in further constraints on its capacity and longer waiting periods. The medical facility consists of three

small doctors' offices, a medium sized waiting room with a reception area, and a medium sized dispensary.

5.1.5 Church

The village church was constructed as part of a former Anglican mission. The church has a maximum capacity of 200 within a large main hall, 100 within a small secondary hall and 8 within pastor's office. The community regularly gather here during the week for various events and meetings and on Sundays for a morning and evening service.

5.2 Electricity Demand

5.2.1 Households

Table 2 - Estimated Average Energy Demand of Rural Households - Appliances and Duration of Use

APPLIANCE	ESTIMATED DURATION OF USAGE (HOURS)	ESTIMATED RATING (W)	AVERAGE NO. PRESENT IN HOUSEHOLD
LIGHTBULB	4	60	4
DESK LAMP	8	60	1
OUTDOOR LAMP	6.2	60	1
ELECTRONIC FAN	7	21	1
RADIO	12	3.75	1
FRIDGE-FREEZER	24	50	1
COOKER	4.75	730	1

Table 3 - Estimated Average Energy Demand of Rural Households – Daily and Annual

APPLIANCE	ELECTRICITY CONSUMPTION RATE (KWH)	DAILY ELECTRICITY CONSUMPTION (PER HOUSEHOLD – KWH)	ANNUAL ELECTRICITY CONSUMPTION (PER HOUSEHOLD - KWH)	ANNUAL ELECTRICITY CONSUMPTION (VILLAGE TOTAL - KWH)
LIGHTBULB	0.06	0.96	350.4	9110.4
DESK LAMP	0.06	0.48	175.2	4555.2
OUTDOOR LAMP	0.06	0.372	135.78	3530.28
ELECTRIC FAN	0.021	0.147	53.655	1395.03
RADIO	0.00375	0.045	16.425	427.05
FRIDGE-FREEZER	0.05	1.2	438	11,388
COOKER	0.73	3.4675	1265.6375	32,906.575

5.2.2 Primary School

Table 4 - Estimated Average Energy Demand of Rural Primary School - Appliances and Duration of Use

APPLIANCE	ESTIMATED DAILY USAGE (HOURS)	ESTIMATED RATING (W)	AVERAGE NUMBER PRESENT
LIGHTBULB	6	60	12
DESK LAMP	2	60	2
COMPUTER	2	65	4
ELECTRIC FAN	6	21	4
FRIDGE-FREEZER	24	24	2
COOKER	2.375	730	2

Table 5 - Estimated Average Energy Demand of Rural Primary School – Daily and Annual

APPLIANCE	ELECTRICITY CONSUMPTION RATE (KWH)	DAILY ELECTRICITY CONSUMPTION (KWH)	ANNUAL ELECTRICITY CONSUMPTION (KWH)
LIGHTBULB	0.06	4.32	1317.6
DESK LAMP	0.06	0.24	73.2
COMPUTER	0.065	0.52	158.6
ELECTRIC FAN	0.021	0.504	153.72
FRIDGE-FREEZER	0.024	1.152	351.36
COOKER	0.73	3.4675	1057.5875

5.2.3 Medical Facility

Table 6 - Estimated Average Energy Demand of Rural Medical Facility - Appliances and Duration of Use

APPLIANCE	ESTIMATED DAILY USAGE (HOURS)	ESTIMATED RATING (W)	AVERAGE NUMBER PRESENT
LIGHTBULB	10	60	10
DESK LAMP	10	60	3
COMPUTER	10	65	5
ELECTRIC FAN	10	21	5
FRIDGE	24	20	3

Table 7 - Estimated Average Energy Demand of Rural Medical Facility - Daily and Annual

APPLIANCE	ELECTRICITY CONSUMPTION RATE (KWH)	DAILY ELECTRICITY CONSUMPTION (KWH)	ANNUAL ELECTRICITY CONSUMPTION (KWH)
LIGHTBULB	0.06	6	2190
DESK LAMP	0.06	1.8	657
COMPUTER	0.065	3.25	1186.25
ELECTRIC FAN	0.021	1.05	383.25
FRIDGE	0.02	1.44	525.6

