DESIGN OF AN OPTIMAL STAND ALONE HYBRID RENEWABLE ENERGY SYSTEM WITH STORAGE FOR SUPPLYING PRIORITY LOADS IN A TYPICAL OFF GRID COMMUNITY

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Title

Design of an optimal stand alone hybrid renewable energy system with storage for supplying priority loads in a typical off grid community.

Description

There have been huge discrepancies in the energy consumption between the haves and the have nots and thus the residents of most typical rural off-grid communities hardly receive adequate electricity access. This report therefore aims at designing an optimal Hybrid Renewable Energy System (HRES) with storage for supplying priority loads in a typical off-grid community. The use of an energy storage option as backup storage is crucial because of the need of prioritized loads such as hospitals to be constantly supplied with electricity even during power outages.

Deliverables

i. Literature review of standalone HRESs for powering prioritized loads in off-grid communities and pollution mitigation analysis of these systems.
ii. Designing a cost-effective standalone HRES adhering to the design procedures.
iii. Conducting technical, environmental and economic feasibility analysis to obtain an optimal system.
iv. Interpretation and discussion of results.

Skills/Requirements

i. EEE4117F: Machines and power electronics course (Preferred)
ii. HOMER software

Area

Renewable Energy Systems.

Acknowledgements

This report is dedicated to my parents, Atul Mehta and Kamini Mehta whose love, teachings and values have shaped me into the person I am today. My siblings, Reetisha and Dhrumit, who have been there in all spectrums of my life, day in and day out encouraging me to strive for excellence. My Nana and Nani for always keeping me grounded and providing the best summer vacations ever and my late Dada and Dadi for always having my back and blessing me from above.

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Abstract

This report was aimed at designing and modelling an optimal Hybrid Renewable Energy System (HRES) with storage for supplying priority loads in an off-grid sub-Saharan African community. Two sites namely Upanga and Ngamiani located in Tanzania (country in East Africa) were chosen due to their presence of off-grid communities and their solar and wind renewable resource availabilities. The use of a storage option was crucial because of the need of prioritized loads such as hospitals to be constantly supplied with electricity even during power outages. Thus, a storage option would act as a backup option to continuously supply and meet the load demands of both these locations.

Upanga is a region in the city of Dar es Salaam which is located near the shores of the Indian ocean containing two hospitals as its prioritized loads in its off-grid communities. The load profile for Upanga indicated an average energy consumption of 20.26 kWh per day with a peak power consumption of 2.96kW. The optimal HRES configuration chosen from the case studies analysed was CSIV which involved a hybrid combination of solar PV and diesel generator with a storage option. This system consisted of a 6.34kW CS6U-330P solar PV module with an 8-string battery option, a 10-kW fixed capacity diesel generator and a 2.77kW converter, combining to an initial cost of $20,111.47 and a relatively low COE of $0.66 with a total NPC of just $63,136.93. The fuel cost was at a minimum of only 12.3% of the overall system cost which indicated that the system was largely running on the renewable solar resource as a primary source of energy.

Ngamiani on the other hand is a region in the city of Tanga also highly rich in solar resources but does not contain adequate wind resources. This region consists of only one hospital as its prioritized load. The load profile for Ngamiani indicated an average energy consumption of 16.22 kWh per day with a peak power consumption of 2.37kW. The optimal HRES configuration chosen from the case studies analysed was also CSIV which involved a hybrid combination of solar PV and diesel generator with a storage option. This system consisted of a 3.46kW CS6U-330P solar PV module with a 6-string battery option, a 10-kW fixed capacity diesel generator and a 2.53kW converter, combining to an initial cost of $16,861.25 and a relatively low COE of $0.673 with a total NPC of just $51,544.75. The fuel cost was at a minimum of only 13.35% of the overall system cost which indicated that the system was largely running on the renewable solar resource as a primary source of energy and that it was not only cost effective but also electrically and environmentally efficient.

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1. Introduction

1.1 Background to the study

In this modern age, electricity has taken its shape from a luxury to a necessity in most of the places worldwide ranging across sectors from residential, commercial to industrial fields. It has become a topmost priority to sustaining a living as it not only powers important utilities but also connects people and data across the globe through the internet, which in today's era has been revolutionary [1]. However, there are still more than a billion people without adequate access to electricity which shows the discrepancy between the haves and the have nots. Africa alone in 2018, had a total primary energy supply of around 9700 GWh (Gigawatt hour), from which Tanzania had 250 GWh. However, less than 5% of the people living in the rural areas of Tanzania had access to this 250GWh grid electricity [2], while all the other rural residents mostly used paraffin lamps as their primary source of electricity.

With this limited supply of electricity in rural Tanzania, having to power prioritized loads such as hospitals would further be a challenge due to its continuous power requirements. Several attempts have been made through government policies to utilize the renewable resources into these settlements to aid the grid in meeting the load demands [3]. Tanzania is highly rich in solar, wind and hydro renewable resources and thus has the capacity to generate electricity through these resources. The focus of this paper would be on the implementation of such a hybrid renewable energy system (HRES) mostly using solar and wind resources to power prioritized loads in typical off-grid communities in Tanzania.

1.2 Objectives of this study

1.2.1 Problems to be investigated

Some of the core questions to be investigated include:

- What does a prioritized load entail?
- Which locations contain prioritized loads in Tanzanian off-grid communities?
- What constitutes of an HRES configuration and would it aid in powering priority loads in off-grid Tanzanian communities?
- Would solar and wind resources be sufficient to meet the load demands?
- Would an HRES be reliable to power these loads and if so, which HRES configuration would be the most optimal?
- What are the various energy storage options available and which ones would be able to continuously support the optimal system?
- Which software to select for conducting the necessary simulations and optimizations?

1.2.2 Purpose of the study

The purpose of this study was to investigate and design an optimal standalone system consisting of various renewable resources to power prioritized loads in the remote off-grid locations of Tanzania. This entailed having a cost effective, technically efficient and environmentally friendly system without the need to be connected to the national grid.

1.3 Scope and Limitations

The scope for this research consisted of designing and modelling an optimal hybrid renewable energy system to power prioritized loads in off-grid locations in the Sub-Saharan African communities. Two sites falling into these categories were chosen and their respective load demands were assessed, followed by having a detailed resource assessment to study whether these energy resources would be capable to meet the load demands. These data were then fed into the HOMER software for analysis and optimization results were obtained, from which the most optimal HRES configuration was chosen containing qualities such as being cost effective and technically and environmentally efficient.

Some of the limitations to this study involved not having enough sensitivity parameters like a varying annual solar irradiance value or varying annual wind speed values which would have made for an even better optimal system. The study was also limited to off-grid sub-Saharan African countries, which excludes the north African countries and also places with semi-grid connections.

1.4 Plan of development

i. *Section 1: Introduction*
This section introduces the research topic by providing a brief background to the study and highlighting some of the core objectives of this study including the problems to be investigated and the purpose of the study. It further explains the scope and limitations involved and concludes by providing an overview and layout of the remaining chapter to follow.

ii. *Section 2: Literature Review*
This section provides an in-depth view on the hybrid renewable energy systems, focusing on the driving factors for HRES, the renewable resources to be used and the possible energy storage systems suitable for the study. It also goes on to discuss the power demands for the priority loads and the optimization and feasibility analysis of the software selected.

iii. *Section 3: Methodology*
This section starts with an introduction to the methodology steps involved in planning for the research and then goes on to discuss each one of these steps to lay a foundation for the next sections to follow. Finally, the chapter ends by developing the various case studies to figure out the optimal HRES configuration.

iv. *Section 4: Results*
This chapter provides detailed optimization results for the selected locations, discussing and analysing the cost summary, electrical summary and the emissions summary for each of the case studies developed in Section 3. It concludes with the sensitivity analysis by discussing the effects of varying discount rates and fuel prices on various system parameters.

v. *Section 5: Discussion*
This section compares all the case studies obtained for each of the locations and plots the comparison results obtained in each of the cost, electrical and emissions categories.

vi. *Section 6: Conclusion*
This section brings the study together by concluding the optimal HRES configurations for each of the locations and summarizing why the chosen system was the most suitable.

vii. *Section 7: Recommendations*
This section advises and suggests on improvements to be made to this study in order to obtain better, more accurate results for any future research work conducted on this topic.

2. Literature Review

2.1 Renewable energy

Renewable energy are sources of natural energy available abundantly from Earth unlike its fossil fuels counterparts which deplete over time. According to [4], fossil fuels such as petroleum and coal are key sources to about 70% - 80% of the Earth's total available commercial energy leaving a carbon footprint on the planet. However, in recent years, people are becoming more aware of the risks these sources are posing to the planet and hence many are now switching to renewable energies to generate electricity. Figure 2.1 indicates how Africa alone from 1990-2018 had a large dependence on energy sources derived from fossil fuels such as coal, oil and gas for its annual energy productions [5]. It also shows how less of a percentage the renewable resources got as compared to their fossil fuels derived counterparts.

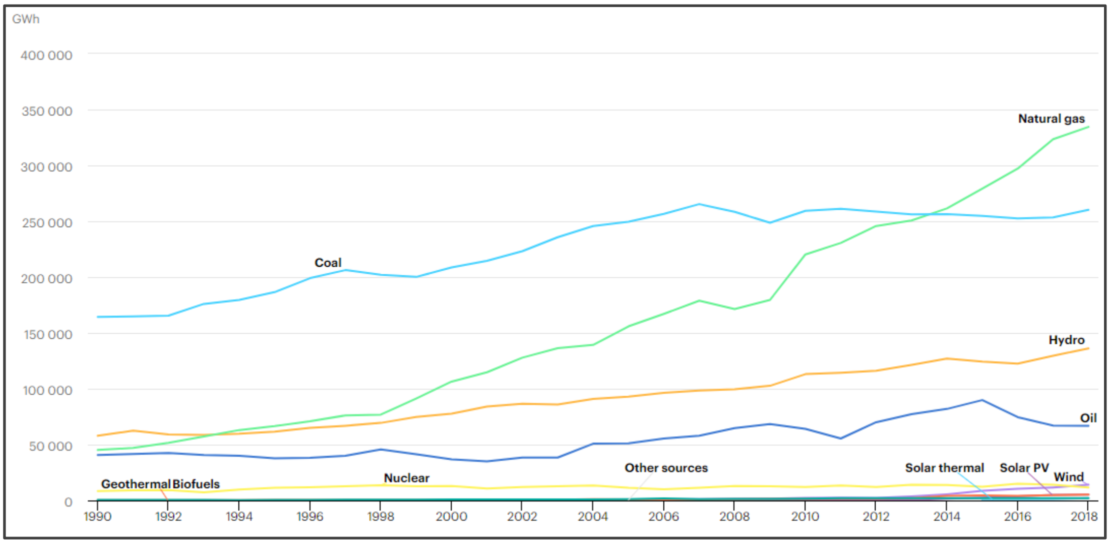

Figure 2.1: Summary of Africa's sources of energy

Figure 2. 2 on the other hand represents the predicted energy sources distribution by the year 2040 which has heavy reliance on renewable resources such as hydro, wind, solar and geothermal accounting for more 50% of energy production through renewable resources indicating a shift towards clean energy.

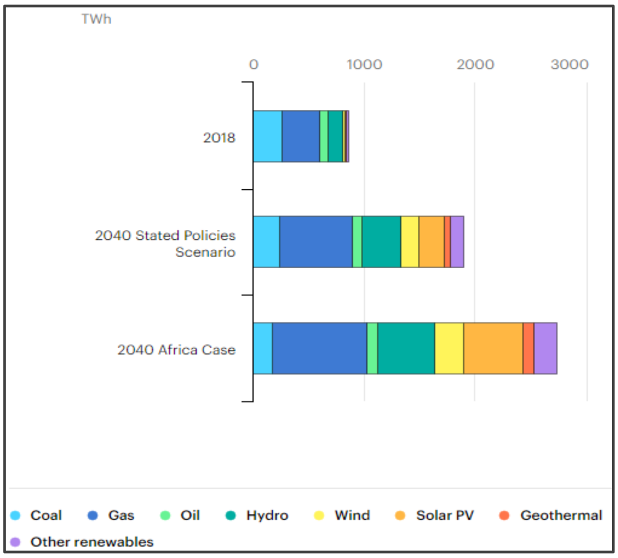

Figure 2.2: Summary of Africa's future sources of energy

2.2 Hybrid Renewable Energy System (HRES)

HRES is a collection of a variety of available renewable energies derived from solar, wind, biogas and others to provide with a sustainable system which is both economically feasible and environmentally friendly. A collection of such renewable energy systems is utilized instead of using just one source for the sole purpose of increasing the efficiency and longevity of the power system i.e. a single renewable energy system is not reliable enough to operate on its own due to its unpredictable nature. Storage systems are hence usually accompanied with HRES to provide for backups when these natural resources are unable to meet the load demands.

2.2.1 Driving Factors for HRES

i. Powering priority loads in off grid communities
Consistent and reliable power supply in rural areas especially for powering priority loads is challenging and economically not feasible due to the harsh terrain, scarcely populated and isolated constructions of rural settlements [6]. Stand-alone hybrid renewable energy systems are promising alternatives to increase the access of clean reliable energy in these regions.

ii. Resource Availability
Africa is a continent rich in natural resources with an abundancy in solar and wind energies. This review will hence discuss these two sources for generating a stand-alone HRES for electrifying priority loads in an African community. Figure 2. 3 from [7] shows that Africa consists of some of the sunniest places on the planet and that the total solar energy readily available in Africa is around 660 petawatt hours.

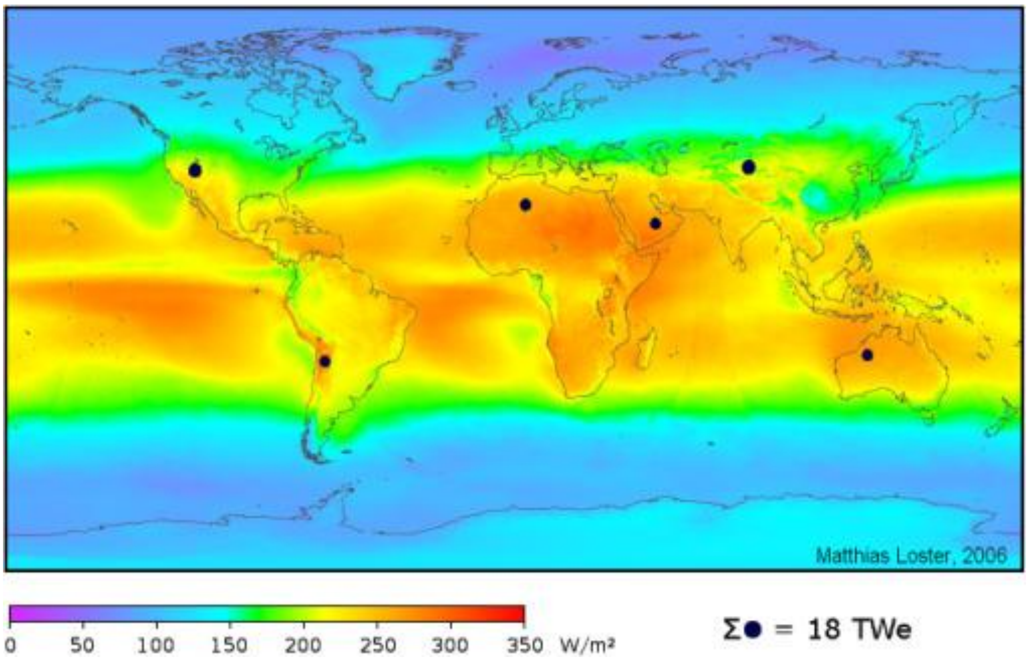

Figure 2.3: Yearly average solar irradiance distribution over the Earth surface

iii. Environmentally friendly

Over the past couple of decades, we have seen a global increase in Earth's average temperature which is mainly due to increased carbon emissions. For instance, [7] indicates that in a span of just four decades (1980s to 2010s), Africa has experienced an increase in the yearly CO_2 emissions by almost twice the size from 0.6 tonnes in 1980 to around 1.2 tonnes in 2010. Thus, in order to reduce the carbon footprint on our planet, we have to switch towards renewable approaches.

2.2.2 Solar energy

Solar energy is one of the most used renewable energy resource in the world due to its readily available harnessing power and relatively low cost [8]. The energy from the sun is converted to electrical energy through the use of photovoltaic cells (PV cells). A Solar PV System consists of semiconductor-based materials which directly converts solar energy into electricity. Table 2. 1 below mentions some of the solar PV types and tabulates the feasibility studies in terms of cost and eco-friendliness [9]. This table indicates that the high concentration advanced PV system has the least CO_2 emissions rate and with a payback period ranging from only 0.7-2.0 years. This is closely followed by the thin film PV type with a payback period of 0.75-3.5 years.

S/No	PV type	Payback period range (years)	Emission rate (gCO_2-eq/KWh)	Remarks
1	Thin film	0.75–3.5	10.5–50	Environmentally friendly and suitable
2	Mono-silicon	1.7–2.7	29–45	Ditto
3	Advanced PV system technologies			
I	High concentration	0.7–2.0	Lower than above rate	Environmentally friendly and suitable
II	Hetero-junction	Ditto	Higher than above rate	Ditto
III	Dye-sensitized	–	–	Rate research is ongoing

Table 2.1: Feasibility on PV types with payback period and environmental impacts.

2.2.3 Wind energy

Wind energy is another resource readily available on the Earth's surface. One of the key technologies to extract this resource from mother nature is through installing wind turbines in locations of abundant and mostly constant wind supply. Apart from being rich in solar energy, Africa also possesses tremendous wind energy capability as seen from the wind density map in Figure 2. 4 indicating the suitability of areas for turbine installations [10]. These wind turbines consist of a shaft which rotates due to the wind movements and this shaft is connected to the generator to transform the kinetic energy to electric energy resulting in electricity generation.

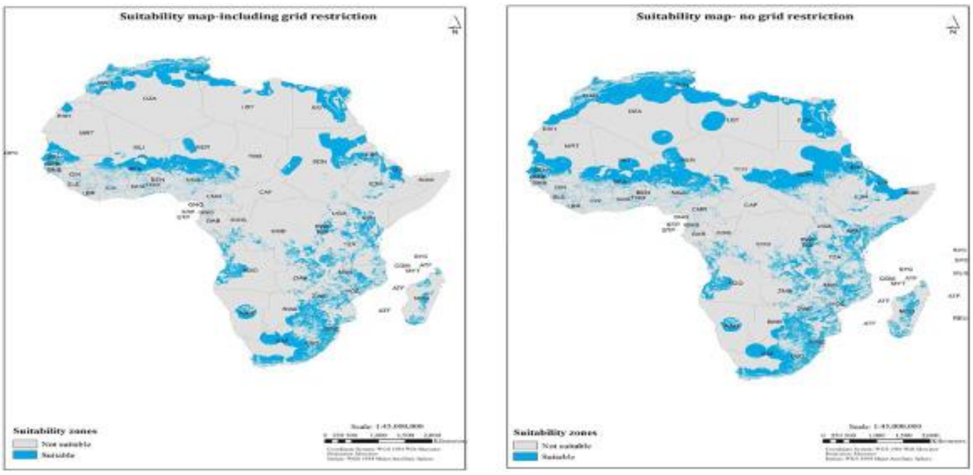

Figure 2.4: Suitability map with and without grid restriction

Wind turbine are normally of two types, namely Fixed Speed Wind Turbine (FSWT) operating at constant speed and Variable Speed Wind Turbine (VSWT) enabling maximum aerodynamic control. Figure 2. 5 below indicates African countries with powerful wind energy potential with the highest being South Africa generating wind energy in the range of around 5000 – 10000 MWh yearly per 1km^2, which is approximately 25% of its area availability [10].

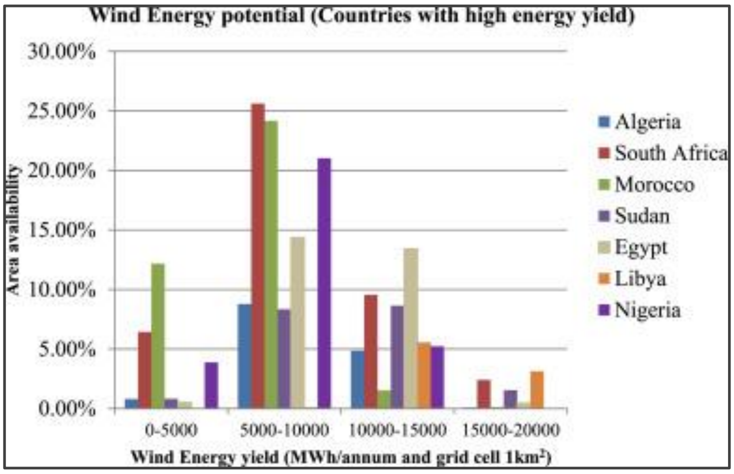

Figure 2.5: Wind energy yield-area availability

2.3 Storage systems

Power generated by an HRES is unpredictable as it depends on the availability of these resources. Solar energy for instance may be insufficient during rainy days or wind energy may be absent on a particular day. These irregularities reduce the reliability of the system to meet the load demand. Thus, an energy storage system is important as it provides backup to the HRES. These storage systems allow energy to be stored when there is excess energy produced and supply this excess energy to the loads to compensate any shortage in energy. The following are some of the types of storage systems currently available in the market.

2.3.1 Flywheel Energy Storage

A flywheel storage device stores mechanical energy in the form of rotational kinetic energy by matching it from the converted electrical energy storage option [11]. It releases this rotational kinetic energy during a power outage or when load demands are not met by the HRES which is released to supply the facility as AC power. Flywheels generally have a long lifespan of roughly around 20 years depending on the application and functionality. The energy storage and performance of flywheels does not diminish with repeated use and thus increases its durability and also saves cost. However, these storage systems are purely mechanical and thus can pose risks of malfunctioning and also requires timely servicing.

2.3.2 Battery Energy Storage

Battery storage is the most widely acceptable electrical energy storage option in renewable energy systems. For this type of storage, the battery stores energy in the form of chemical energy which can be reverted back to electrical energy at any time required. There are four common battery types currently used depending on various parameters as seen in Table 2. 2 below. It is seen that although Lead Acid (PbA) has the lowest efficiency, they have lower costs than the others so a detailed feasibility analysis must be carried out to weigh in the trade off and determine the best possible storage option to choose.

Type	Efficiency [%]	Cost	Power Density [W/kg]	Lifetime [cycles]
PbA	72-78	Low	25-100	1000-2000
NiCd	89	High	140-180	3000
NaS	85	High	120-220	3000-9000
Li Ion	70-95	High	360	3000

Table 2.2: Comparison of battery energy storage [12]

2.4 Power demands for priority loads

For this report, priority loads include hospitals and medical facilities. In a typical off grid community, there are generally very few priority loads (around 3 to 4 maximum) but these are extremely important for the community and thus require a sustainable and reliable system with a storage option to enable the off-grid community to meet their demands. Figure 2. 6 below shows the load demands for the equipment's required to run a typical hospital setting [13].

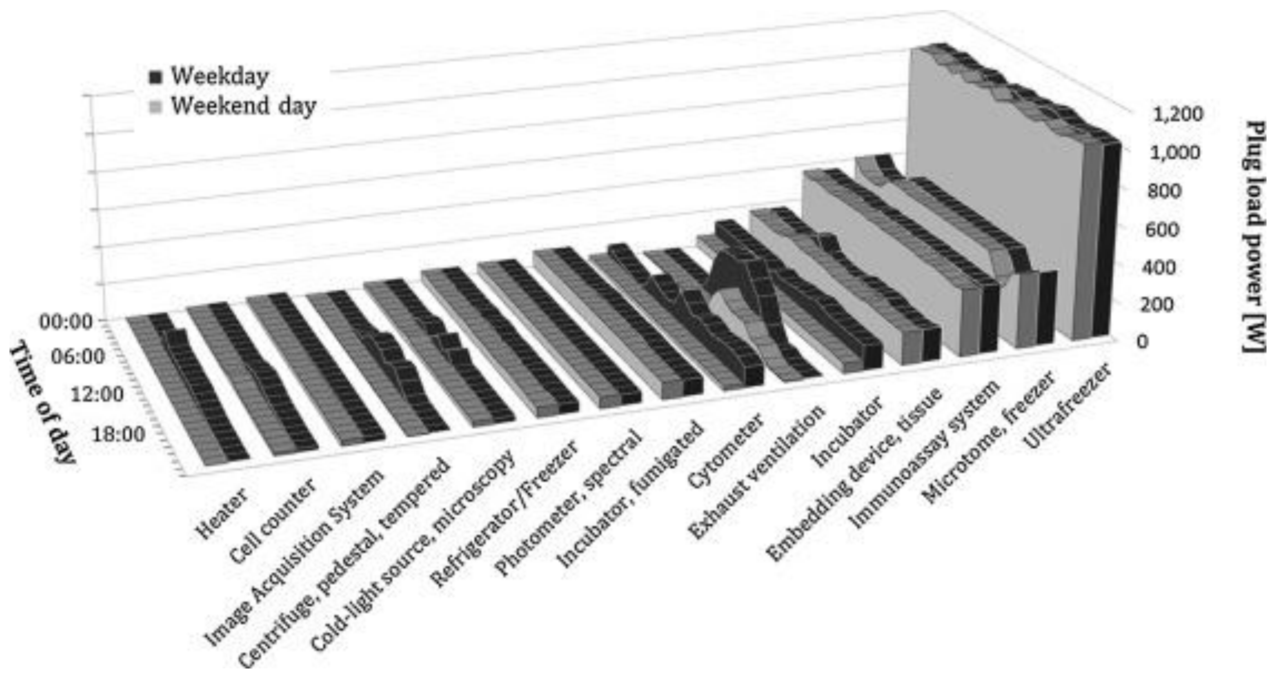

Figure 2.6: Hourly electrical load of the most relevant device groups for a weekday and a weekend day [13]

From the figure above, it is seen how different loads in a typical hospital setting have different power ratings at different operating hours. Ultra-freezer for example has the highest power rating every hour of the day throughout the week. This is because hospitals constantly need to freeze samples for future use and thus a constant power utilization is experienced. Similarly, but at lower power ratings, lies the microtome freezer, immunoassay system and the tissue embedding device. For the exhaust ventilation on the other hand, it is seen to have its peak power usage in the afternoons during weekdays with flattening curves on the weekends and early mornings. For all the other devices, the power usage is pretty constant every hour of the day for the entire week.

This study helps to design the load profile of hospitals in a typical off grid community and would be inputted in the design software for providing the necessary load information.

2.5 Optimization and feasibility analysis

The feasibility analysis of the HRES considers finding the most cost effective, reliable and environmentally friendly method given any constraints. This analysis requires load and resource allocation and assessment to help determine which combination of renewable resources would be appropriate for powering the priority loads in the community. For obtaining an optimal HRES design, various configurations can be implemented using numerous optimization algorithms like the probabilistic, numeric and heuristic methods [14]. Optimization techniques mentioned in Table 2. 3 below provides technical, economic and environmental energy efficient supply approaches.

S/N	Optimization technique	Elements	Remarks
1	Graphical construction	Battery and PV array	Use two parameters
2	Probabilistic approach	Performance of hybrid system	Based on statistical data collection approach
3	Deterministic approach	Stand-alone PV with battery bank	Use an equation for determining specific values with constant parameters
4	Iterative approach: hill climbing, dynamic programming, linear, and multiple objective	Hybrid-solar-wind system	Based on LPSP to find possible combination of solar-wind combination
5	Artificial intelligence: generic algorithm, particle swarm, fuzzy logic, artificial neural network, and hybrid model	Hybrid solar-wind system with battery	Based on evolution technique
6	Software based: homer, and developed GUI application software	All of the above	Input file with all necessary information is supplied. The software takes care of other things

Table 2.3: List of possible optimization techniques [14]

For the purposes of the research report, the Hybrid Optimization Model for Electric Renewable (HOMER) software-based optimization technique will be used to carry out the design of the optimal HRES. Homer is widely used in the renewable market for optimization of design models as it strongly emphasizes on minimizing costs and maximizing performance constraints. One of the other key reasons for choosing HOMER was the flexibility, simplicity and the user-friendly interface it had to offer. Alongside that, it also provided with the HOMER optimizer function which would generate large combinations of different HRES configurations depending on the sensitivity parameters and the input components fed into the system.

2.6 Similar studies

This sub section will view and discuss existing HRES installations with their respective applications conducted in sub-Saharan African communities using the HOMER software.

2.6.1 Kenya case study:

This study [15] was conducted in the remote village of Korr, which is located in the Marsabit district of Northern Kenya. The available renewable resources for generating power in this region were solar and wind resources. The yearly average wind speed at Korr was found to be at 4.39 m/s and having an annual daily solar irradiance of around 5.87 kWh/m^2/day with the primary load demand of 5592.2 kWh per day and a fixed diesel price of $0.95 per litre. A total of six different HRES configurations as shown below were analysed:

- Solar PV + generator
- Solar PV + generator + storage
- Wind turbine + generator + storage
- Solar PV + wind turbine + generator
- Solar PV + wind turbine + storage
- Solar PV + wind turbine + generator + storage

The optimal HRES configuration from the above list was found out to be the combination of solar PV, wind turbine, generator and storage option having a total NPC of $10.8 million and an initial cost of $4.26 million with a COE of $0.314. This configuration turned out to be a feasible solution for the residents of Korr as it provided a cost effective, reliable and sustainable source of energy generation.

2.6.2 Ethiopia case study:

This study [16] was conducted in the Golbo II village, which was located in the Adaa district of Ethiopia. The available renewable resources for generating power in this region were solar and wind resources. The yearly average wind speed at Golbo was found to be at 3.901 m/s and having an annual daily solar irradiance of around 6.06 kWh/m^2/day with the primary load demand of 108 kWh per day and a fixed diesel price of $0.70 per litre. A total of four different HRES configurations as shown below were analysed:

- Diesel generator + storage
- Solar PV + diesel generator + storage
- Wind turbine + diesel generator + storage
- Solar PV + wind turbine + diesel generator + storage

The optimal HRES configuration from the above list was found out to be the combination of 20kW solar PV, three 3kW wind turbines, a 5kW diesel generator and 24 strings battery storage option having a total NPC of $82,734.00 with a COE of $0.207. This configuration turned out to be a feasible solution for the residents of Golbo II village as it provided a technical, reliable and sustainable source of energy.

3. Methodology

3.1 Introduction

The aim of this research was to design and implement a cost effective and an optimal hybrid renewable system to provide electricity to prioritized loads in two off-grid Tanzanian communities. The proposed research topic was broadly based, and the selection of the location was left to the researcher (i.e. the student). The steps involved in planning for the methodology of this study were outlined in the sub sections below.

The design thinking process largely entailed identifying and comparing various HRES configurations amongst different combinations of wind turbines, solar PV, diesel generator and energy storage options. These various combinations were grouped under seven different case studies and the use of a storage system was included as a fixed component in all the case studies because of the need of prioritized loads to immediately access electricity in case of a power failure or unmet load requirements. Thus, a continuous back up system such as the battery storage system was an essential component in providing a reliable optimal HRES combination.

3.2 Methodology steps

The following methodology steps were proposed to facilitate a research thinking process in order to explain how these were analyzed and brought about in the study:

- Site selection in Tanzania with locations having prioritized loads.
- Resource assessment to analyze the renewable capacity of the chosen sites.
- Software selection to simulate and optimize the required HRES configurations.
- Data collection and preparation for modelling the prioritized loads.
- HRES modelling and its components in HOMER.
- Optimization and Sensitivity analysis of the various configurations involved.
- Case studies identification and discussion.

3.3 Site selection

Two off-grid communities were chosen for facilitating this research. Both these locations were based in Tanzania, a sub-Saharan country in the East of Africa. Some of the criterions considered during the site selection were:

- The sites must be located in sub-Saharan Africa.
- They must be off-grid settlements.
- The sites must have adequate availability of renewable resources, preferably solar and wind energy resources.
- The areas must have prioritized loads such as hospitals and/or medical centers.
- They must face with frequent power outages and/or poor load handling capabilities.

The first site was the Upanga settlement in the city of Dar es Salaam. Upanga is a region located near the shores of the Indian ocean which contains two hospitals as its prioritized loads in the off-grid communities. It has had numerous power outages in recent years especially during peak summer months (i.e. November to February) due to the water dams being dried up. Thus, it would be of great importance to generate power to run the prioritized loads in Upanga through utilizing the renewable energy resources available in this region. Figure 3. 1 displays the map of Upanga alongside the hospitals available in the region.

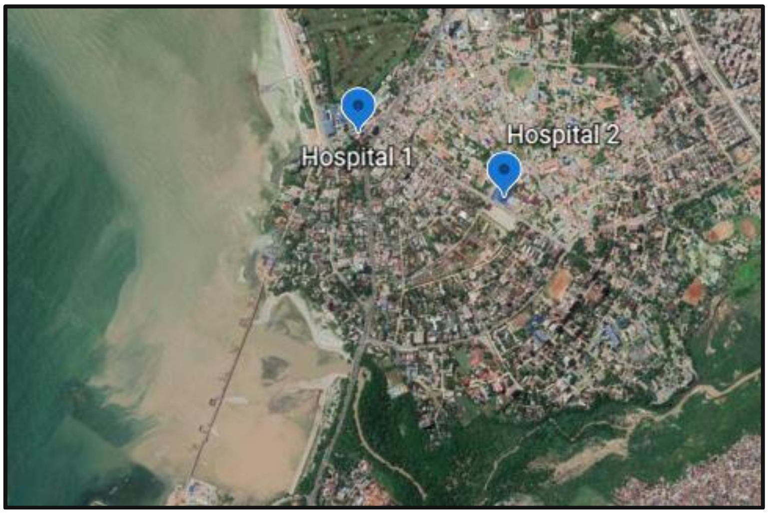

Figure 3.1: Top view of Upanga, Dar es Salaam [Google Earth]

The second location was the Ngamiani settlement in the city of Tanga which contained one hospital as its prioritized load. Ngamiani is also a region highly rich in solar resources. The primary source for power generation however is through the Hydro-Electric Power (HEP). Thus, just like in Upanga, Ngamiani also faces power shortages during extreme summer conditions. The need to develop a more sustainable source of electricity is hence crucial to not only power the prioritized loads in Ngamiani but also to be used as a daily household source of energy. Figure 3. 2 below displays the map of Ngamiani alongside the only hospital available in the region.

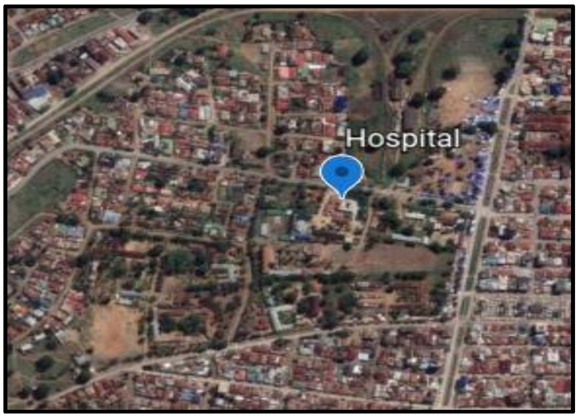

Figure 3.2: Top view of Ngamiani, Tanga [Google Earth]

3.4 Resource assessment

Once the load profile data had been modelled and analyzed, a renewable resource assessment was conducted to determine the availability and reliability of the renewable resources (solar and wind resources) in both the locations and whether these resources could support the load demand for the analyzed load profiles. The solar and wind data for both the locations were obtained from the National Aeronautics and Space Administration's (NASA) solar energy and surface meteorology database via HOMER's online library. Alongside this, an average daily temperature and clearness index were also recorded and saved for both the locations.

3.4.1 Upanga assessment

<u>Solar resource assessment:</u>

Upanga is located at 6°48.2' South, 39°17.3' East, in the city of Dar es Salaam with an annual average solar global horizontal irradiance (GHI) of 1900 kWh/m^2 and an average annual temperature of 26°. Table 3. 1 below shows the average monthly clearness index, solar radiation and temperature of Upanga with Figure 3. 3 indicating this information in a graph format.

Months	Clearness Index	Daily radiation [kWh/m²/day]	Daily temperature [°C]
January	0.538	5.76	26.76
February	0.557	6.00	26.87
March	0.509	5.34	26.83
April	0.467	4.57	26.62
May	0.493	4.42	26.28
June	0.536	4.56	25.66
July	0.522	4.55	25.04
August	0.515	4.86	24.83
September	0.545	5.57	25.04
October	0.533	5.67	25.53
November	0.534	5.70	26.00
December	0.537	5.71	26.48

Table 3.1: Solar data for Upanga

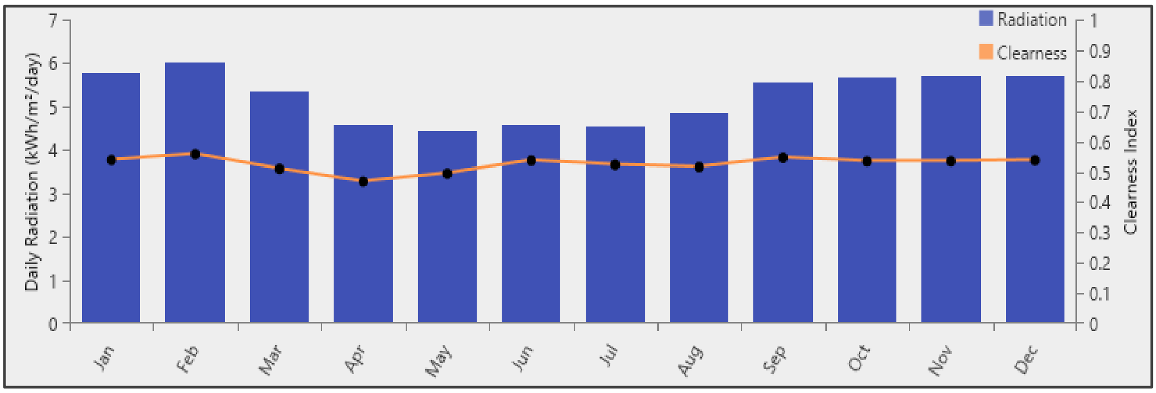

Figure 3.3: Average daily solar radiation for Upanga

From the above figures, the daily solar radiation was low from April to August, with a lowest of 4.42 kWh/m^2/day in May and a highest of 6.00 kWh/m^2/day in February. The average daily temperature and the clearness index however stay relatively similar throughout the year indicating the independency of the solar penetration power to the yearly seasons.

Wind resource assessment:

Upanga is located on the shores of the Indian ocean and it thus has an abundant supply of wind energy with a yearly average wind speed of 5.74m/s. Table 3. 2 below shows the monthly average wind speed of Upanga with Figure 3. 4 indicating this information in a graph format.