5.2.4 Church

Table 8 - Estimated Average Energy Demand of Rural Church - Appliances and Duration of Use

APPLIANCE	ESTIMATED DAILY USAGE (HOURS)	ESTIMATED RATING (W)	AVERAGE NUMBER PRESENT
MAIN HALL LIGHTBULBS	5	60	20
OFFICE LIGHTBULBS	8	60	1
SMALL HALL LIGHTBULBS	8	60	6
DESK LAMP	8	60	1
COMPUTER	4	65	1
ELECTRIC FAN	8	21	4
KETTLE	0.5	2200	1
FRIDGE	24	20	1

Table 9 - Estimated Average Energy Demand of Rural Church - Daily and Annual

APPLIANCE	ELECTRICITY CONSUMPTION RATE (KWH)	DAILY ELECTRICITY CONSUMPTION (KWH)	ANNUAL ELECTRICITY CONSUMPTION (KWH)
MAIN HALL LIGHTBULBS	0.06	6	2190
OFFICE LIGHTBULBS	0.06	0.48	175.2
SMALL HALL LIGHTBULBS	0.06	2.88	1051.2
DESK LAMP	0.06	0.48	175.2
COMPUTER	0.065	0.26	94.9
ELECTRIC FAN	0.021	0.672	245.28
KETTLE	2.2	1.1	401.5
FRIDGE	0.02	0.48	175.2

5.2.5 Total Demand

Table 10 - Estimated Total Energy Demand of Rural Village - Daily and Annual

	DAILY ENERGY CONSUMPTION (KWH)	ANNUAL ENERGY CONSUMPTION (KWH)
HOUSEHOLD	173.46	63,312.54
PRIMARY SCHOOL	10.2	3112.07
MEDICAL FACILITY	13.54	4942.1
CHURCH	12.35	4508.48
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TOTAL	209.55	75,875.19
WITH SAFETY MARGIN	251.46	91,050.23

6 Energy System

6.1 Optimal Generation Source

To determine the optimal generation system there are some important considerations to be made between each of the potential systems. These include but are not limited to, system type, lifespan, output capacity and to some extent cost.

6.2 System Type

Based on the literature review, it can be concluded that the most suitable system type for the village would be a mini-grid system, with this applying to both the solar and wind options.

For a SPV or ST system, the study (Mathee et al., 2021) has shown that standalone home generation systems are not feasible due to the prevalence of partly missing or insecure corrugated iron roofs in the average residence, as well as the homes themselves generally being unstably constructed. Consequently, affixing a standalone generation system to such roofs or other areas of the household, would not be appropriate. Another possibility for the solar systems would be the use of Pico systems, however due to these applying to individual appliances, it would require appliances to be purchased for the community and would not provide a local source of electricity generation. This may again not be considered the most appropriate solution.

In terms of a wind system, a roof mounted system would simply not be able to produce enough electricity to meet demand, they may be feasible in an isolated instance, for example on the school roof, but application to individual buildings village wide does not seem an appropriate option. As previously discussed, the homes themselves would likely not be able to support such a system and would be at risk of damage or collapse, rendering the home uninhabitable and the system inactive. Further, deploying individual systems would complicate operational and maintenance procedures, compared to having a centralised mini-grid system.

Using a mini-grid system will provide a centralised source of electricity generation that can be distributed across the area. Centralising the energy generation will reduce the complications of operation and maintenance, as if systems were standalone, it may be contended that the home occupiers would be at least partially responsible for these activities. Of which they will likely have little to no knowledge, which may potentially cause system damage or breakdown due to improper maintenance or neglect.

6.3 Solar PV

The two major problems that a solar system will face in the village will be, dust and ambient temperature. This can be known to be an issue from the climate and weather data gathered. However, despite this, it can be assumed that with correct maintenance procedures, that these issues can be overcome.

Given the persistent high temperatures and the ongoing rise in rates caused by climate change, a SPV system may not be the optimal choice for the community. If a larger system were to be acquired, it may be assumed that any drop in efficiency would be insignificant given the demand levels. However, this would substantially raise the deployment costs. The threshold for decreased efficiency begins at 25°C. On an average day, temperatures do go below this threshold. However, most of this decrease occurs during the evening and night hours when sunlight is at its lowest and cannot be effectively utilised.