Months	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Avg. speed [m/s]	4.33	3.98	4.46	5.84	7.21	7.63	7.47	6.64	5.89	5.90	5.26	4.32

Table 3.2: Wind data for Upanga

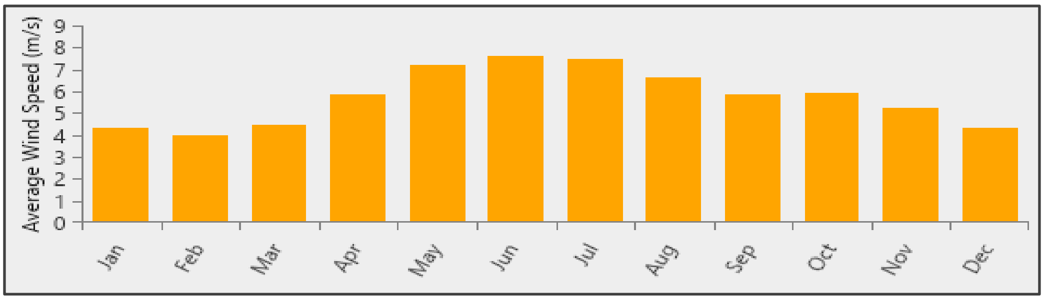

Figure 3.4: Average wind speed for Upanga

3.4.2 Ngamiani assessment

Solar resource assessment:

Ngamiani is located at 5°4.6' South, 39°6.1' East, in the city of Tanga with an annual average solar GHI of 2000 kWh/m^2 and an average annual temperature of 25.76°. Table 3. 3 below shows the average monthly clearness index, solar radiation and temperature of Ngamiani with Figure 3. 5 indicating this information in a graph format.

Months	Clearness Index	Daily radiation [kWh/m^2/day]	Daily temperature [°C]
January	0.596	6.29	26.42
February	0.613	6.55	26.53
March	0.569	5.98	26.61
April	0.497	4.92	26.43
May	0.485	4.43	26.16
June	0.514	4.48	25.52
July	0.521	4.64	24.88
August	0.542	5.19	24.62
September	0.588	6.03	24.82
October	0.583	6.16	25.27
November	0.573	6.04	25.67
December	0.586	6.13	26.15

Table 3.3: Solar data for Ngamiani

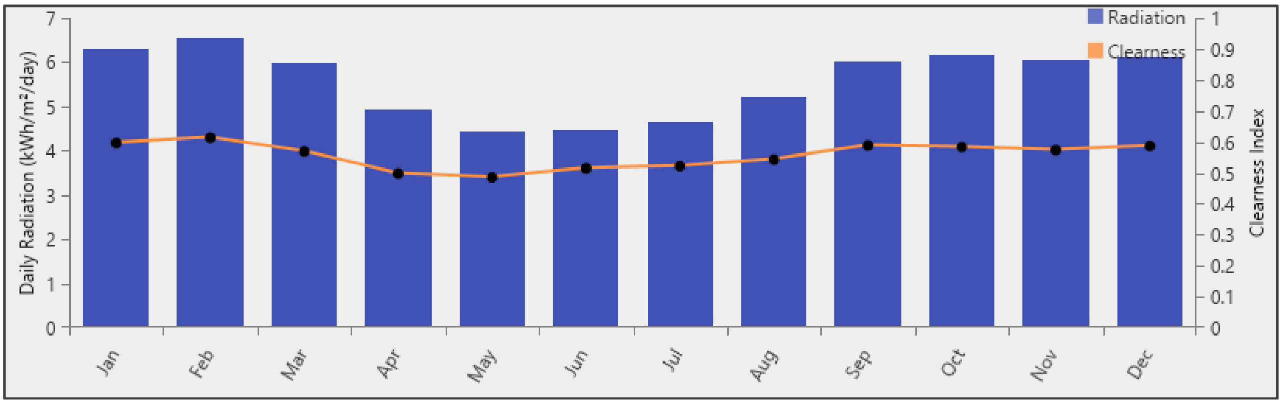

Figure 3.5: Average daily solar radiation for Ngamiani

From the above figures, the daily solar radiation was low from April to August, with a lowest of 4.43 kWh/m^2/day in May and a highest of 6.55 kWh/m^2/day in February. The average daily temperature and the clearness index however stay relatively similar throughout the year indicating the independency of the solar penetration power to the yearly seasons.

3.5 Software selection

Designing a hybrid renewable energy system is a complex procedure requiring numerous input parameters and generating various combinations of possible HRES configurations. The chosen software would also need to simulate, optimize and generate sensitivity analysis for designing the hybrid system for the chosen locations and thus it must be able to:

- Feed in load profiles of the system under observation.
- Model and simulate the system as accurately as possible to the real world.
- Provide numerous HRES configurations based on different models of cost effectiveness, technical feasibility and environmental impacts.

The chosen software for this study was HOMER (Hybrid Optimization Model for Electric Renewables). One of the key reasons for choosing HOMER was the flexibility, simplicity and the user-friendly interface it had to offer. Alongside that, it also provided with the HOMER optimizer function which would generate large combinations of different HRES configurations depending on the sensitivity parameters and the input components fed into the system.

3.6 Data collection and preparation

It was then important to collect the required load data for the prioritized loads to further the design process. These load profiles would then be utilized for calculations of the approximate power generation required by the HRES. Since it was difficult to obtain actual load data for the hospitals in the above-mentioned locations, a literature review was conducted to provide an estimate for loads in such hospitals. Table 3. 4 below shows the load demands which were open sourced from the literature reviewed for the equipment's required to run a typical hospital setting [13].

S/N	Hospital Loads	Power rating [kW]	Avg. load per day [%]	Avg. time per day [hrs]	Avg. consumption per day [kWh/day]
1	**Ultra-freezer**	1.10	83.0	24	21.91
2	**Microtome freezer**	0.94	64.0	14	8.40
3	**Immunoassay system**	0.80	66.0	15	7.92
4	**Embedding device**	1.00	21.0	18	3.78
5	**Incubator**	1.10	9.0	24	2.38
6	**Exhaust Ventilation**	0.48	18.0	22	1.90
7	**Cytometer**	0.60	21.0	14	1.76
8	**Fumigated Incubator**	0.60	18.0	18	1.94
9	**Spectral photometer**	0.08	68.0	23	1.25
10	**Refrigerator/Freezer**	0.12	40.0	24	1.15
11	**Microscopy source**	0.15	5.0	4	0.03
12	**Centrifuge**	3.30	1.0	19	0.63
13	**Acquisition system**	0.32	45.0	5	0.73
14	**Cell counter**	0.12	17.0	24	0.49
15	**Heater/AC**	0.45	80.0	18	6.48
				TOTAL	60.76

Table 3.4: Table showing the hospital loads and their average energy consumption per day

The above table indicates fifteen of the most common loads used in a hospital setting. The above load data was open source data and was collected from the University Medical Center of Hamburg/Germany [13] which had a total capacity of around 1500 hospital beds. The power rating of each of the loads, the average percentage of load used per day, the average percentage of time used per load per day and the average energy consumption per day for each load was indicated in Table 3.4 above. The estimated average energy consumption per day per load was calculated using the formula below:

Energy [kWh/day] = Power rating [kW] * Avg. load per day [%] * Avg. time per day [hrs] *Equation 1*

The load data indicated an estimate of **60.76 kWh/day** of average energy consumption per day in this hospital setting of 1500 beds. For processing this data and estimating average consumptions for the hospitals in Upanga and Ngamiani, HOMER required hourly load profile of such a data. Table 3. 5 below shows this hourly load profile based on the data collected from the hospital.

Time	Load [kWh]	Time	Load [kWh]
00:00 - 01:00	1.2	12:00 - 13:00	5.1
01:00 - 02:00	1.1	13:00 - 14:00	4.8
02:00 - 03:00	0.7	14:00 - 15:00	4.9
03:00 - 04:00	0.9	15:00 - 16:00	4.4
04:00 - 05:00	1.4	16:00 - 17:00	3.5
05:00 - 06:00	2.2	17:00 - 18:00	2.6
06:00 - 07:00	2.7	18:00 - 19:00	2.5
07:00 - 08:00	2.5	19:00 - 20:00	2.2
09:00 - 10:00	3.6	21:00 - 22:00	1.5
10:00 - 11:00	4.9	22:00 - 23:00	1.9
11:00 - 12:00	5.0	23:00 - 24:00	1.2

Table 3.5: Hourly load profile of the model hospital

Figure 3. 6 indicates the above load profile data in a bar graph for ease of interpretation.

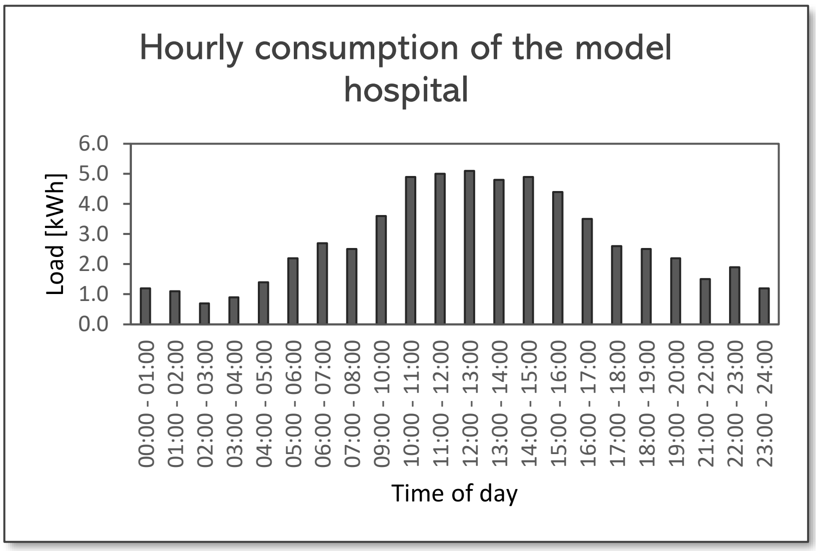

Figure 3.6: Hourly energy consumption of the model hospital

Table 3. 5 and Figure 3. 6 indicate that most of the energy was consumed during the daytime especially starting from 10h00 in the morning up to 16h00. During this period, an average energy consumption of 5kWh was observed with the peak time being from 12h00 to 13h00 with an energy consumption of 5.1kWh. It was also observed that the least energy was consumed past midnight from 02h00 to 03h00 with the total consumed energy of just 0.7kWh. These peaks and troughs were justified by considering that most of the people using hospital services would attend during the daytime whereas in the nighttime, hospital traffic would have been reduced to mostly existing patients and severe cases/accidents [17].

3.6.1 Upanga load profile

Upanga consisted of two hospitals in its region with approximately 250 hospitals beds each. Thus, when modelling the load profile for Upanga, it was important to make use of a scaling factor. This factor provided a scaled energy consumption value for the Upanga hospitals based on the ratio of the bed capacity in Upanga hospitals (≈500 beds in total) to the bed capacity of the model Hamburg hospital (≈1500 beds). For example: if a heater in the Hamburg hospital (1500 beds) utilized 6.48kWh then for the Upanga hospital (500 beds), the heater would utilize: 6.48kWh * (500/1500) = 6.48kWh * (0.33) = 2.16kWh ; where 0.33 was the scaling factor. This factor was then applied to Table 3. 5 above to generate an estimated load profile for Upanga as shown in Table 3. 6 and Figure 3. 7 below.

Time	Load [kWh]	Time	Load [kWh]
00:00 - 01:00	0.40	12:00 - 13:00	1.70
01:00 - 02:00	0.37	13:00 - 14:00	1.60
02:00 - 03:00	0.23	14:00 - 15:00	1.63
03:00 - 04:00	0.30	15:00 - 16:00	1.47
04:00 - 05:00	0.47	16:00 - 17:00	1.17
05:00 - 06:00	0.73	17:00 - 18:00	0.87
06:00 - 07:00	0.90	18:00 - 19:00	0.83
07:00 - 08:00	0.83	19:00 - 20:00	0.73
09:00 - 10:00	1.20	21:00 - 22:00	0.50
10:00 - 11:00	1.63	22:00 - 23:00	0.63
11:00 - 12:00	1.67	23:00 - 24:00	0.40

Table 3.6: Estimated hourly load profile for Upanga

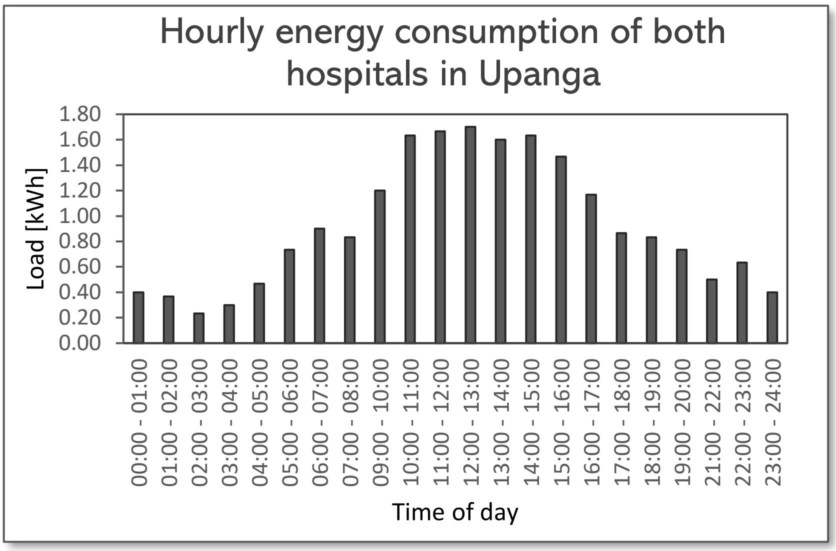

Figure 3.7: Hourly energy consumption of both hospitals in Upanga

Average energy consumption per day [kWh/day]	20.26
Average power consumption [kW]	0.845
Peak power consumption [kW]	2.960
Scaling factor	0.333

Table 3.7: Load data summary for hospitals in Upanga

3.6.2 Ngamiani load profile

Ngamiani consisted of only one hospital in its region with approximately 400 hospitals beds. Thus, when modelling the load profile for Ngamiani, it was important to make use of a different scaling factor. This factor provided a scaled energy consumption value for the Ngamiani hospital based on the ratio of the bed capacity in Ngamiani hospital (≈400 beds in total) to the bed capacity of the model Hamburg hospital (≈1500 beds). For example: if a heater in the Hamburg hospital (1500 beds) utilized 6.48kWh then for the Ngamiani hospital (400 beds), the heater would utilize: 6.48kWh * (400/1500) = 6.48kWh * (0.267) = 1.73kWh ; where 0.267 was the scaling factor. This factor was then applied to Table 3. 5 to generate an estimated load profile for Ngamiani as shown in Table 3. 8 and Figure 3. 8 below.

Time	Load [kWh]	Time	Load [kWh]
00:00 - 01:00	0.32	12:00 - 13:00	1.36
01:00 - 02:00	0.29	13:00 - 14:00	1.28
02:00 - 03:00	0.19	14:00 - 15:00	1.31
03:00 - 04:00	0.24	15:00 - 16:00	1.17
04:00 - 05:00	0.37	16:00 - 17:00	0.93
05:00 - 06:00	0.59	17:00 - 18:00	0.69
06:00 - 07:00	0.72	18:00 - 19:00	0.67
07:00 - 08:00	0.67	19:00 - 20:00	0.59
09:00 - 10:00	0.96	21:00 - 22:00	0.40
10:00 - 11:00	1.31	22:00 - 23:00	0.51
11:00 - 12:00	1.33	23:00 - 24:00	0.32

Table 3.8: Estimated hourly load profile for Ngamiani

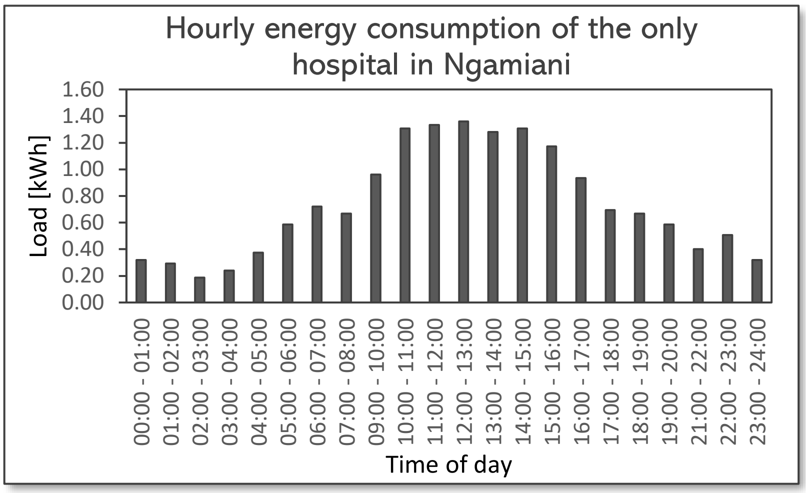

Figure 3.8: Hourly energy consumption of the only hospital in Ngamiani

Average Energy consumption per day [kWh/day]	16.22
Average power consumption [kW]	0.675
Peak power consumption [kW]	2.370
Scaling factor	0.267

Table 3.9: Load data summary for Ngamiani hospital

3.7 HRES modelling and its components in HOMER

Once, all the required data had been obtained, the modelling process for the various HRES configurations would take its shape. The following components from the HOMER library were chosen from a wide range of alternatives based on their respective characteristics and functionalities aiding in an optimal HRES system.

3.7.1 Solar PV

For this research, the solar PV system used was the CanadianSolar MaxPower CS6U-330P which consisted of 72 poly-crystalline cells and featured a reliable 4BB P-type solar cells. The output from this poly-crystalline module offered a nominal maximum power of 330W with an efficiency of up to 16.97%. The nominal operating cell temperature was 45°C and the PV module had a lifetime of up to 25 years. The following input data as seen in Table 3. 10 below was fed into HOMER for the chosen PV system with its datasheet seen in the Appendix. This component was chosen due to its high output power of 330W and comparatively low cost. Also, the nominal cell operating temperature being 45°C meant that it was perfectly suitable for the warm Tanzanian weather.

Description	Input data
Lifetime [years]	25
Derating factor [%]	88.00
Output power [W]	330.00
Temperature effects on power [%/°C]	-0.410
Nominal operating cell temperature [°C]	45.00
Efficiency at test conditions [%]	16.97
Ground Reflectance [%]	20.00
Capital cost [$/kW]	2500
Replacement cost [$/kW]	2500
Operational & Maintenance cost [$/year]	500

Table 3.10: Solar PV input data for HOMER

3.7.2 Wind Turbine

The chosen wind turbine for the hospitals in Upanga was the AWS HC 3.3kW which had a nominal capacity of 3.3kW with rotor diameter of 4.65m. This was a passive pitch control wind turbine with a hub height of 12m. This wind turbine was chosen due to its high-power output at a wind speed of around 6 m/s, which was nearly what the Upanga weather condition had to offer. The table below shows different wind turbines with their power outputs at 6m/s.

Wind turbines	Power output at 6m/s [kW]
Ennera Windera S	0.77
AWS HC 3.3kW	0.92
Generic 3kW	0.28
Xzeres Skystream 3.7	0.39

Table 3.11: Comparison of wind turbines

The following input data as seen in Table 3. 12 was fed into HOMER for the chosen wind turbine with its datasheet seen in the Appendix.

Description	Input data
Lifetime [years]	20
Rated power [kW]	3.30
Hub height [m]	12.00
Capital cost [$/kW]	25000
Replacement cost [$/kW]	25000
Operational & Maintenance cost [$/year]	800

Table 3.12: Wind turbine input data for HOMER

3.7.3 Storage

The energy storage system chosen for both the locations was the Discover 12VRE-3000TF lead acid battery due to its relatively high efficiency, reliability and cost effectiveness. The battery would be used to store the excess energy produced which would further be used either during power outages or to reduce the grid load. The table below shows different storage options with their respective roundtrip efficiencies.

Storage	Roundtrip efficiency [%]
Trojan SIND 06375	80
Discover 12VRE-3000TF	80
Gildemeister 20-40kWh CELLCUBE	64
Hoppecke 8OPz 800	86

Table 3.13: Comparison of wind turbines

Although the chosen storage did not have the highest roundtrip efficiency, it was optimal for this study as it provided a relatively high efficiency at a lower cost. The following input data as seen in Table 3. 14 below was fed into HOMER for the chosen energy storage option with its datasheet seen in the Appendix.