When calculating the system size requirement to meet energy demands, the efficiency loss will need to be factored in (Narkwatchara et al., 2020). This can be tricky due to the high losses experienced, sometimes reaching as much as 92.5%. It may be optimal to ensure that capacity is always able to meet energy demands even at the maximum level of inefficiency. Any excess power generated during periods of higher efficiency, could potentially be stored as backup or distributed to neighbouring villages. Although if energy demands are high, considering there will likely be growth within the community during the lifespan of the system, there may not be sufficient generation available to store ample energy for periods where sunlight is not available, whether this occurs initially or later. The inefficiencies experienced due to high ambient temperatures will cause the system size to be significantly increased, perhaps as much as double, even when assuming a maximum average SPV efficiency of 20%. Consequently, this also increases costs of system purchase and deployment.

Based on the power output model from (The World Bank, 2023), to meet energy demands a 50kWp system will be needed. In the methodology section of the model, it is stated that the model uses air temperature data in order to account for system inefficiencies in the calculation. It is not clear however what temperature data is being utilised. In the setup section it seems to imply that the temperature is assumed to be linearly 23.4°C, in which case, does not accurately reflect the system inefficiencies that will be experienced. From the literature review it was concluded that the cut-in temperature for system inefficiency is 25°C, from the weather data it can be known that in a typical day the temperature will exceed this, especially during the peak sunlight hours where the PV system will be most active. In order to verify these results further calculations will be necessary.

If it is to be assumed that the desired system capacity will be such that it can continually output at full capacity during its expected maximum inefficiency, then the system size will undoubtedly be greater than 50kWp. The methodology employed is based on methods used in (Unbound Solar, 2020) (Khamisani et al., 2018) and (NLRE, 2023).

To determine the system size required the following equations were used:

$$(Daily\ kWh \div average\ sunlight\ hours) \times System\ Loss = Required\ System\ Size$$

$$(251.46 \div 9.52) \times 1.14 = 30.11\ kW$$

Equation 6-1

In order to meet energy requirements a system size of 30.11 kW would be needed in an ideal scenario; however, this does not factor in the inefficiencies experienced by the system as a result of temperature.

$$Required\ System\ Size \times Temperature\ Loss = True\ Required\ System\ Size$$

$$30.11 \times 1.925 = 57.96\ kW$$

Equation 6-2

It is difficult to accurately determine what the true output capacity of the system will be due to the varying temperature and its harsh effect on power production. If a system size were to be deployed based on providing full production capacity at the maximum level of inefficiency, its size would need to be around 58 kW. The analytical results calculated are only slightly higher than the 50kW that the (The World Bank, 2023) model predicted, therefore it is fair to assume that these results are accurate.

For a standard large-scale 58 kW PV system, total installation costs will be in the range of £26,042-£90,306 at cost of £449-£1557/kW. Although the average global total installation costs fall at approximately £673/kW, pricing an average system at £39,034 (Mandys et al., 2023) (IRENA, 2022) (GOV UK, 2020). Some data used for determining the system installation cost is intended for utility-scale projects of 1MW or higher. In determining the cost, it is hard to find accurate information pertaining to smaller scale projects, although some less reliable resources, mainly regional PV manufacturers, such as (Ecopreneurist, 2023) (Sykes, 2023) (UK Solar Power Panels, 2021) and (Business Solar UK, 2024) state

average prices that fall within the estimated range, so it may be fair to assume that the cost is expected within the range, average price on the other hand may not be too accurate as the prices indicated by these sources, suggest that costs will be on the upper end of the range, around £40,000 - £66,000.

Generally, a SPV system can be expected to have a lifespan of around 25 years (Chowdhury, et al., 2020) (Rahman, et al., 2023), where they can operate at the full installed capacity without degradation provided the correct maintenance procedures are followed (Tasnim, et al., 2022). Although it should be noted that the actual lifespan of a SPV system can be far greater, although optimal performance will not be achieved (Lee and Jang, 2023).

6.4 Solar Thermal

For the purposes of this project, a low- or medium-temperature ST system will not be considered. Insufficient evidence exists to support the presence of a reliable water supply in the region, which would be necessary for the implementation of a solar water heater and to thereby justify the investment. By use of the electrical appliances available to the community, the village will have the possibility, albeit potentially less conveniently, to obtain heated water. Introducing a ST system would result in the inclusion of an additional energy system alongside the existing power generation system. This would lead to a substantial increase in expenses, as the village would essentially have two energy systems in place, of which the electricity generation system would already be a means by which to acquire heated water.

CSP thermal systems used for electricity production tend to come in large scale configurations, with the smallest systems producing 1MW (Channaoui et al., 2016) (Carbon Trust, 2013) (Kee et al., 2023), far outside of the scope of this project and requirements of the village. Some CSP technologies may seem an appropriate solution such as the more modest dish and engine systems, which can produce between 5 – 25W per dish (Office of Energy and Efficiency and Renewable Energy, 2024), although amongst the entire CSP configuration the overall system output will still be far greater than necessary, with small systems still producing upwards of 1MW (Channaoui et al., 2016) (Kee et al., 2023). For a wider-scale project, it may be found as an appropriate solution. For example, in a multi-village project considering a centralised generation system for wider power distribution.

CSP is also a very expensive technology with a volatile installation cost. As of 2022 the average global installation costs were upwards of £3,000,000 (Statista, 2024) (Cubero, 2023).

As with SPV the impact of dust will be a dominant issue which will need to be addressed, although provided the correct maintenance procedures are followed, the impact to the system should be able to remain minimal.

6.5 Wind

Meeting the energy requirements of the village using wind will require the use of a system rated at a minimum of 40kW, and ideally a system rating of 50kW in order to account for further safety margin and capacity for growth. A 50kW wind system is expected to be able to generate approximately 60,000 – 250,000 kWh per year (Endurance Wind Power, n.d.) (Earthmill, 2024). On average the hub elevation tends to be around 25-35m between the various models available (U.S. Department of Energy, 2024) (U.S. Energy Information Association, 2023) (Endurance Wind Power, n.d.). Further data from (The World Bank, 2023) reveals that at an elevation of 25m, wind speed averages 4m/s. Data pertaining to various models available at this wind speed estimate that the turbine should be capable of producing around 60,000kWh annually (Endurance Wind Power, n.d.). In order to meet the requirements of the village using these system sizes, it would be necessary to deploy multiple systems. While this excess capacity may seem to be a drawback to implementation, there is potential for power redistribution to other nearby villages, in the short to medium term future, provided that this does not cut access to supply for the primary village.

Alternatively, however, there may be a case for selecting a larger system size, as maintaining, operating and purchasing one system will likely be more cost effective than a single system. This may also come with an increased hub height and therefore a faster wind speed, meaning that the system may have a greater overall efficiency. A 100kW turbine for example, would also stand on average at 25m elevation and be able to output approximately 100,000 – 220,000kWh per year (Earthmill, 2024) (Bauer, 2024) (Renewables First, 2024). The viability of deploying a 100kW turbine, will require the model to be carefully selected. Some models have relatively low cut in wind speeds around 2.5-3m/s (Earthmill, 2024) (Bauer, 2024), whilst others can be as high as 4.5m/s (Bauer, 2024), which is outside the range of the village's average wind speed.

A 100kW turbine could cost around £60,000 – £144,000 for the base unit and around £2750 - £9,000 annually to operate and maintain (Benn, 2023) (McCabe et al., 2022).

The main issue which a wind system will face, will be dust impacting the system, causing erosion long term. The main way this is combatted is by adding protective layers to the outer material of the turbine, although this is likely to increase capital purchase costs. Additionally,

accumulation of dust will impact the system, although as with SPV, this can be addressed with simple regular maintenance.

On average an onshore wind turbine can be expected to have a lifespan of approximately 20 years (Beauson et al., 2021) (Ziegler et al., 2018).

6.6 Battery Storage

Due to the intermittency of renewable power sources, battery storage will likely be an essential component of the system design. For a single generator system, it will be necessary in order to provide a stable supply of energy during the off-peak periods, typically either summer or winter, depending on the resource being harnessed.