Description	Input data
Lifetime [years]	20
Minimum state of discharge [%]	20.00
Roundtrip efficiency [%]	80.00
Capital cost [$/kW]	410
Replacement cost [$/kW]	410
Operational & Maintenance cost [$/year]	10
Nominal capacity [Ah]	260

Table 3.14: Storage input data for HOMER

3.7.4 Diesel Generator

Diesel generators were also used in the HRES configuration as they would either act as a backup option when the renewable resources and the energy storage system fail to meet the load demand or they could work in parallel with the renewable resources to lessen the load burden on these resources. The diesel generator used for this study was the Generic 10kW fixed capacity genset diesel generator as it matched appropriately with the peak load demands of the hospitals in both Upanga and Ngamiani locations. The following input data as seen in Table 3. 15 was fed into HOMER for this chosen diesel generator.

Generator Description	Generic 10kW fixed capacity genset
Lifetime [hours]	15000
Minimum load ratio [%]	25.00
Rated Capacity [kW]	10.00
Capital cost [$/kW]	5000
Replacement cost [$/kW]	5000
Operational & Maintenance cost [$/year]	1500

Table 3.15: Diesel generator input data for HOMER

3.7.5 Converter

Converters were also added to the HRES configuration as they would provide with the interaction and conversion between the AC bus and the DC bus elements. The chosen converter (System Converter) consisted of both a rectifier and an inverter to provide for the electrical conversion on both the busses using only a single component. This component was chosen due to its duality of an inverter and rectifier, enabling to save cost purchasing individual components. The following input data as seen in Table 3. 16 was fed into HOMER for this chosen converter.

Converter Description	Input
Capital cost [$]	300
Replacement cost [$]	300
Operational & Maintenance cost [$/year]	0
Inverter lifetime [years]	15
Inverter efficiency [%]	95
Rectifier efficiency [%]	95
Rectifier capacity [%]	100

Table 3.16: Converter input data for HOMER

The summary of all the selected components for the HRES configuration is shown in Table 3. 17 below and their respective datasheets in the Appendix.

COMPONENT DESCRIPTION	INPUT DATA
Solar PV - CanadianSolar MaxPower CS6U-330P	
Lifetime [years]	25
Derating factor [%]	88
Output power [W]	330
Nominal operating cell temperature [°C]	45
Efficiency at test conditions [%]	16.97
Capital cost [$/kW]	2500
Replacement cost [$/kW]	2500
Operational & Maintenance cost [$/year]	500
Wind turbine - AWS HC 3.3kW	
Lifetime [years]	20
Rated power [kW]	3.3
Hub height [m]	12
Capital cost [$/kW]	25000
Replacement cost [$/kW]	25000
Operational & Maintenance cost [$/year]	800
Energy storage - Discover 12VRE-3000TF lead acid battery	
Lifetime [years]	20
Minimum state of discharge [%]	20
Roundtrip efficiency [%]	80
Nominal capacity [Ah]	260
Capital cost [$/kW]	410
Replacement cost [$/kW]	410
Operational & Maintenance cost [$/year]	10
Diesel generator - Generic 10kW fixed capacity genset	
Lifetime [hours]	15000
Minimum load ratio [%]	25
Rated Capacity [kW]	10
Capital cost [$/kW]	5000
Replacement cost [$/kW]	5000
Operational & Maintenance cost [$/year]	1500
Converter - System Converter	
Capital cost [$]	300
Replacement cost [$]	300
Operational & Maintenance cost [$/year]	0
Inverter lifetime [years]	15
Inverter efficiency [%]	95
Rectifier efficiency [%]	95
Rectifier capacity [%]	100

Table 3.17: Summary of selected components

3.8 Optimization and sensitivity analysis

During simulations, various variables specified by the designer (i.e. the student) needs optimization in order to meet the requirements. These variables include the likes of the total number of PV arrays utilized, the total number of wind turbines used, the size of the generator and storage components selected and many other such parameters. HOMER optimizes these selections and outputs a wide range of options to select the optimal configuration from. These simulations are ranked in an order of increasing net present cost.

Once these various configurations were obtained based on their environmental impacts and technical feasibilities, an environmental analysis was conducted through determining the annual pollutant emission for each of the configurations presented. The pollutants under investigation were concentrations of carbon dioxide, carbon monoxide, sulphur dioxide, unburned hydrocarbons, particulate matter and nitrogen oxides. For the sensitivity analysis, various diesel prices and discount rates were considered for each location to determine the best possible HRES configuration. According to the global petrol prices website [18], the diesel prices in Tanzania for the year 2020 ranged from \$0.74 to \$0.78 with an average of \$0.767 per liter.

3.9 Parameters for simulation

In order to get a better picture of different HRES configurations and to compare them against one another, it was crucial to analyze and evaluate key parameters which act as baseline criterions for selection. Some of these key parameters involved when running the HRES simulations on HOMER include:

3.9.1 Net Present Cost (NPC)

For a selected component, the net present cost states the difference between the current value of all available operating and installing costs for that component to the current value of all available revenue the component accumulates throughout the project life cycle.

$$NPC = (current\ operating\ \&\ installing\ costs) - (current\ revenue\ of\ the\ component)$$

Equation 2

3.9.2 Cost of Energy (COE)

As defined in HOMER, the cost of energy refers to the average cost per kWh of useful energy generated by the component or system under investigation.

$$COE = \frac{[Ca] - [Cb*H]}{E} \quad \text{Equation 3}$$

Where: Ca = yearly system cost (\$/year)
Cb = boiler marginal cost (\$/kWh)
H = total thermal load served (kWh/year)
E = total electrical load served (kWh/year)

3.9.3 Operating cost

For a chosen system, the operating cost states the yearly value of the total revenues and costs apart from the initial capital costs.

$$Operating\ cost = Ca - C_{cap} \quad \text{Equation 4}$$

Where: Ca = total yearly cost (\$/year)
C_{cap} = total yearly capital cost (\$/year)

3.9.4 Renewable fraction percentage

This refers to the percentage of electrical energy distributed to the desired prioritized load which was extracted from one or more renewable resources. i.e. solar and wind resources for this research.

$$Ren.frac = \left[1 - \frac{En+Hn}{E+H}\right] * 100\% \quad Equation\ 5$$

Where: En = yearly production of nonrenewable electrical energy (kWh/year)
Hn = yearly nonrenewable thermal production (kWh/year)
H = total thermal load served (kWh/year)
E = total electrical load served (kWh/year)

3.9.5 Unmet load

This refers to the amount of load which the power generation system is unable to meet because the load demand exceeds the total power supplied to the load. This parameter is really important where there are priority loads because priority loads should never be unmet as they require constant power supply to run machineries and equipment's for saving a person's life. Thus, if the HRES configuration shows that there is a significant amount of unmet load then that system would either need to improve its storage option or have a better power generation capacity. All the loads described in HOMER, are categorized as only prioritized loads and thus whenever the unmet load is shown as 0%, it means that the priority load demands are being met.

3.9.6 Excess electricity

This parameter deals with the surplus of electrical energy accumulated when energy is neither used up by the load nor the storage option. This scenario occurs when the minimum output energy from either the generator or the renewable resource exceeds the load and the storage option. The excess energy cannot be absorbed by the storage option as it would be fully charged and thus, this excess electricity would be dissipated in a dump load. The presence of this parameter indicates that the HRES is overdesigned resulting in a higher cost for the system.

3.10 Case studies

The case studies implemented in this section consists of an amalgamation of the above-mentioned components in the HOMER simulation software to provide for an optimal HRES configuration. These studies rely on the following few assumptions to assist in simplifying the HRES modelling process.

- Maintaining a constant electric load throughout the years. The load data was based on hospital loads for one year, but it assumed that this electric load profile will remain constant for the whole project lifetime.
- A fixed 2% inflation rate was also considered.
- Energy and environmental losses in the solar PV and wind turbines were neglected.
- The HRES configurations were assumed to be constantly running 24/7.
- Storage option was considered vital due to the need of prioritized loads to immediately access electricity in case of a power failure or unmet load requirements. Thus, a continuous back up system such as the battery storage system was an essential component in providing a reliable optimal HRES combination and was hence used in all case studies as a fixed component.

Based on the above assumptions, seven case studies were developed, each with a different HRES configuration than the previous one. The following were the seven case studies that were used for hospitals in both the locations; Upanga and Ngamiani.

3.10.1 Case study I: Diesel generator with storage

This was the base case for the system as it was widely used in most of the typical off-grid communities in Tanzania. Both, Upanga and Ngamiani hospitals would use this stand-alone diesel generator as their primary source of electricity which would be connected to the AC bus for direct supply to the priority loads. The excess electricity generated would be stored in the battery pack which would be connected on the DC bus and be linked to the load via the converter. Figure 3. 9 below indicates these configurations for Upanga and Ngamiani.

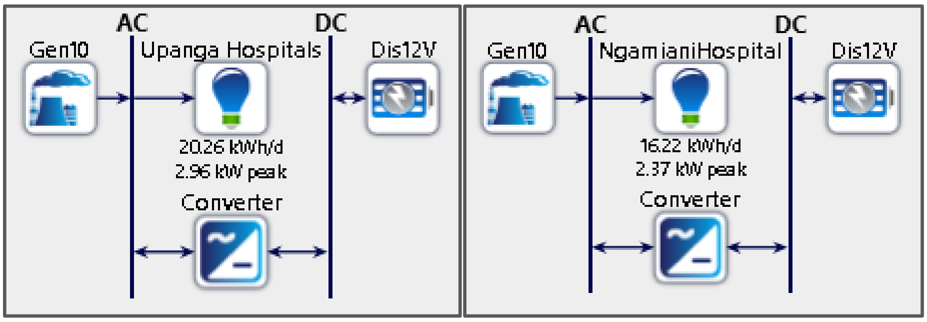

Figure 3.9: CSI schematic for Upanga and Ngamiani

3.10.2 Case study II: Solar PV with storage

This HRES configuration only considered a single renewable energy resource (solar PV) without a diesel generator to meet the priority load demands for both the locations. The solar PV array and the storage option were both connected to the DC bus and were supplying the priority loads in the AC bus using the system converter. Figure 3. 10 demonstrates this configuration.

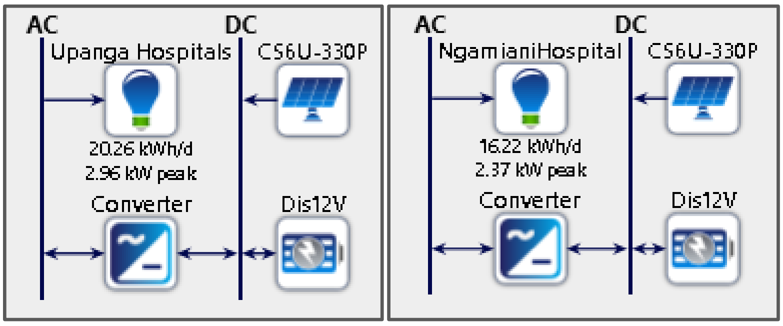

Figure 3.10: CSII schematic for Upanga and Ngamiani

3.10.3 Case study III: Wind turbine with storage

This HRES configuration only considered a single renewable energy resource (wind turbine) without a diesel generator to meet the priority load demands for Upanga. The wind turbine was supplying the priority loads in the AC bus and excess energy was stored in the battery using the system converter. Figure 3. 11 demonstrates this configuration.

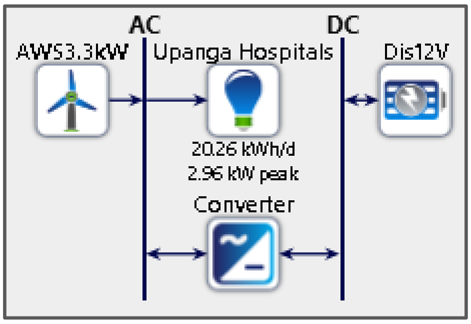

Figure 3.11: CSIII schematic for Upanga

3.10.4 *Case study IV: Solar PV and diesel generator with storage*

This HRES configuration only considered a single renewable energy resource (solar PV) with a diesel generator to meet the priority load demands for both the locations. Both the solar PV and the diesel generator were intended to work in unison to meet the required load demands. The solar PV array and the storage option were connected to the DC bus and were supplying the priority loads in the AC bus using the system converter whereas the diesel generator directly supplied to the load in the AC bus. Figure 3. 12 demonstrates this specific configuration.

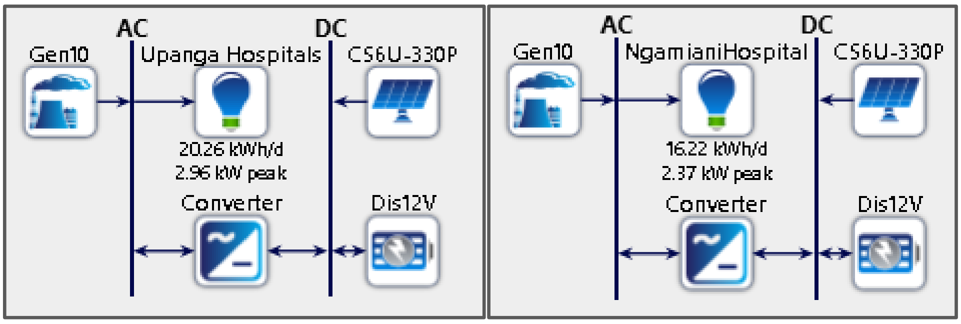

Figure 3.12: CSIV schematic for Upanga and Ngamiani

3.10.5 *Case study V: Wind turbine and diesel generator with storage*

This HRES configuration only considered a single renewable energy resource (wind turbine) with a diesel generator to fulfill the priority load demands. Both these components were intended to work in unison to meet the required load demands. The wind turbine and the diesel generator were supplying energy to priority loads in the AC bus and the storage was done by the battery in the DC bus using the system converter. Figure 3.13 demonstrates this configuration.

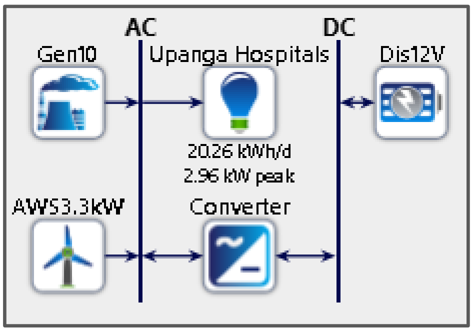

Figure 3.13: CSV schematic for Upanga

3.10.6 Case study VI: Solar PV and wind turbine with storage

This HRES configuration considered both the available renewable energy resources (solar and wind) to meet the priority load demands. Both these renewable resources were intended to work in unison to meet the required load demands. The solar PV and storage option were linked to the DC bus and were supplying the priority loads in the AC bus using the system converter whereas the wind turbine directly supplied to the load in the AC bus. Figure 3. 14 demonstrates this specific configuration.

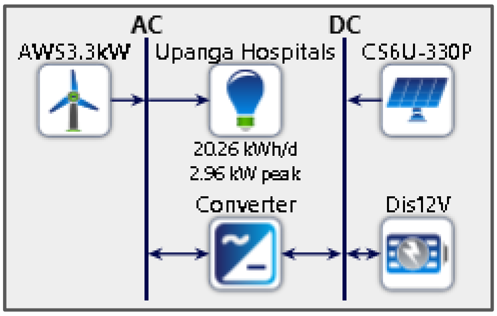

Figure 3.14: CSVI schematic for Upanga

3.10.7 Case study VII: Solar PV, wind turbine and diesel generator with storage

This HRES configuration considered all the three available sources of electricity generation, namely the diesel generator and the two available renewable energy resources (solar and wind) to meet the priority load demands. The solar PV, wind turbine and diesel generator were intended to work in unison to meet the required load demands. The solar PV array and the storage option were connected to the DC bus and were supplying the priority loads in the AC bus using the system converter whereas the wind turbine and diesel generator directly supplied to the load in the AC bus. Figure 3. 15 demonstrates this particular HRES configuration.

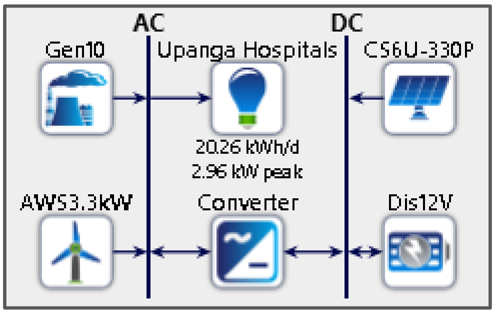

Figure 3.15: CSVII schematic for Upanga

4. Results

The following optimization results for each of the two locations were obtained for the various case studies identified above and then discussed to analyze the most optimal HRES configuration from the numerous combinations obtained. A nominal discount rate of 8% and an average diesel price of $0.767 per liter [18] were used as constant parameters for all the below optimization results. The sensitivity analysis section then covered the effects on NPC, COE, excess electricity and CO_2 emissions due to the variations in the discount rates and the diesel fuel prices.

4.1 Optimization results for Upanga

The Figure below shows the seven different HRES configurations for the hospitals in Upanga derived from the seven case studies discussed previously, with each of the components' respective sizes, quantities, net present costs and cost of energy listed below.

Architecture							
CS6U-330P (kW)	AWS3.3kW	Gen10 (kW)	Dis12V	Converter (kW)	Dispatch	NPC ($)	COE ($)
4.48		10.0	10	2.71	LF	$72,548	$0.623
		10.0	19	8.14	CC	$77,158	$0.662
1.58	1	10.0	6	3.55	LF	$81,121	$0.696
	1	10.0	20	5.83	CC	$81,746	$0.702
6.34			27	2.77	CC	$84,210	$0.723
5.25	1		24	3.33	CC	$113,286	$0.973
	3		68	5.00	CC	$171,720	$1.47

Figure 4.1: Optimization summary for Upanga

4.1.1 CSI: Standalone diesel generator with storage

The following model that was utilized in HOMER optimizer consisted of a 10kW fixed capacity diesel generator, a 9-string battery option and a 5kW converter. Figure 4. 2 indicates the optimization results for case study I for Upanga.

Architecture							
CS6U-330P (kW)	AWS3.3kW	Gen10 (kW)	Dis12V	Converter (kW)	Dispatch	NPC ($)	COE ($)
		10.0	9	5.00	CC	$65,153	$0.682

Figure 4.2: Optimization results for CSI for Upanga

<u>Cost analysis:</u>

It was evident from Table 4.1 and Figure 4.3 which represented the cost summary for the base case, that the optimal standalone model for the diesel generator had an initial system cost of $10,190.00 and a relatively high COE of $0.682 with a total NPC of $65,152.91 or TZS 151,075,264.65 Tanzanian Shillings (taking an exchange rate of 2318.78 TZS per 1 US dollar as of 07/11/2020) [19]. The fuel cost totaled to 54% of the whole system cost indicating that running this system solely on fuel as a primary source of energy would be costly in the long run. The system however had a good operational and maintenance cost of $7,884.50 with a decent savings worth $713.51 making it economically feasible.