While there is no way to definitively define how much battery storage should be used, in general, as needs vary based on individual projects, studies tend to suggest that a good margin of safety is around 10-20% of the total installed capacity (Zhang et al., 2023) (Ruhnau et al., 2022). Therefore, rendering the battery capacity around 10kW – 20kW. Although this will require consideration for the resources hours of productivity to determine when battery storage will need to be utilised, and therefore the amount of storage required.

The predominant source of RES battery storage is lithium-ion batteries (Huang and Li, 2022), hence the system will employ this technology.

6.6.1 Solar PV

The size of the storage system is likely to vary considerably depending on the generation system deployed. For the SPV system, sunlight is very active year-round, although there are drops in productivity, the lowest amount of sunlight received in the year is during February at an average 8 hours 59 minutes.

$$\text{Daily Output (kWh)} = \text{Wattage (W)} \times \text{Sunlight Hours} \div 2$$

$$58,000 \times 9 \div 2 = 261 \text{ kWh}$$

Equation 6-3

Assuming a 58kW system is used, at the daily electricity requirement of 256.41kWh, the system should be able to produce approximately 261kWh. The above methodology is based

on (Exeo Energy Ltd., 2023) (Sunbase, 2023). These results are confirmed by data from (The World Bank, 2023), which estimates 266.7-kWh of production during the month of February.

Since the system is able even in the least productive month to produce enough energy to cover the villages energy requirement, it may be argued that for a SPV system a battery storage system size larger than the base capacity is not needed. It should be noted that the 'energy requirement', already contains a large amount of contingency in forms such as the safety factor, meaning that a slight decrease in productivity during an anomalous month or gain in population, should be without effect to the energy supply. Further, the 58kW system size assumes a maximum level of system inefficiency at 7.5%, the efficiency the majority of the time will be higher than this, which creates additional extra capacity and margin for error. Therefore, it can be concluded that a SPV battery storage does not need to account for extra capacity, rather it would be more appropriate to be sized such that it's capacity is mostly to deliver electricity during off-peak hours such as nighttime.

6.6.2 Wind

The least productive period for wind energy occurs during the months of November and December, with a wind index rating of 0.75 and 0.76 respectively. The amount of wind produced is highly contingent upon the model and design of the turbine selected. As discussed in section 6.5 some models would not begin to generate electricity with wind speeds as low as 4m/s. Due to this ambiguity, calculating an accurate measure of wind output, without having a specific model or final design, becomes very difficult and hard to accurately predict.

Given the expected range of annual wind power output for a 100kW system, 100,000kWh – 220,000kWh, if it assumed that the upper and lower values represent the base wind index speed, in the estimated range of lowest productivity, power output during the month of November could be between 6,250kWh – 13,750kWh, although this calculation neglects whether the individual models themselves are capable of production at a wind speed of 4m/s. With a monthly energy requirement of 7,692.3kWh (based on a 30-day month), depending on the model used a battery storage system, may or may not be necessary.

However it should be noted that the Solar Atlas from (The World Bank Group, 2024), shows the productive hours of wind systems to be during the night and early morning hours of 00:00 to 10:00, therefore in order to deliver electricity to the village a very large amount of

battery storage will be required, since production occurs during the hours that energy will be the least desired.

6.7 Comparison

From the above discussion, it can be concluded that the most appropriate generation systems for the village will be a wind system and/or SPV system. Both of these system types are able to generate electricity within the desired range given the villages estimated energy requirements. A CSP system may be appropriate for a larger scale application, however in assessing the delivery of electricity to a single village, the system capacity is simply too large.

Generally, wind systems have a much higher capital cost than SPV systems (Alam et al., 2023). Additionally, as discussed wind systems are also much less flexible in the available sizes, whereas SPV is much more customisable to the specific size required.

Considering that the lowest estimated price for a 100kW wind turbine will be £20,000 higher than the average cost of a 58kW SPV system there is clearly far more cost effectiveness found in PV. There is also then further the issue of overproduction, in a multi-village project it may be found that the greater capacity with wind is a more optimal solution, however in assessing the average villages requirements it is not. If grid connection were available the excess electricity could be redistributed potentially to nearby villages, however this not being available complicates matters significantly.

Further wind turbines as wind turbines are expected to last for only 20 years compared to the 25-year lifespan of SPV, and since there is not a significant case for deploying the wind turbine with an oversized capacity to accommodate for population growth, as the population will be unlikely to grow at such a rate, it cannot be noted as a worthwhile investment.

Battery storage as expected will need to be deployed alongside the generation system in order to provide electricity during unproductive hours and harness the full extent of the electricity generated, regardless of the system type used.

Typically, within Namibia solar irradiation is very stable and the only notable declines in productivity will be during the night, for most of which energy will not be required. However, with wind there is no guarantee of continual production. Furthermore, it is likely that the battery storage size will need to be far larger, to accommodate for distribution of energy during non-productive hours. According to (The World Bank Group, 2024) Wind Atlas, the majority of wind productivity occurs during the nighttime and early morning hours of 0:00 to

10:00 year-round. Whereas, SPV productivity will occur within the daylight hours, when electricity is most desired as shown in the Solar Atlas (The World Bank Group, 2024). Increasing the size of the battery storage for a wind system, would further increase costs and compound increased capital investments on the already high initial cost of a wind system.

6.8 Optimal System

From the comparison and analysis above it can be concluded based on the several factors considered, that the most optimal electricity generation system for the village will be a ground-mounted 58kW SPV system with an approximately 12-kW lithium-ion battery storage system.

An SPV system was deemed more suitable due to its lower capital cost, more flexible power rating availability, higher productivity stability, and longer lifespan. The system is ground-mounted as a result of the poorly maintained structures found in typical homes making roof-mounting unsuitable. Finally, the battery storage is given at the maximum recommended capacity of 20%, to ensure that power is always sufficiently available when needed, and as a means to not waste any excess electricity generated.

The estimated cost of this will be around £58,928 for the ground mounted PV system, and around £5254 for battery storage, totalling approximately £64,182 for the entire system.

7 Discussion

As discussed in section 3.1, SPV is already a proven source of energy in Namibia, being the second largest source of renewable energy and contributing 20-24% to Namibia's RES portfolio. As Namibia's most abundant source of renewable energy it seems only logical that it would be found to be the most stable and appropriate choice of energy system for the village. Furthermore, this will tackle Namibia's overreliance on Hydropower, and unlike Hydropower, solar irradiance is not an energy source that can be drastically cut off overnight by extreme weather events. If anything, solar irradiance in Namibia is so abundant that even a temporary marginal decrease in irradiation level is unlikely to affect the systems generation output.

When constructing this system, considerations will need to be made that were not in this paper, such as the angle of tilt, the effect of shading, and the direction of sunlight. Further, there may be additional energy losses found in the inverter, cable and storage system, that were not taken applied in the calculations here. Although enough contingency should be available from the assumptions made to render these additional losses negligible, as they are most likely to be minimal at best.

In designing a system to be deployed, the scale of the system should be considered. It may be that there are neighbouring villages to the specified deployment area, and it would likely be more cost-effective and beneficial to increase the scale of the system, in order to provide electricity across multiple villages. This will increase costs, although will likely reduce the cost per village. Furthermore, this will introduce the possibility of alternative energy systems such as ST, which were deemed to be too large-scale to fulfil the energy requirements of the average village.

Additionally, in application to a real village, the operational, installation and maintenance costs will require far more consideration, as well as how the system will be managed. There should be plans in place to enable the development of the village, to a point where they can begin to afford to pay for, or at least partially subsidise the energy costs. Ideally, it should be such that by the end of the systems lifespan, the village either has grid connection available, or will be able to pay for the installation of a new system. How this will be organised is dependent on the individual circumstances of the village.

Further it has not been considered how the village inhabitants will acquire the appliances listed within the energy demand calculations, each of these appliances are intended to be under an ideal scenario, wherein the village are able to obtain them, such as to improve their quality of life to an ideal standard. Therefore, the cost of these appliances has not been

considered and only the cost of the energy system itself is taken into account for the final estimated total cost.

8 Conclusion

In summary, a comprehensive investigation was conducted using various research methods to gain a deep understanding of the current state of electrification in Namibia. Based on this analysis, along with reasonable assumptions, an assessment was made, leading to a recommendation for an effective measure to enhance electrification in the country.