Component	Capital	Replacement	O&M	Fuel	Salvage	Total [$]	Total [TZS]
Discover 12VRE-3000TF	3,690.00	7,079.11	1,163.48	-	-459.98	11,472.61	26,602,458.62
Generic 10kW Fixed capacity genset	5,000.00	4,907.53	6,721.02	35,168.87	-133.75	51,663.67	119,796,684.72
System converter	1,500.00	636.41	-	-	-119.78	2,016.63	4,676,121.31
System	10,190.00	12,623.05	7,884.50	35,168.87	-713.51	65,152.91	151,075,264.65

Table 4.1: Cost summary for CSI for Upanga

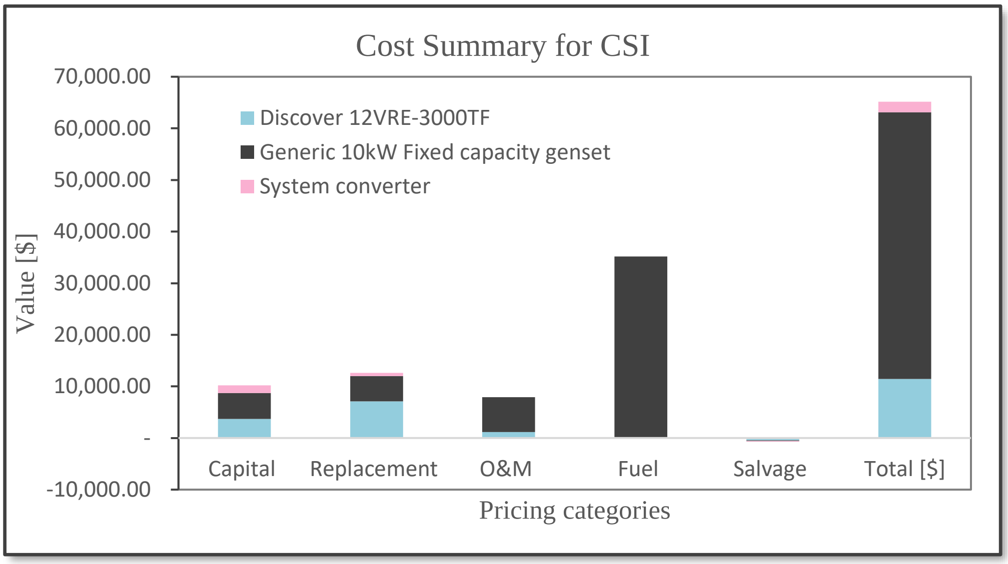

Figure 4.3: Cost Summary for CSI for Upanga

<u>Electrical analysis:</u>

The total yearly electrical production using a standalone diesel generator was 8,647 kWh/year with the AC primary load consumption standing at 7,395 kWh/year indicating an excess electricity of 220 kWh/year (which is 2.32% of the total electrical production) as seen from Table 4.2. Also, since this case study was solely based on a standalone generator, no renewable fraction was produced in this model and the unmet load percentage being 0% also indicated that the system was reliable.

Quantity	Value
Total electrical production [kWh/year]	8647.00
AC primary load [kWh/year]	7395.00
Excess electricity [kWh/year]	220.00
Excess electricity [%]	2.32
Unmet Electric load [%]	0.00
Renewable fraction [%]	0.00

Table 4.2: Electrical summary for CSI for Upanga

Figure 4.4 indicates that the monthly electric production using the diesel generator was fairly constant due to no dependence on the intermittent and irregular solar and wind resource availability. Figure 4.5 on the other hand, displays the annual generator power output capacity per hour. From there, it was seen that around 6 kW were used daily in the midday from 10:00 to 16:00 when the prioritized loads for Upanga also peaked as seen previously from Figure 3. 7.

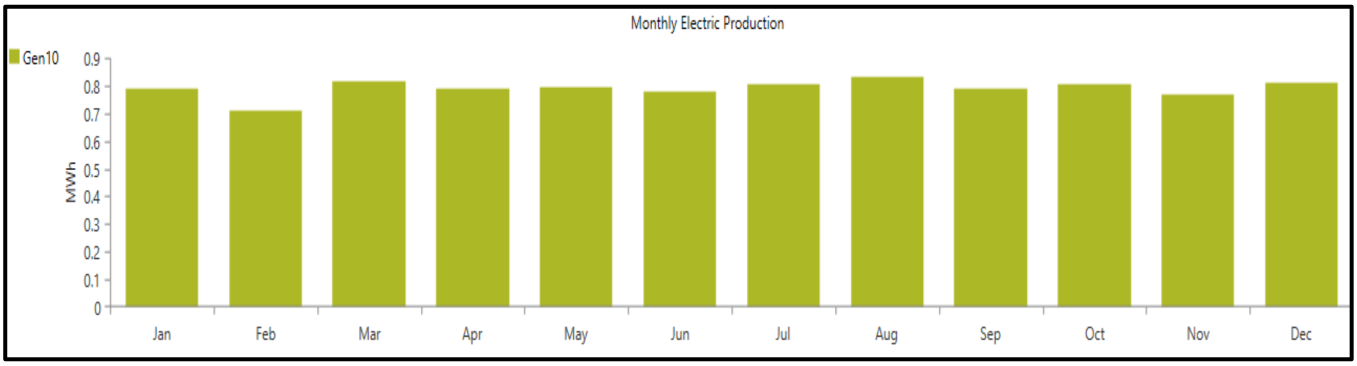

Figure 4.4: Monthly electrical production for CSI for Upanga

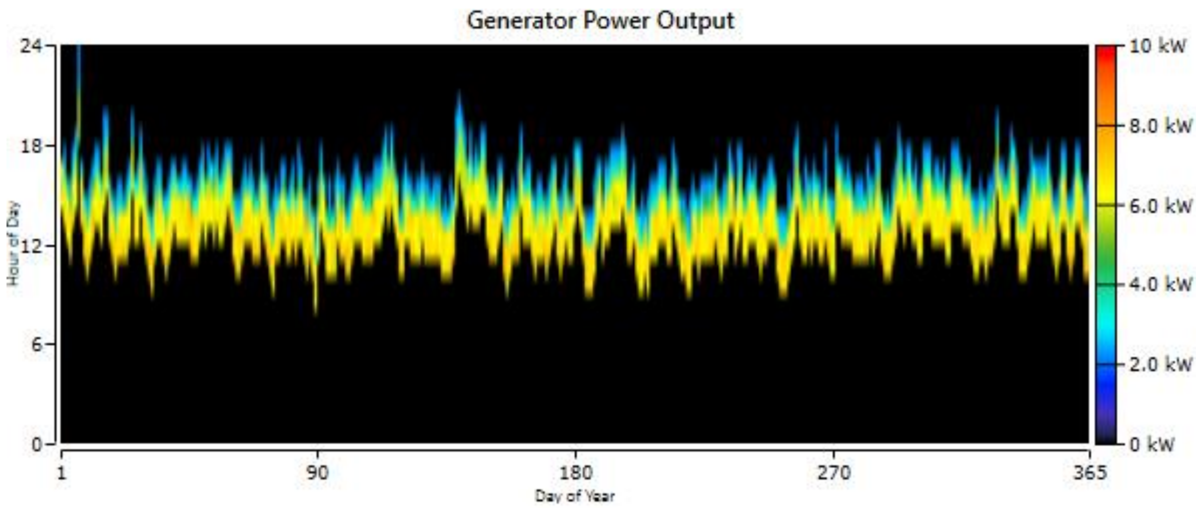

Figure 4.5: Generator power output for CSI for Upanga

Emissions analysis:

As seen from Table 4.3, the diesel generator on average had a total pollution quantity of 9445.30 kg/year from which 98.1% were carbon dioxide emissions. This was a relatively high number of CO_2 emissions considering that it is one of the leading factors for global warming and greenhouse gas emissions. The presence of such large quantities of pollutants was an indication of how non-environment friendly this system was.

Pollutant	Quantity [kg/year]
Carbon dioxide	9266.00
Carbon monoxide	70.10
Unburned hydrocarbons	2.55
Particulate matter	4.25
Sulphur dioxide	22.70
Nitrogen oxides	79.70
Total:	**9445.30**

Table 4.3: Emissions summary for CSI for Upanga

4.1.2 *CSII: Solar PV with storage*

The optimal model that was utilized in the HOMER optimizer consisted of a 6.34kW CS6U-330P solar PV module with a 27-string battery option and a 2.77kW converter. Figure 4.6 indicates the optimization results for this case study in Upanga.

Architecture							
CS6U-330P (kW)	AWS3.3kW	Gen10 (kW)	Dis12V	Converter (kW)	Dispatch	NPC ($)	COE ($)
6.34			27	2.77	LF	$74,009	$0.774
6.34			27	2.77	CC	$74,009	$0.774

Figure 4.6: Optimization summary for CSII for Upanga

<u>Cost analysis:</u>

It was evident from Table 4.4 and Figure 4.7 which represented the cost summary for this case study, that the optimal solar PV HRES model had an initial cost of $27,740.82 and a relatively high COE of $0.774 with a total NPC of $74,008.77 or TZS 171,610,055.70 Tanzanian Shillings (taking an exchange rate of 2318.78 TZS per 1 US dollar as of 07/11/2020) [19]. There was no fuel cost which indicated that the system was solely running on renewable solar resource as a primary source of energy. The system however had a relatively high operational and maintenance cost of $44,441.04 making it economically unfeasible.

Component	Capital	Replacement	O&M	Fuel	Salvage	Total [$]	Total [TZS]
CanadianSolar MaxPower CS6U-330P	15,838.54	-	40,950.61	-	-	56,789.15	131,681,545.24
Discover 12VRE-3000TF	11,070.00	3,529.20	3,490.43	-	- 1,988.93	16,100.70	37,333,981.15
System converter	832.27	353.11	-	-	- 66.46	1,118.92	2,594,529.32
System	27,740.82	3,882.31	44,441.04	-	- 2,055.39	74,008.77	171,610,055.70

Table 4.4: Cost summary for CSII for Upanga

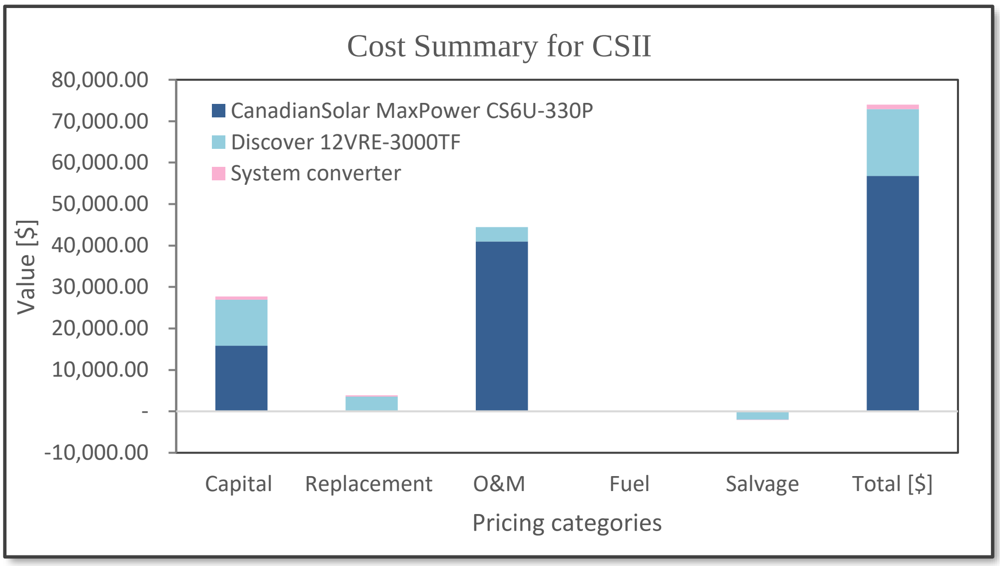

Figure 4.7: Cost summary for CSII for Upanga

Electrical analysis:

The total yearly electrical production using just a solar PV system was 9,845 kWh/year with the AC primary load consumption standing at 7,395 kWh/year indicating an excess electricity of 1418 kWh/year (which is 14.40 % of the total electrical production) as seen from Table 4.5. This excess electricity could neither be absorbed by the storage nor the load and was thus dissipated in a dump load [such as a resistive heater]. The large presence of this excess electricity parameter indicated that this HRES was overdesigned resulting in a higher cost for the system and lower energy efficiency. Also, since this case study was solely based on solar PV, the renewable fraction produced in this model was 100% and the unmet load percentage being close to 0% indicated that the system was reliable in meeting the load demands.

Quantity	Value
Total electrical production [kWh/year]	9,845.00
AC primary load [kWh/year]	7,395.00
Excess electricity [kWh/year]	1,418.00
Excess electricity [%]	14.40
Unmet Electric load [%]	0.01
Renewable fraction [%]	100.00

Table 4.5: Electrical summary for CSII for Upanga

Figure 4.8 indicates that the monthly electric production using the solar PV was not constant throughout the year due to its dependence on the intermittent and irregular solar resource availability. Figure 4.9 on the other hand, displays the annual PV power output capacity per hour. From there, it was seen that around 5 kW were used daily in the midday from 10:00 to 16:00 when the prioritized loads for Upanga also peaked as seen previously from Figure 3.7 and gradually decreased to around 1.2 kW at 18:00 up to no solar power in the evening after sunset. During this period (18:00 – 06:00), the battery which stored energy during daytime would be used to meet the load demands and supply relevant power to the hospitals. Thus, a large number of battery capacity (27-strings) as seen in Figure 4.6 were used.

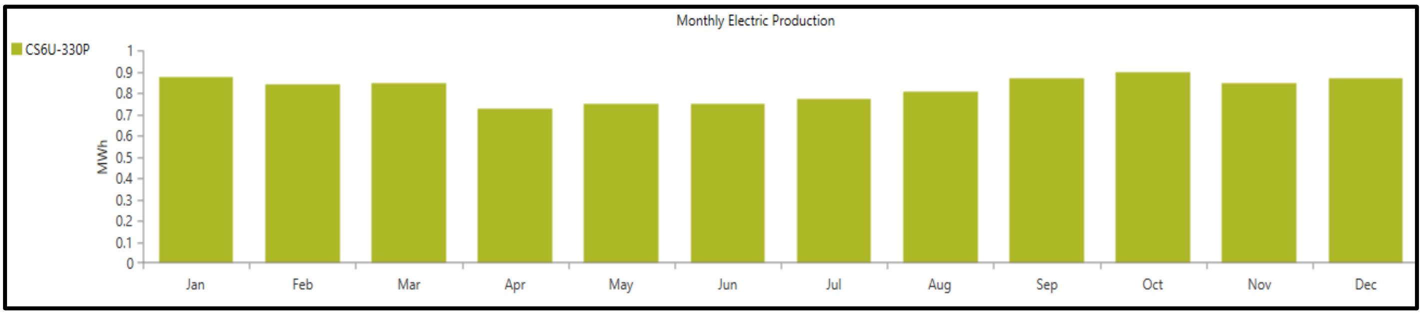

Figure 4.8: Monthly electrical production for CSII for Upanga

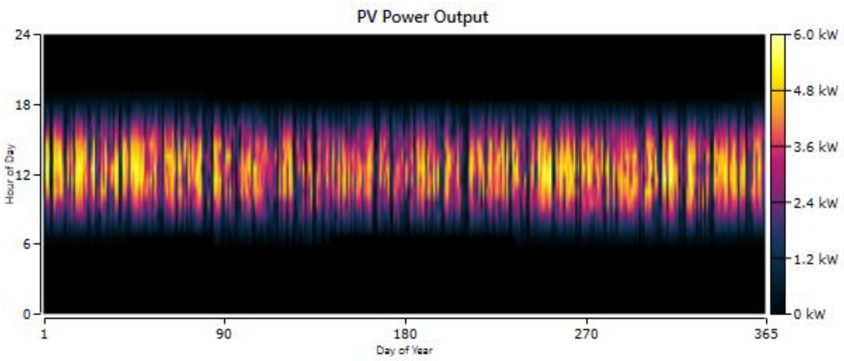

Figure 4.9: Solar PV output for CSII for Upanga

Emissions analysis:
Since this was a purely renewable system, no emissions were obtained and calculated from it and it thus had a renewable fraction of 100% making it completely environmentally friendly.

4.1.3 CSIII: Wind turbine with storage

The optimal model that was utilized in the HOMER optimizer consisted of three 3.3kW AWS wind turbines with a 68-string battery option and a 5.00 kW converter. Figure 4.10 indicates the optimization results for this case study in Upanga. The system used three wind turbines in the optimal model due to wind being irregular in nature and it would thus be unsafe to depend on just one wind turbine to meet the load demands and ensure consistent power was supplied to the hospitals.

Architecture												
					CS6U-330P (kW)	AWS3.3kW	Gen10 (kW)	Dis12V	Converter (kW)	Dispatch	NPC ($)	COE ($)
						3		68	5.00	CC	$159,028	$1.66

Figure 4.10: Optimization summary for CSIII for Upanga

Cost analysis:
From Table 4.6 and Figure 4.11 which represented the cost summary for case study III, the optimal wind turbine HRES model had an initial cost of $104,380.00 and a very high COE of $1.66 with a total NPC of $159,028.00 or TZS 368,750,945.84 Tanzanian Shillings (taking an exchange rate of 2318.78 TZS per 1 US dollar as of 07/11/2020) [19]. There was no fuel cost which indicated that the system was solely running on renewable wind resource as a primary source of energy. The system however had a relatively high operational and maintenance cost of $39,816.75 making it economically unfeasible.

Component	Capital	Replacement	O&M	Fuel	Salvage	Total [$]	Total [TZS]
AWS HC 3.3kW Wind turbine	75,000.00	23,910.55	31,026.04	-	-13,475.13	116,461.46	270,048,504.22
Discover 12VRE-3000TF	27,880.00	8,888.35	8,790.71	-	- 5,009.15	40,549.91	94,026,320.31
System converter	1,500.00	636.41	-	-	- 119.78	2,016.63	4,676,121.31
System	104,380.00	33,435.31	39,816.75	-	-18,604.06	159,028.00	368,750,945.84

Table 4.6: Cost summary for CSIII for Upanga

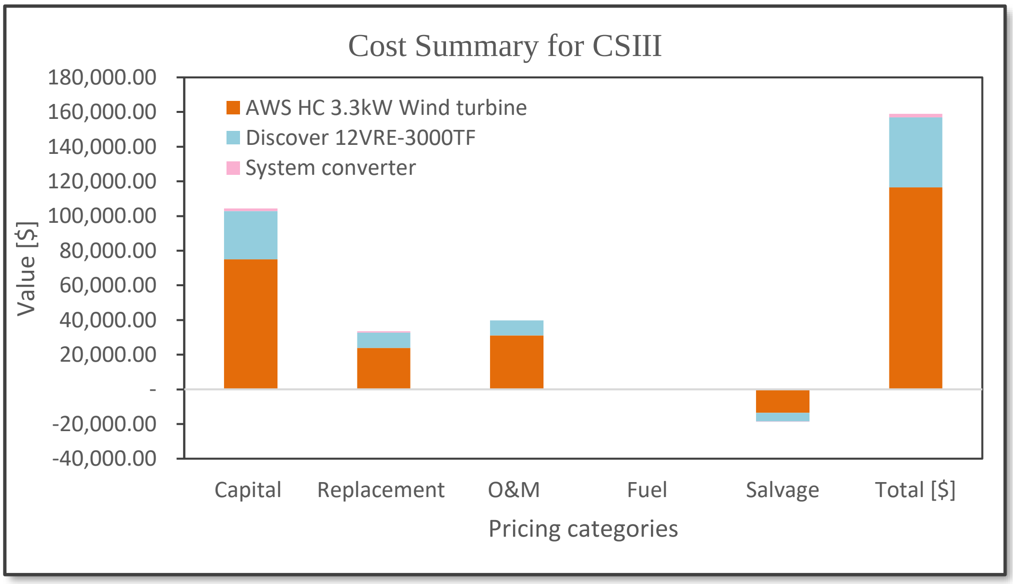

Figure 4.11: Cost summary for CSIII for Upanga

Electrical analysis:

The total yearly electrical production using the three wind turbines system were 16,239 kWh/year with the AC primary load consumption standing at 7,392 kWh/year indicating an excess electricity of 8106 kWh/year (which is 49.90 % of the total electrical production) as seen from Table 4.7. This excess electricity could neither be absorbed by the storage nor the load and was thus dissipated in a dump load. The large presence of this excess electricity parameter indicated that this HRES was overdesigned resulting in a higher cost for the system and lower energy efficiency. Also, since this case study was solely based on wind turbines, the renewable fraction produced in this model was 100% and the unmet load percentage of 0.04% indicated that the system was reliable in meeting the load demands.