The research revealed a significant gap in the electrification rates between rural and urban residents, with a respective electrification rate of 36% and 78%. Previous projects in other African nations have demonstrated that in order to successfully increase the electrification rate, specific targeted plans are needed down to the community level, whilst also taking full advantage of the most plentiful renewable resources available. Therefore, data regarding the availability of resources in Namibia and renewable energy generators was gathered to assess each potential type of system and ascertain the most suitable one.

Furthermore, to comprehend how renewable systems can be applied to a Namibian village and to understand their specific needs, data on rural Namibian communities was gathered with the objective of establishing a model village. The model was created as a means to provide insight into the practical implementation of a renewable energy system in a rural community.

After collecting the data and creating a model village, an electricity demand was able to be estimated, which was found to be around 251.46 kWh daily and 91,050.23 kWh annually with a 20% safety margin. Various renewable energy systems were then evaluated for their appropriateness, taking into account criteria such as the availability of resources, required generation capacity, cost, and life expectancy.

Based on the analysis, it was concluded that the most suitable system for the village is a 58kW solar PV system accompanied by a 12kW lithium-ion battery storage, with a projected cost for the system around £64,182.

Introducing an energy system into a community will significantly improve the residents' quality of life. Enhancing the personal, social, and educational advantages and prospects for the populace. The electricity provided to a village would enable them to attain a more modern standard of living, easing the burden of many tasks. Indoor and outdoor lighting offer increased flexibility by eliminating the dependence on the natural daylight cycle. While a cooker can significantly enhance health, especially for women, by eliminating the need for bio-waste to prepare a meal. In addition, the system has ample capacity to accommodate modern facilities, including a medical centre and furthermore, electrification can be provided to already existing public buildings, such as a church and primary school.

The deployment of SPV, will actively contribute to the worldwide efforts to combat climate change and global warming. Creating a more sustainable pathway for rural Namibian communities and in some sense bypassing them from the use of traditional fossil fuel electricity sources.

In order to accomplish global goals of achieving 100% electrification, reducing the effects of climate change, and decreasing global warming, it is imperative to make focused and determined efforts to aid and meet the needs of individual communities. This project enables a more precise comprehension of the requirements of local rural Namibian communities, as well as specific measures which can be taken and the estimated expenses necessary to implement them.

9 Further Work

As the purpose of this work is that it is intended to serve as a basis for which expectations for deploying energy generation systems in rural areas can be based. The logical next step will be to develop a project using the data of a real village for which this project can be used as a research basis for which to measure expectations against. Although this project is intended to provide a basis for understanding what addressing the electricity requirements of an average rural Namibian village will require, it should not be viewed as a definite solution, as the conditions of the specific village(s) being considered for development will need to be accounted for. In no way should this project be viewed as a one size fits all solution, rather it should be used to provide insight and measure expectations against. Although when assessing a real village, there will be far more complexities and considerations that will need to be made that were not addressed within this project.

Additional consideration will need to be taken based upon the resource availability to the deployment area, as there may be factors not present in the Epinga village studied, that would constitute an alternative RES a better solution. As with this project a range of factors should be considered, in order to determine which RES will provide the most optimal solution. In real applications, there may be factors that were not present here, such as budget constraints, development permits, cabling, etc. which were not taken into consideration.

Further it should be noted that there are additional applications of RES that could be made available which were not considered in this project. Streetlighting for example, when using RES, will generally come in the form of a standalone system with a single panel attached to its head. Since applications such as this do not connect to a central RES system, they were not considered within the project. If they were to be considered it would be very difficult to estimate the quantity needed, given that villages will vary in size and therefore in streetlighting requirements. In applying the research here to a real village, these additional RES applications should be considered, although they will likely not utilise the central system.