Quantity	Value
Total electrical production [kWh/year]	16,239.00
AC primary load [kWh/year]	7,392.00
Excess electricity [kWh/year]	8,106.00
Excess electricity [%]	49.90
Unmet Electric load [%]	0.04
Renewable fraction [%]	100.00

Table 4.7: Electrical summary for CSIII for Upanga

Figure 4.12 indicates that the monthly electric production using the three wind turbines was not constant throughout the year due to its dependence on the intermittent and irregular wind resource availability. During the months of April to August, the system had electric production due to increased wind activities in these months. Figure 4.13 on the other hand, displays the annual wind turbine power output capacity per hour. From there, it was seen that the wind turbine did not operate continuously and that around 8 kW were used in the evenings in the mid-months of the year. During the other times, the battery storage system would be used to meet the load demands and supply relevant power to the hospitals. Thus, a large number of battery capacity [68-strings] as seen in Figure 4.10 were used.

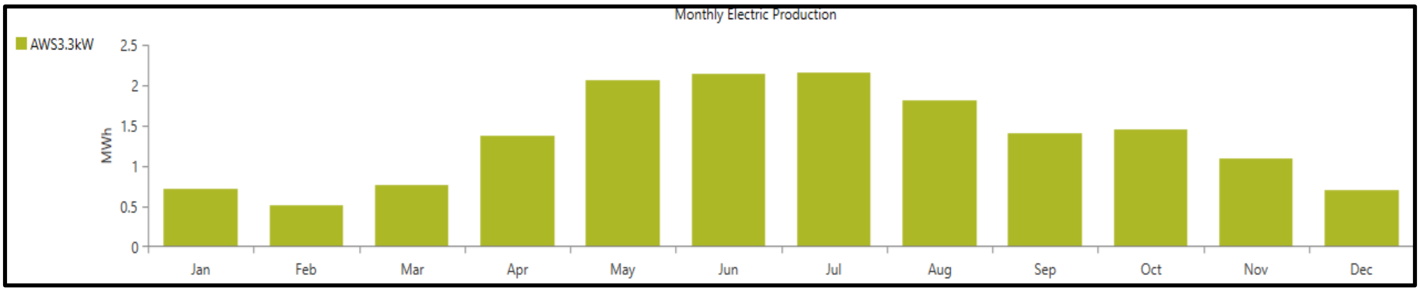

Figure 4.12: Monthly electrical production for CSIII for Upanga

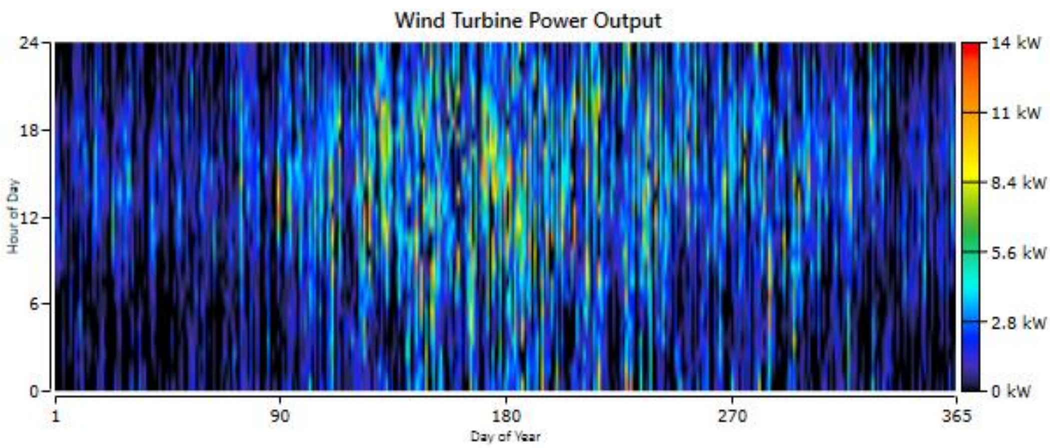

Figure 4.13: Wind turbine power output for CSIII for Upanga

Emissions analysis:

Since this was a purely renewable system, no emissions were obtained and calculated from it and it thus had a renewable fraction of 100% making it completely environmentally friendly.

4.1.4 CSIV: Solar PV and diesel generator with storage

The optimal model that was utilized in the HOMER optimizer consisted of a 6.34kW CS6U-330P solar PV module with an 8-string battery option, a 10-kW fixed capacity diesel generator and a 2.77kW converter. Figure 4.14 indicates the optimization results for this case study in Upanga.

Architecture							
CS6U-330P (kW)	AWS3.3kW	Gen10 (kW)	Dis12V	Converter (kW)	Dispatch	NPC ($)	COE ($)
4.41		10.0	8	2.71	LF	$63,137	$0.660
4.41		10.0	8	2.68	LF	$63,146	$0.661
4.44		10.0	8	2.74	LF	$63,147	$0.661

Figure 4.14: Optimization summary for CSIV for Upanga

Cost analysis:

Table 4.8 and Figure 4.15 which represented the cost summary for case study IV, showed that the optimal HRES model had an initial cost of $20,111.47 and a relatively low COE of $0.66 with a total NPC of just $63,136.93 or TZS 146,400,650.55 Tanzanian Shillings (taking an exchange rate of 2318.78 TZS per 1 US dollar as of 07/11/2020) [19]. The fuel cost was at a minimum of only 12.3% of the overall system cost which indicated that the system was largely running on the renewable solar resource as a primary source of energy. The system costs were relatively low with savings worth of $1,520.31 making it economically feasible.

Component	Capital	Replacement	O&M	Fuel	Salvage	Total [$]	Total [TZS]
CanadianSolar MaxPower CS6U-330P	11,019.89	-	28,491.97	-	-	39,511.86	91,619,310.73
Discover 12VRE-3000TF	3,280.00	2,912.98	1,034.20	-	- 379.49	6,847.69	15,878,286.62
Generic 10kW Fixed capacity genset	5,000.00	1,366.63	2,563.53	7,832.13	- 1,076.01	15,686.28	36,373,032.34
System converter	811.58	344.33	-	-	- 64.81	1,091.10	2,530,020.86
System	20,111.47	4,623.94	32,089.70	7,832.13	- 1,520.31	63,136.93	146,400,650.55

Table 4.8: Cost summary for CSIV for Upanga

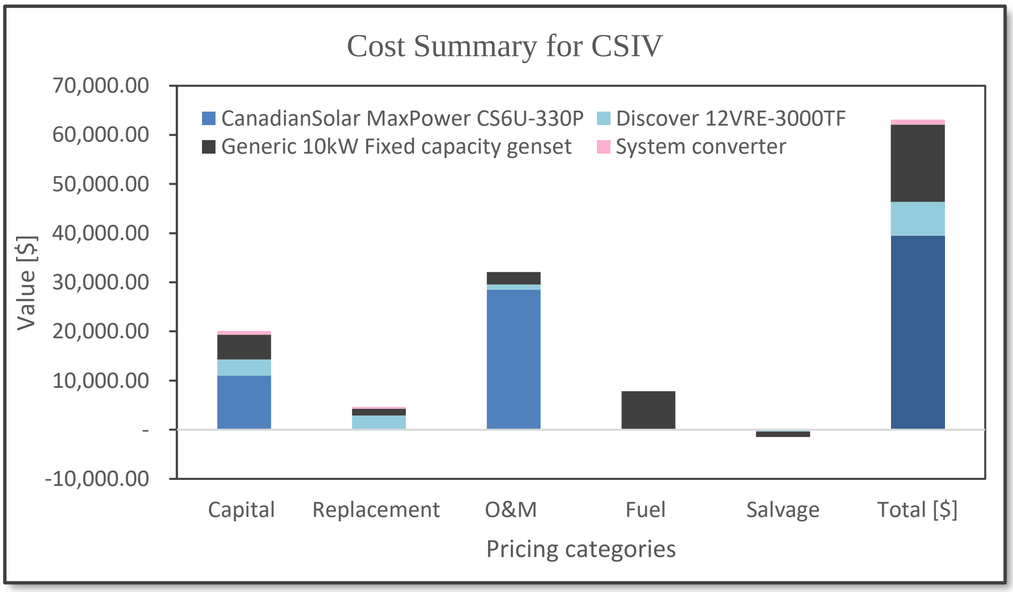

Figure 4.15: Cost summary for CSIV for Upanga

Electrical analysis:

The total yearly electrical production using a combination of both solar PV and generator was 8,503 kWh/year with the AC primary load consumption standing at 7,395 kWh/year indicating an excess electricity of just 86.30 kWh/year (which is only 1.01 % of the total electrical production) as seen from Table 4.9. Furthermore, since this case study was largely based on solar PV but also had a diesel generator presence, the renewable fraction produced by this model was 77.70% and the unmet load percentage was 0% indicating that the system was reliable in meeting the load demands.

Quantity	Value
Total electrical production [kWh/year]	8503.00
AC primary load [kWh/year]	7395.00
Excess electricity [kWh/year]	86.30
Excess electricity [%]	1.01
Unmet Electric load [%]	0.00
Renewable fraction [%]	77.70

Table 4.9: Electrical summary for CSIV for Upanga

Figure 4.16 indicates that the monthly electric production using this combination was relatively constant throughout the year. It showed how the solar PV and the generator worked in tandem to supply the desired electric demand by the load. It also indicated that the majority of the electricity generated was from the PV module indicating a high presence of renewable resource.

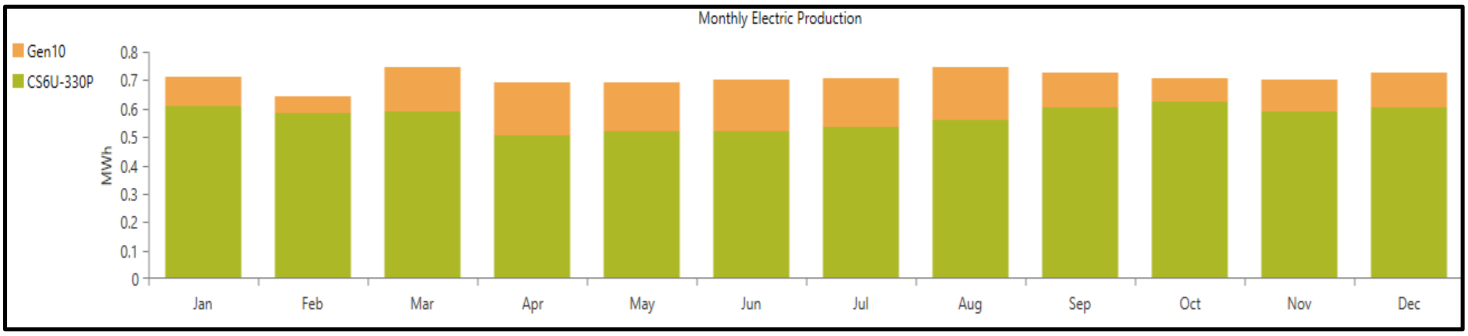

Figure 4.16: Monthly electrical production for CSIV for Upanga

Figure 4.17 and 4.18 on the other hand, displays the annual generator and PV power output capacity per hour respectively. From there, it was seen how both these components worked in tandem to meet the load demands. i.e. when the sun was out, it was mostly the solar PV generating power whereas at night and early mornings, it was the generator which was responsible to deliver power to the load.

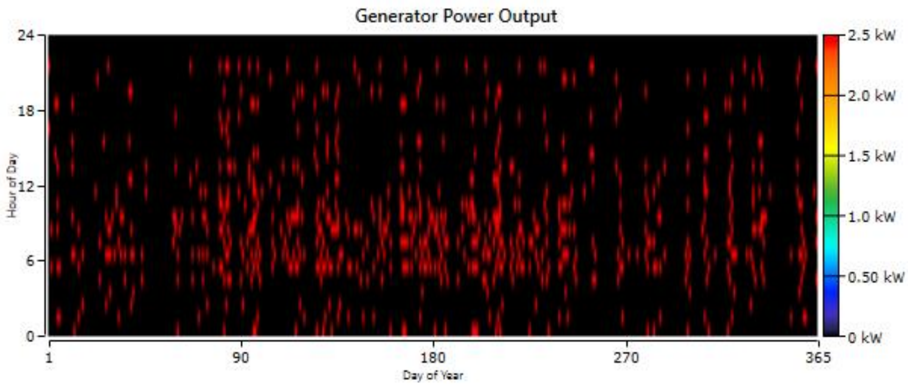

Figure 4.17: Generator power output for CSIV for Upanga

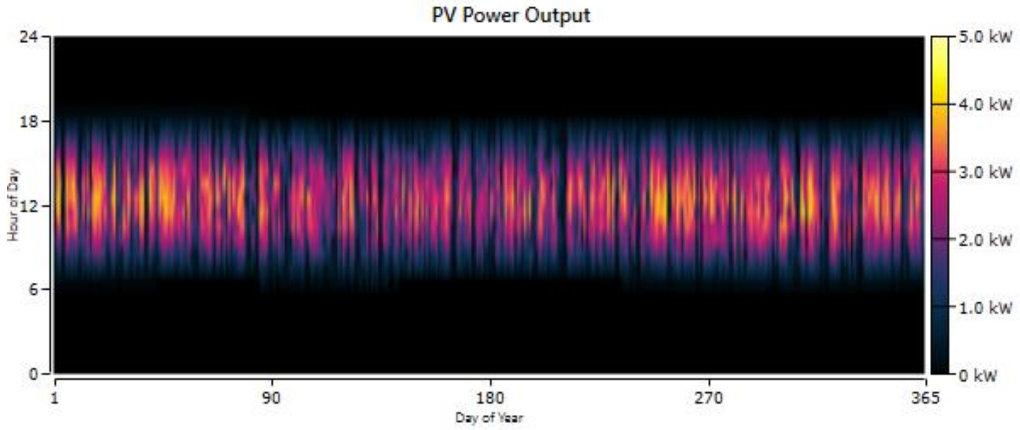

Figure 4.18: Solar PV power output for CSIV for Upanga

Emissions analysis:

From Table 4.9, it was seen that this system had a renewable fraction of 77.70% as most of it was run by solar PV which is a clean source of energy. The diesel generator on the other hand does produce emissions as its by product which harms the environment as seen from Table 4.10. The chosen diesel generator for this system on average had a total pollution quantity of 2064.00 kg/year from which 98.11% was carbon dioxide emissions. Despite having pollutants, this system does ensure that these emissions are at a minimum by having as much dependence on solar as possible and only utilizing the generator during extreme load crisis.

Pollutant	Quantity [kg/year]
Carbon dioxide	2064.00
Carbon monoxide	15.60
Unburned hydrocarbons	0.57
Particulate matter	0.95
Sulphur dioxide	5.06
Nitrogen oxides	17.70
Total:	**2103.88**

Table 4.10: Emissions summary for CSIV for Upanga

4.1.5 *CSV: Wind turbine and diesel generator with storage*

The optimal model that was utilized in the HOMER optimizer consisted of a 3.3kW AWS wind turbine with a 20-string battery option, a 10-kW fixed capacity diesel generator and a 5.83kW converter. Figure below indicates the optimization results for this case study in Upanga.

Architecture												
					CS6U-330P (kW)	AWS3.3kW	Gen10 (kW)	Dis12V	Converter (kW)	Dispatch	NPC ($)	COE ($)
						1	10.0	20	5.83	CC	$74,017	$0.774
						1	10.0	17	7.69	CC	$74,044	$0.775
						1	10.0	19	7.18	CC	$74,074	$0.775

Figure 4.19: Optimization summary for CSV for Upanga

Cost analysis:

Table 4.11 and Figure 4.20 which represented the cost summary for case study V, showed that the optimal HRES model had an initial cost of $39,950.00 and a relatively low COE of $0.774 with a total NPC of $74,017.13 or TZS 171,629,440.70 Tanzanian Shillings (taking an exchange rate of 2318.78 TZS per 1 US dollar as of 07/11/2020) [19]. The fuel cost was at a minimum of only 17.44% of the overall system cost which indicated that the system was largely running on the renewable wind resource as a primary source of energy. The system costs were relatively low with savings worth of $7,003.18 making it economically feasible.

Component	Capital	Replacement	O&M	Fuel	Salvage	Total [$]	Total [TZS]
AWS HC 3.3kW Wind turbine	25,000.00	7,970.18	10,342.01	-	- 4,491.71	38,820.48	90,016,152.61
Discover 12VRE-3000TF	8,200.00	2,942.45	2,585.50	-	- 1,189.91	12,538.04	29,072,956.39
Generic 10kW Fixed capacity genset	5,000.00	1,220.52	2,357.98	12,909.19	- 1,181.82	20,305.87	47,084,845.24
System converter	1,750.00	742.48	-	-	- 139.74	2,352.74	5,455,486.46
System	39,950.00	12,875.63	15,285.50	12,909.19	- 7,003.18	74,017.13	171,629,440.70

Table 4.11: Cost summary for CSV for Upanga

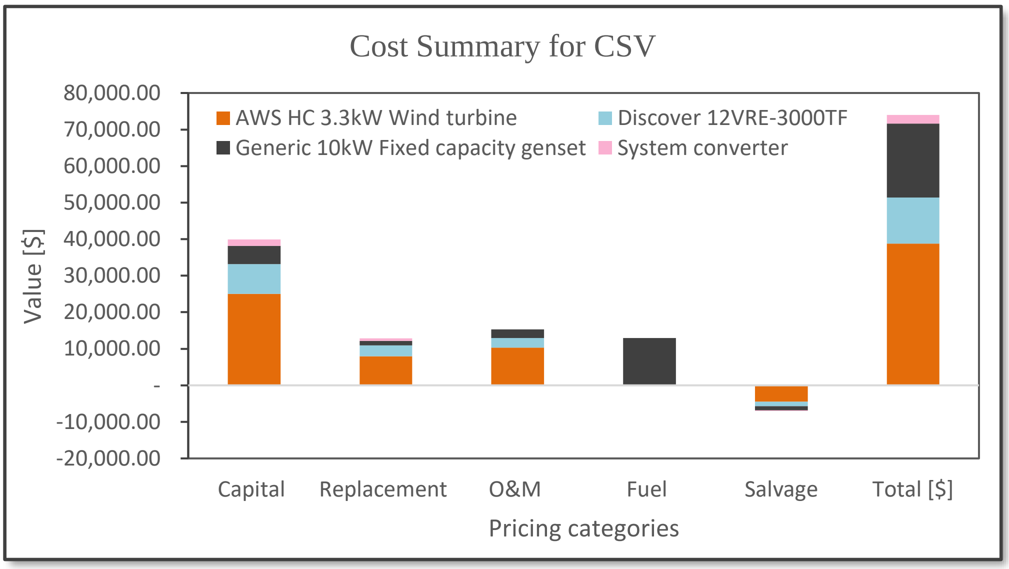

Figure 4.20: Cost summary for CSV for Upanga

Electrical analysis:

The total yearly electrical production using a combination of both the wind turbine and generator was 8,945 kWh/year with the AC primary load consumption standing at 7,395 kWh/year indicating an excess electricity of 289.00 kWh/year (which is only 3.23 % of the total electrical production) as seen from Table 4.12. Furthermore, since this case study was largely based on wind turbine but also had a diesel generator presence, the renewable fraction produced by this model was 52.20% and the unmet load percentage was 0% indicating that the system was reliable in meeting the load demands.

Quantity	Value
Total electrical production [kWh/year]	8945.00
AC primary load [kWh/year]	7395.00
Excess electricity [kWh/year]	289.00
Excess electricity [%]	3.23
Unmet Electric load [%]	0.00
Renewable fraction [%]	52.20

Table 4.12: Electrical summary for CSV for Upanga

Figure 4.21 indicates that the monthly electric production using this combination was relatively constant throughout the year. From this, it was seen how both these components worked in tandem to meet the load demands. i.e. when the wind speeds were high, it was mostly the wind turbine generating power whereas during off-peak wind months, the diesel generator took over to supply most of the load demands.

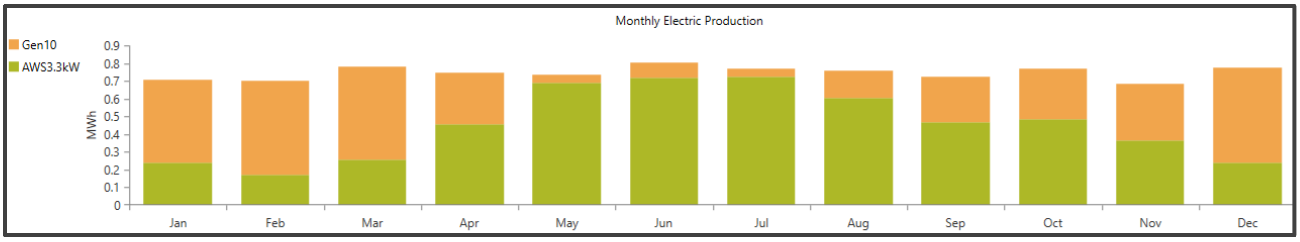

Figure 4.21: Monthly electrical production for CSV for Upanga

<u>Emissions analysis</u>:

From Table 4.12, it was seen that this system had a renewable fraction of 52.20% as almost half of it was run by wind which is a clean source of energy. The diesel generator on the other hand does produce emissions as its by product which harms the environment as seen from Table 4.13. The chosen diesel generator for this system on average had a total pollution quantity of 3401.00 kg/year from which 98% was carbon dioxide emissions. Despite having pollutants, this system does ensure that these emissions are at a minimum by having as much dependence on wind as possible and only utilizing the generator during extreme load crisis.

Pollutant	Quantity [kg/year]
Carbon dioxide	3401.00
Carbon monoxide	25.70
Unburned hydrocarbons	0.94
Particulate matter	1.56
Sulphur dioxide	8.35
Nitrogen oxides	29.20
Total:	**3466.75**

Table 4.13: Emissions summary for CSV for Upanga

4.1.6 CSVI: Solar PV and wind turbine with storage

The optimal model that was utilized in the HOMER optimizer consisted of a 5.25kW CS6U-330P solar PV module, a 3.3kW AWS wind turbine with a 24-string battery option and a 3.33kW converter. Figure below indicates the optimization results for this case study in Upanga.

Architecture												
					CS6U-330P (kW)	AWS3.3kW	Gen10 (kW)	Dis12V	Converter (kW)	Dispatch	NPC ($)	COE ($)
					5.25	1		24	3.33	CC	$101,536	$1.06

Figure 4.22: Optimization summary for CSVI for Upanga

Cost analysis:

Table 4.14 and Figure 4.23 which represented the cost summary for this case study, showed that the optimal HRES model had an initial cost of $48,965.00 and a relatively high COE of $1.06 with a total NPC of $101,536.35 or TZS 235,440,457.65 Tanzanian Shillings (taking an exchange rate of 2318.78 TZS per 1 US dollar as of 07/11/2020) [19]. There was no fuel cost to this system which indicated that it was solely running on the renewable solar and wind resources as the primary sources of energy. The system costs were however relatively high making this system economically unfeasible.

Component	Capital	Replacement	O&M	Fuel	Salvage	Total [$]	Total [TZS]
AWS HC 3.3kW Wind turbine	25,000.00	7,970.18	10,342.01	-	- 4,491.71	38,820.48	90,016,152.61
CanadianSolar MaxPower CS6U-330P	13,125.00	-	33,934.73	-	-	47,059.73	109,121,160.73
Discover 12VRE-3000TF	9,840.00	3,137.06	3,102.60	-	- 1,767.94	14,311.72	33,185,730.10
System converter	1,000.00	424.27	-	-	- 79.85	1,344.42	3,117,414.21
System	48,965.00	11,531.51	47,379.34	-	- 6,339.50	101,536.35	235,440,457.65

Table 4.14: Cost summary for CSVI for Upanga

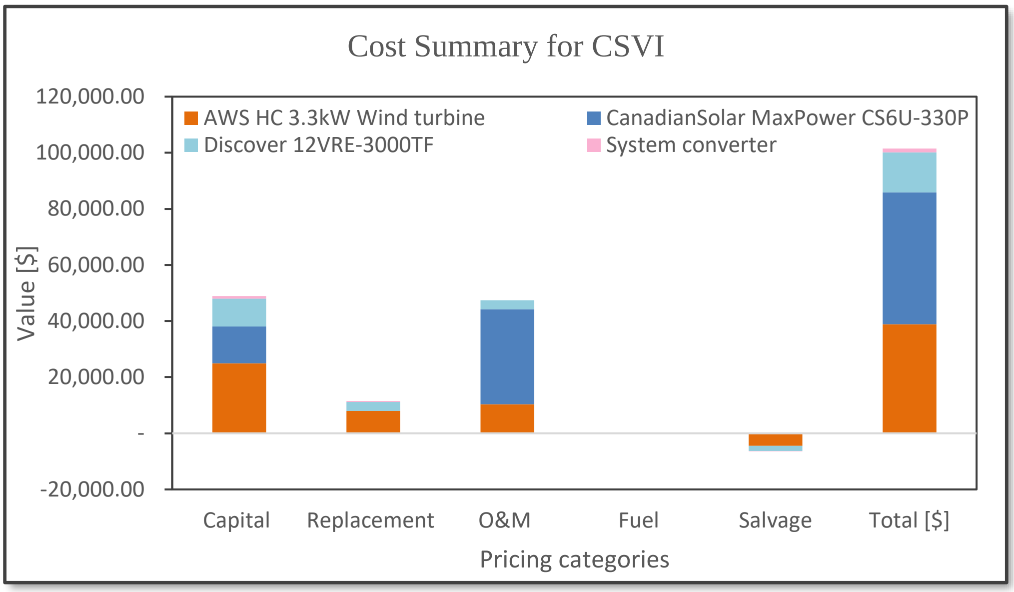

Figure 4.23: Cost summary for CSVI for Upanga

Electrical analysis:

The total yearly electrical production using a combination of both the solar and wind turbine was 13,572 kWh/year with the AC primary load consumption standing at 7,395 kWh/year indicating an excess electricity of 5651.00 kWh/year (which is 41.60 % of the total electrical production) as seen from Table 4.15. Furthermore, since this case study was solely based on wind and solar resources, the renewable fraction produced by this model was 100% and the unmet load percentage was 0% indicating that the system was reliable in meeting the load demands. However, the presence of a high percentage of excess electricity made this system less energy efficient due to large wastage of energy.

Quantity	Value
Total electrical production [kWh/year]	13572.00
AC primary load [kWh/year]	7395.00
Excess electricity [kWh/year]	5651.00
Excess electricity [%]	41.60
Unmet Electric load [%]	0.00
Renewable fraction [%]	100.00

Table 4.15: Electrical summary for CSVI for Upanga

Figure below indicates that the monthly electric production using this combination was relatively constant throughout the year. From this, it was seen how both these components worked in tandem to meet the load demands. i.e. when the wind speeds were high, it was mostly the wind turbine generating power whereas during off-peak wind months and peak summer months, the solar PV took over to supply most of the load demands.

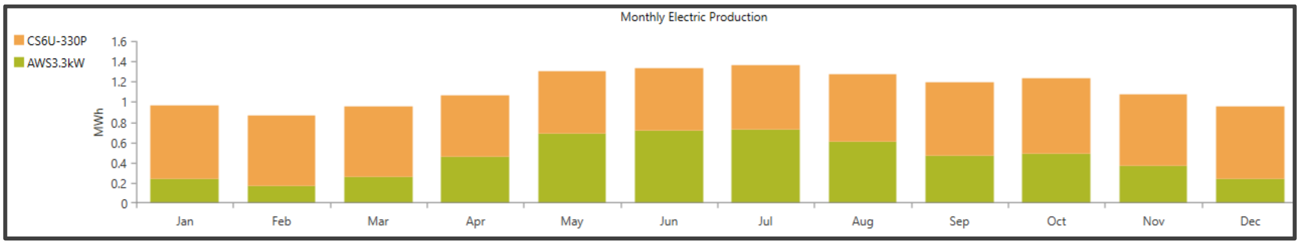

Figure 4.24: Monthly electric production for CSVI for Upanga

Emissions analysis:
Since this was a purely renewable system, no emissions were obtained and calculated from it and it thus had a renewable fraction of 100% making it completely environmentally friendly.

4.1.7 CSVII: Solar PV, wind turbine and diesel generator with storage

The optimal model that was utilized in the HOMER optimizer consisted of a 1.58kW CS6U-330P solar PV module, a 3.3kW AWS wind turbine, a 10kW fixed capacity diesel generator with a 6-string battery option and a 3.55kW converter. Figure below indicates the optimization results for this case study in Upanga.

Architecture												
					CS6U-330P (kW)	AWS3.3kW	Gen10 (kW)	Dis12V	Converter (kW)	Dispatch	NPC ($)	COE ($)
					0.219	1	10.0	5	3.33	LF	$75,074	$0.785
					1.72	1	10.0	4	1.83	LF	$76,084	$0.796
					1.58	1	10.0	6	3.55	LF	$73,122	$0.765

Figure 4.25: Optimization summary for CSVII for Upanga

Cost analysis:

Table 4.16 and Figure 4.26 which represented the cost summary for this case study, showed that the optimal HRES model had an initial cost of $37,481.57 and a relatively high COE of $0.765 with a total NPC of $73,122.02 or TZS 169,553,877.54 Tanzanian Shillings (taking an exchange rate of 2318.78 TZS per 1 US dollar as of 07/11/2020) [19]. The fuel cost was at a minimum of only 8.95% of the overall system cost which indicated that the system was largely running on the renewable solar and wind resources as the primary sources of energy. The system costs were relatively low with savings worth of $4,974.90 making it economically feasible.

Component	Capital	Replacement	O&M	Fuel	Salvage	Total [$]	Total [TZS]
AWS HC 3.3kW Wind turbine	25,000.00	7,970.18	10,342.01	-	- 4,491.71	38,820.48	90,016,152.61
CanadianSolar MaxPower CS6U-330P	3,956.62	-	10,229.85	-	-	14,186.47	32,895,302.91
Discover 12VRE-3000TF	2,460.00	2,164.43	775.65	-	- 302.33	5,097.75	11,820,560.75
Generic 10kW Fixed capacity genset	5,000.00	-	2,140.80	6,540.60	- 95.82	13,585.58	31,501,971.19
System converter	1,064.95	451.83	-	-	- 85.04	1,431.74	3,319,890.08
System	37,481.57	10,586.44	23,488.31	6,540.60	- 4,974.90	73,122.02	169,553,877.54

Table 4.16: Cost summary for CSVII for Upanga

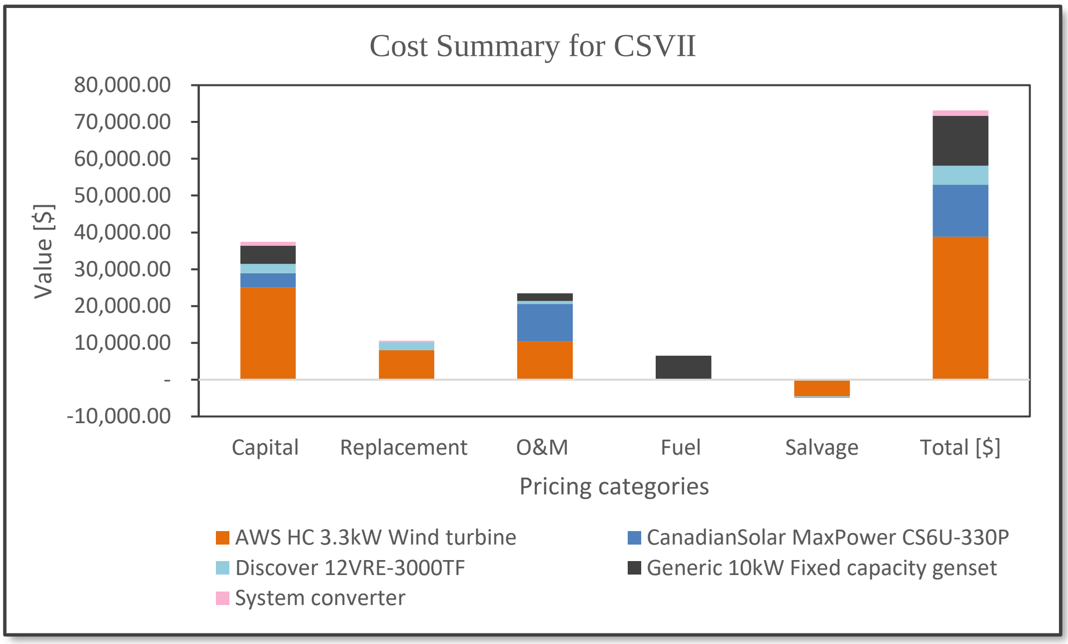

Figure 4.26: Cost summary for CSVII for Upanga

<u>Electrical analysis:</u>

The total yearly electrical production using this combination was 9,252 kWh/year with the AC primary load consumption standing at 7,395 kWh/year indicating an excess electricity of 1,138.00 kWh/year (which is 12.30 % of the total electrical production) as seen from Table 4.17. Furthermore, since this case study was largely based on solar PV and wind turbine but also had a diesel generator presence, the renewable fraction produced by this model was 81.30% and the unmet load percentage was 0% indicating that the system was reliable in meeting the load demands.

Quantity	Value
Total electrical production [kWh/year]	9252.00
AC primary load [kWh/year]	7395.00
Excess electricity [kWh/year]	1138.00
Excess electricity [%]	12.30
Unmet Electric load [%]	0.00
Renewable fraction [%]	81.30

Table 4.17: Electrical summary for CSVII for Upanga

Figure 4.27 indicates that the monthly electric production using this combination was relatively constant throughout the year. Figure 4.28, 4.29 and 4.30 on the other hand, displays the annual generator, PV and wind turbine power output capacity per hour respectively. From these figures, it was seen how all these components worked in tandem to meet the load demands. i.e. during peak wind speed months (May to July), it was the wind turbines generating most of the electricity, then during peak summer months (November to March), it was the solar PV generating most of the electricity and finally the diesel generator aiding these two systems throughout the year.

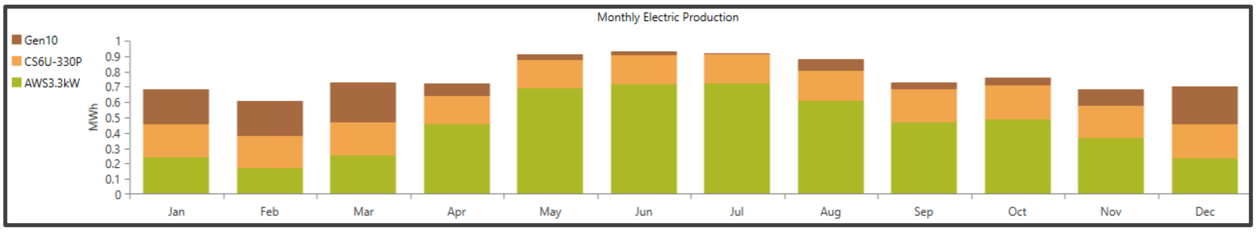

Figure 4.27: Monthly electric production for CSVII for Upanga

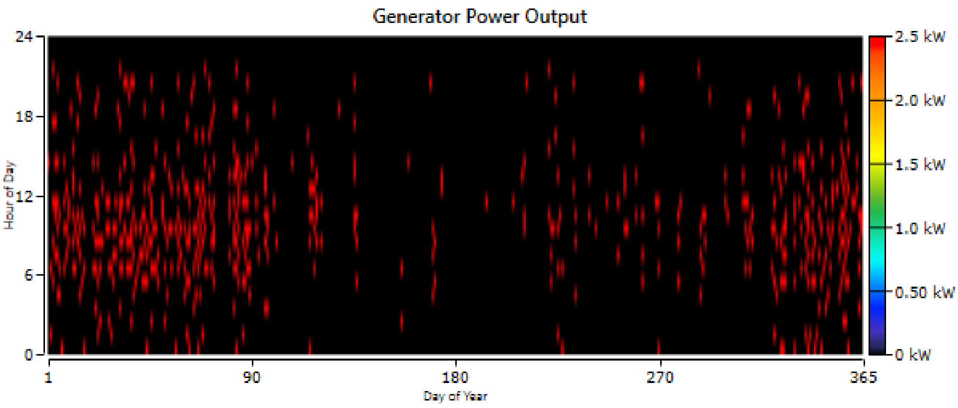

Figure 4.28: Generator power output for CSVII for Upanga

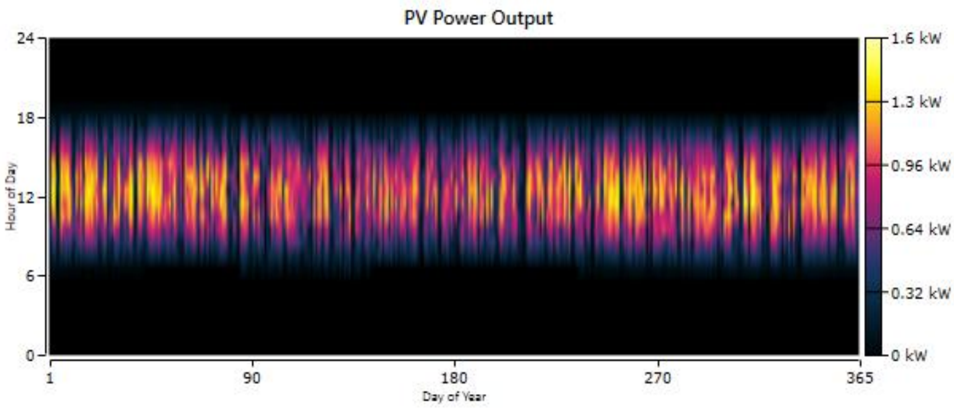

Figure 4.29: Solar PV power output for CSVII for Upanga

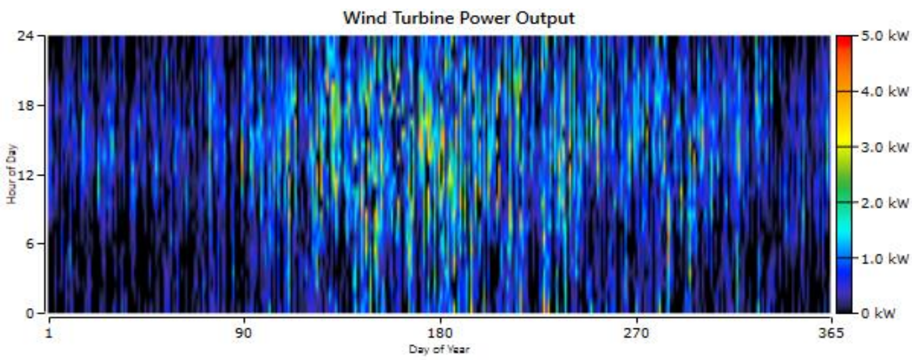

Figure 4.30: Wind turbine power output for CSVII for Upanga

Emissions analysis:
From Table 4.17, it was seen that this system had a renewable fraction of 81.30% as most of it was run by solar and wind which is a clean source of energy. The diesel generator on the other hand does produce emissions as its by product which harms the environment as seen from Table 4.18. The chosen diesel generator for this system on average had a total pollution quantity of 1756.30 kg/year from which 98.12% was carbon dioxide emissions. Despite having pollutants, this system does ensure that these emissions are at a minimum by having as much dependence on solar and wind as possible and only utilizing the generator during extreme load crisis.

Pollutant	Quantity [kg/year]
Carbon dioxide	1723.00
Carbon monoxide	13.00
Unburned hydrocarbons	0.48
Particulate matter	0.79
Sulphur dioxide	4.23
Nitrogen oxides	14.80
Total:	**1756.30**

Table 4.18: Emissions summary for CSVII for Upanga

4.2 Optimization results for Ngamiani

The Figure below shows the different HRES configurations for the hospital in Ngamiani derived from the seven case studies discussed previously, with each of the components' respective sizes, quantities, net present costs and cost of energy listed below. Since Ngamiani did not have sufficient wind resources, only three case studies from the seven discussed earlier were used to model and obtain optimization results for Ngamiani.