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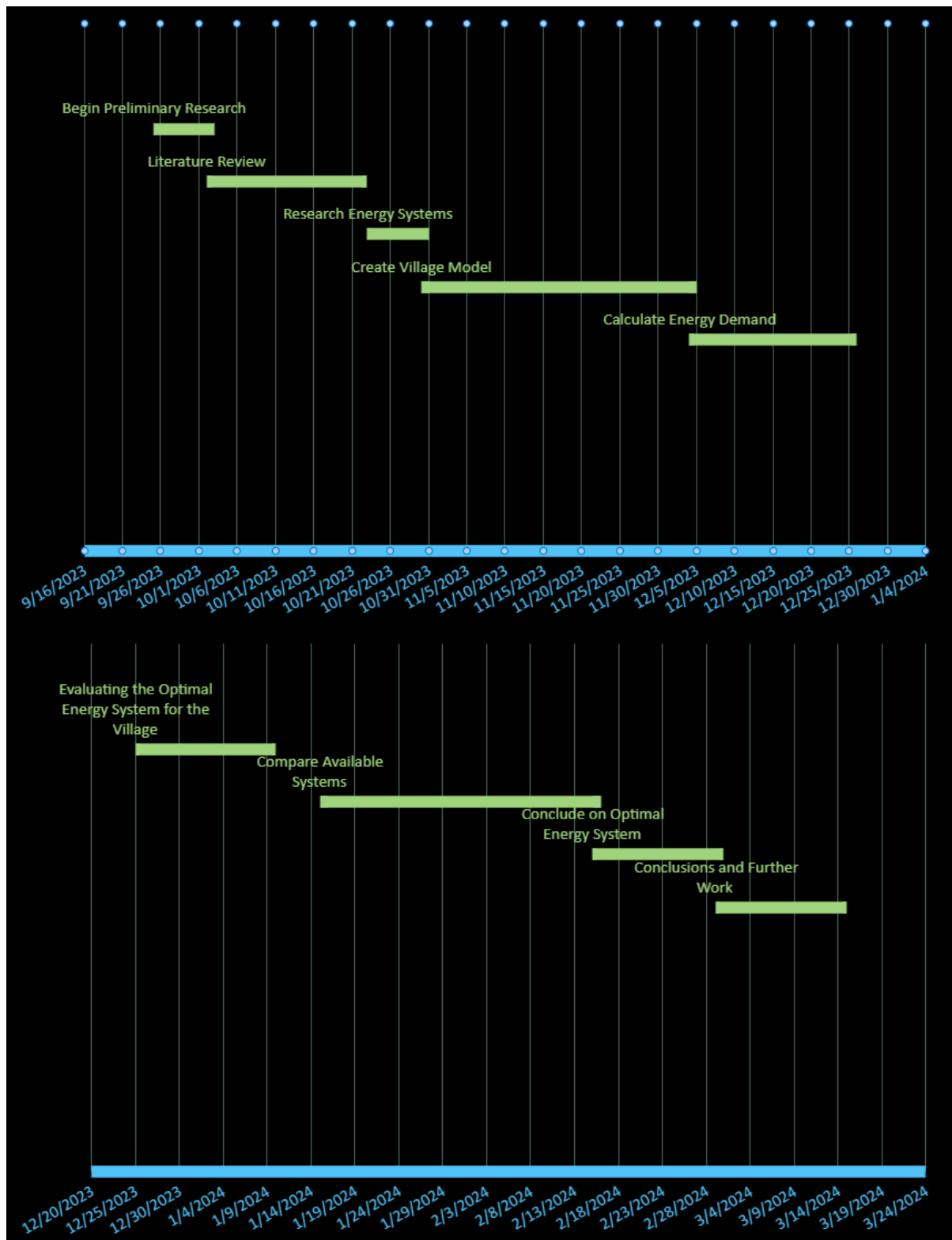
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Appendix A



Appendix B

ROOM	NO. OF LIGHBULBS PRESENT	AVERAGE DURATION OF DAILY USE (HOURS)	SIZE (m ²)	MAX. CAPACITY
MAIN HALL	20	5	286	400
SMALL HALL	6	8	195.5	100
TODDLERS ROOM	4	3	54.4	30
MEETING ROOM	4	2	35.36	30
OFFICE	1	8	15.75	8
SECRETARYS OFFICE	2	9	17.6	6
LIBRARY	3	4	16	15
LOUNGE	1	3	16	12
APPRENTICE ROOM	1	2	16	12
KITCHEN	8	5	36	6