Architecture					
CS6U-330P (kW)	Gen10 (kW)	Dis12V	Converter (kW)	NPC ($)	COE ($)
3.46	10.0	6	2.53	$51,545	$0.673
	10.0	16	6.87	$57,143	$0.747
5.50		19	2.54	$61,623	$0.805

Figure 4.31: Optimization results summary for Ngamiani

4.2.1 *CSI: Standalone diesel generator with storage*

The following model that was utilized in HOMER optimizer consisted of a 10kW fixed capacity diesel generator, a 16-string battery option and a 6.87kW converter. Figure 4.32 indicates the optimization results for case study I for Ngamiani.

Architecture					
CS6U-330P (kW)	Gen10 (kW)	Dis12V	Converter (kW)	NPC ($)	COE ($)
	10.0	16	6.87	$57,143	$0.747

Figure 4.32: Optimization summary for CSI for Ngamiani

Cost analysis:

It was evident from Table 4.19 and Figure 4.33 which represented the cost summary for the base case, that the optimal standalone model for the diesel generator had an initial system cost of $13,620 and a relatively high COE of $0.747 with a total NPC of $57,143.40 or TZS 132,502,973.05 Tanzanian Shillings (taking an exchange rate of 2318.78 TZS per 1 US dollar as of 07/11/2020) [19]. The fuel cost totaled to 49.63% of the whole system cost indicating that running this system solely on fuel as a primary source of energy would be costly in the long run. The system however had a good operational and maintenance cost of $7,071.35 with a decent savings worth $2,201.09 making it economically feasible.

Component	Capital	Replacement	O&M	Fuel	Salvage	Total [$]	Total [TZS]
Discover 12VRE-3000TF	6,560.00	5,519.17	2,068.40	-	-1,018.47	13,129.10	30,443,494.50
Generic 10kW Fixed capacity genset	5,000.00	3,895.67	5,002.95	28,364.30	-1,018.12	41,244.80	95,637,617.34
System converter	2,060.00	874.00	-	-	- 164.50	2,769.50	6,421,861.21
System	13,620.00	10,288.84	7,071.35	28,364.30	-2,201.09	57,143.40	132,502,973.05

Table 4.19: Cost summary for CSI for Ngamiani

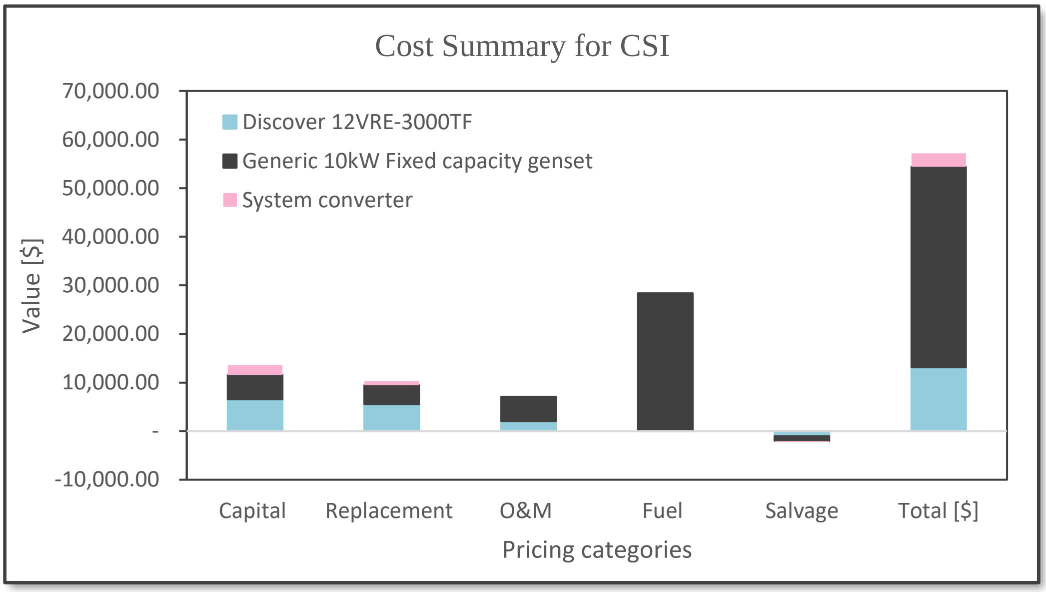

Figure 4.33: Cost summary for CSI for Ngamiani

Electrical analysis:
The total yearly electrical production using a standalone diesel generator was 7,837 kWh/year with the AC primary load consumption standing at 5,920 kWh/year indicating an excess electricity of 193 kWh/year (which is 2.46% of the total electrical production) as seen from Table 4.20. Also, since this case study was solely based on a standalone generator, no renewable fraction was produced in this model and the unmet load percentage being 0% also indicated that the system was reliable.

Quantity	Value
Total electrical production [kWh/year]	7837.00
AC primary load [kWh/year]	5920.00
Excess electricity [kWh/year]	193.00
Excess electricity [%]	2.46
Unmet Electric load [%]	0.00
Renewable fraction [%]	0.00

Table 4.20: Electrical summary for CSI for Ngamiani

Figure 4.34 indicates that the monthly electric production using the diesel generator was fairly constant due to no dependence on the intermittent and irregular solar and wind resource availability. Figure 4.35 on the other hand, displays the annual generator power output capacity per hour. From there, it was seen that around 8 kW were used daily in the midday from 10:00 to 16:00 when the prioritized loads for Ngamiani also peaked as seen from Figure 3.8.

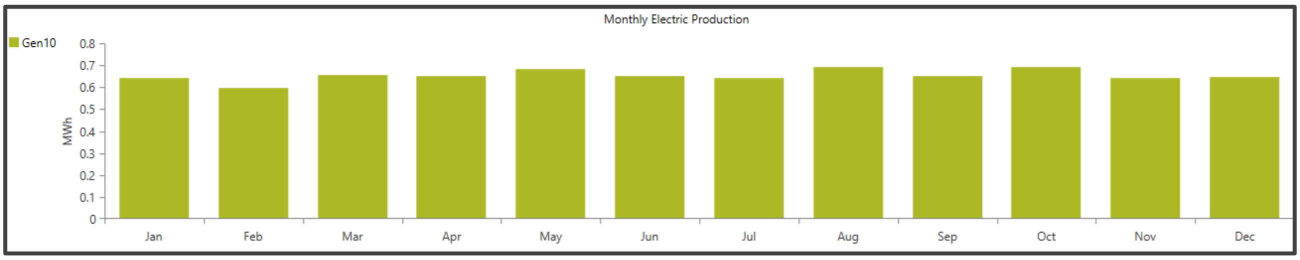

Figure 4.34: Monthly electrical production for CSI for Ngamiani

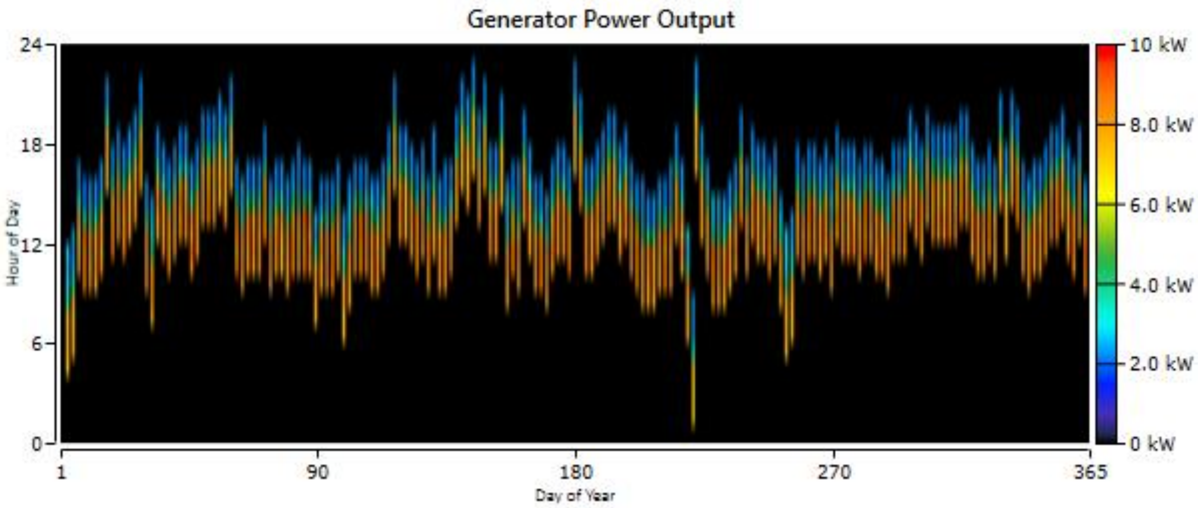

Figure 4.35: Generator power output for CSI for Ngamiani

<u>Emissions analysis</u>:

As seen from Table 4.21, the diesel generator on average had a total pollution quantity of 7,617.49 kg/year from which 98.1% were carbon dioxide emissions. This was a relatively high number of CO_2 emissions considering that it is one of the leading factors for global warming and greenhouse gas emissions. The presence of such large quantities of pollutants was an indication of how non-environment friendly this system was.

Pollutant	Quantity [kg/year]
Carbon dioxide	7473.00
Carbon monoxide	56.50
Unburned hydrocarbons	2.06
Particulate matter	3.43
Sulphur dioxide	18.30
Nitrogen oxides	64.20
Total:	**7617.49**

Table 4.21: Emissions summary for CSI for Ngamiani

4.2.2 CSII: Solar PV with storage

The optimal model that was utilized in the HOMER optimizer consisted of a 5.50kW CS6U-330P solar PV module with a 19-string battery option and a 2.54kW converter. Figure below indicates the optimization results for this case study in Ngamiani.

Architecture									
				CS6U-330P (kW)	Gen10 (kW)	Dis12V	Converter (kW)	NPC ($)	COE ($)
				5.50		19	2.54	$61,623	$0.805

Figure 4.36: Optimization summary for CSII for Ngamiani

<u>Cost analysis:</u>

It was evident from Table 4.22 and Figure 4.37 which represented the cost summary for this case study, that the optimal solar PV HRES model had an initial cost of $22,292.71 and a relatively high COE of $0.805 with a total NPC of $61,623.16 or TZS 142,890,550.94 Tanzanian Shillings (taking an exchange rate of 2318.78 TZS per 1 US dollar as of 07/11/2020) [19]. There was no fuel cost which indicated that the system was solely running on renewable solar resource as a primary source of energy. The system however had a relatively high operational and maintenance cost of $37,984.30.

Component	Capital	Replacement	O&M	Fuel	Salvage	Total [$]	Total [TZS]
CanadianSolar MaxPower CS6U-330P	13,741.26	-	35,528.07	-	-	49,269.33	114,244,737.02
Discover 12VRE-3000TF	7,790.00	2,483.51	2,456.23	-	-1,399.62	11,330.12	26,272,055.65
System converter	761.45	323.06	-	-	- 60.80	1,023.71	2,373,758.27
System	22,292.71	2,806.57	37,984.30	-	-1,460.42	61,623.16	142,890,550.94

Table 4.22: Cost summary for CSII for Ngamiani

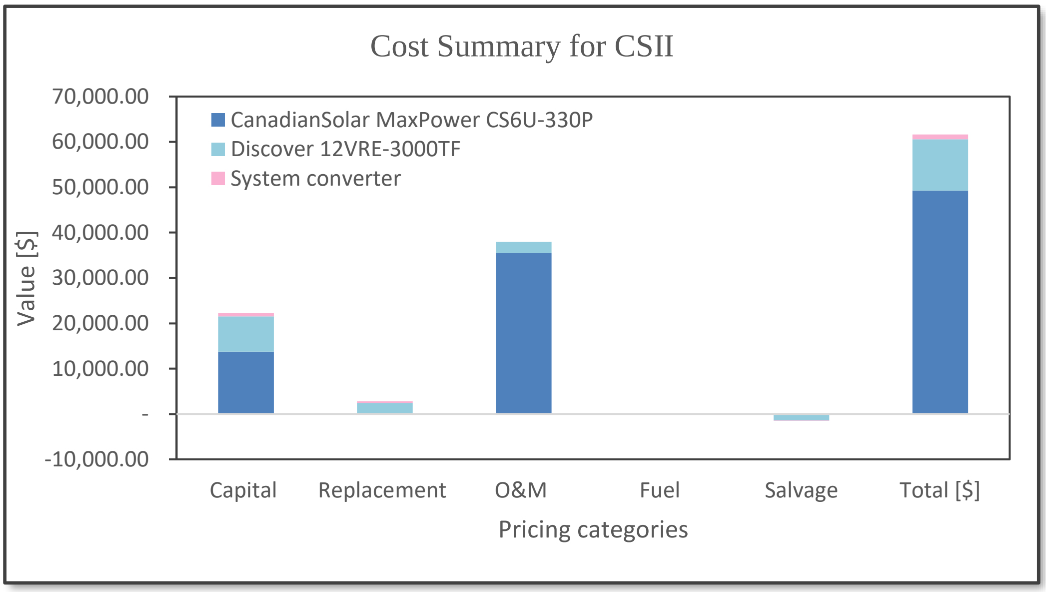

Figure 4.37: Cost summary for CSII for Ngamiani

Electrical analysis:

The total yearly electrical production using just a solar PV system was 8,542 kWh/year with the AC primary load consumption standing at 5,918 kWh/year indicating an excess electricity of 1,806 kWh/year (which is 21.10 % of the total electrical production) as seen from Table 4.23. This excess electricity could neither be absorbed by the storage nor the load and was thus dissipated in a dump load (such as a resistive heater). The large presence of this excess electricity parameter indicated that this HRES was overdesigned resulting in a higher cost for the system and lower energy efficiency.

Also, since this case study was solely based on solar PV, the renewable fraction produced in this model was 100% and the unmet load percentage being close to 0% indicated that the system was reliable in meeting the load demands.

Quantity	Value
Total electrical production [kWh/year]	8,542.00
AC primary load [kWh/year]	5,918.00
Excess electricity [kWh/year]	1,806.00
Excess electricity [%]	21.10
Unmet Electric load [%]	0.04
Renewable fraction [%]	100.00

Table 4.23: Electrical summary for CSII for Ngamiani

Figure 4.38 indicates that the monthly electric production using the solar PV was not constant throughout the year due to its dependence on the intermittent and irregular solar resource availability. Figure 4.39 on the other hand, displays the annual PV power output capacity per hour. From there, it was seen that around 5 kW were used daily in the midday from 10:00 to 16:00 when the prioritized loads for Upanga also peaked as seen from Figure 3.8 and gradually decreased to around 1.2 kW at 18:00 up to no solar power in the evening after sunset. During this period (18:00 – 06:00), the battery which stored energy during daytime would be used to meet the load demands and supply relevant power to the hospitals. Thus, a large number of battery capacity (27-strings) as seen in Figure 4.36.

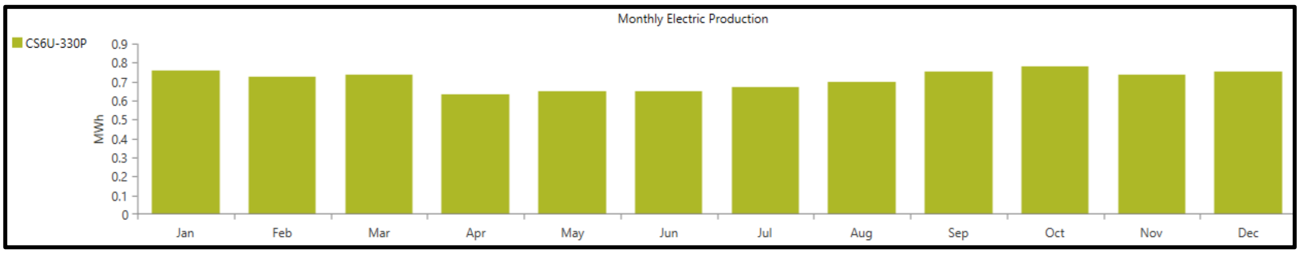

Figure 4.38: Monthly electrical production for CSII for Ngamiani

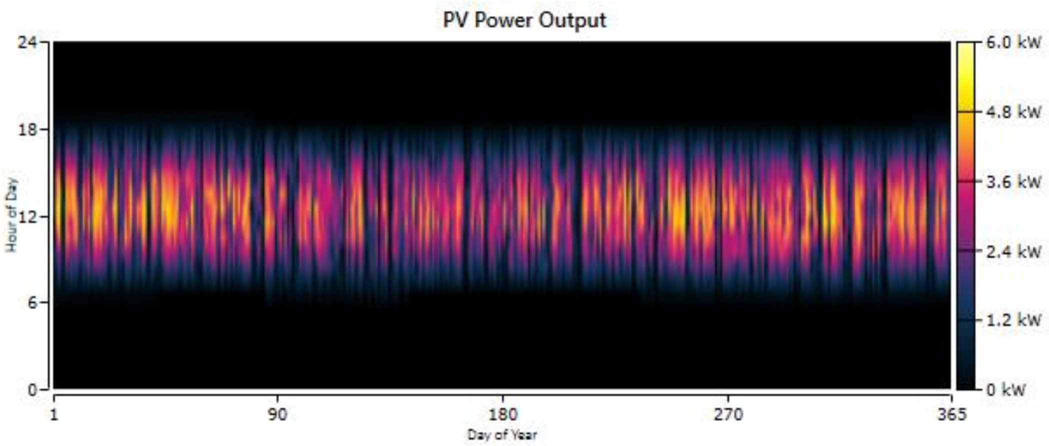

Figure 4.39: Solar PV power output for CSII for Ngamiani

Emissions analysis:
Since this was a purely renewable system, no emissions were obtained and calculated from it and it thus had a renewable fraction of 100% making it completely environmentally friendly.

4.2.3 CSIV: Solar PV and diesel generator with storage

The optimal model that was utilized in the HOMER optimizer consisted of a 3.46kW CS6U-330P solar PV module with a 6-string battery option, a 10-kW fixed capacity diesel generator and a 2.53kW converter. Figure 4.40 indicates the optimization results for this case study in Ngamiani.

Architecture									
				CS6U-330P (kW)	Gen10 (kW)	Dis12V	Converter (kW)	NPC ($)	COE ($)
				3.46	10.0	6	2.53	$51,545	$0.673
				3.48	10.0	6	2.56	$51,557	$0.674
				3.45	10.0	6	2.52	$51,574	$0.674

Figure 4.40: Optimization summary for CSIV for Ngamiani

Cost analysis:
Table 4.24 and Figure 4.41 which represented the cost summary for case study IV, showed that the optimal HRES model had an initial cost of $16,861.25 and a relatively low COE of $0.673 with a total NPC of just $51,544.75 or TZS 119,520,935.41 Tanzanian Shillings (taking an exchange rate of 2318.78 TZS per 1 US dollar as of 07/11/2020) [19]. The fuel cost was at a minimum of only 13.35% of the overall system cost which indicated that the system was largely running on the renewable solar resource as a primary source of energy. The system costs were relatively low making it economically feasible.

Component	Capital	Replacement	O&M	Fuel	Salvage	Total [$]	Total [TZS]
CanadianSolar MaxPower CS6U-330P	8,642.50	-	22,345.21	-	-	30,987.71	71,853,682.19
Discover 12VRE-3000TF	2,460.00	2,341.25	775.65	-	- 139.50	5,437.40	12,608,134.37
Generic 10kW Fixed capacity genset	5,000.00	-	2,253.27	6,884.22	- 37.93	14,099.56	32,693,777.74
System converter	758.75	321.92	-	-	- 60.59	1,020.08	2,365,341.10
System	16,861.25	2,663.17	25,374.13	6,884.22	- 238.02	51,544.75	119,520,935.41

Table 4.24: Cost summary for CSIV for Ngamiani

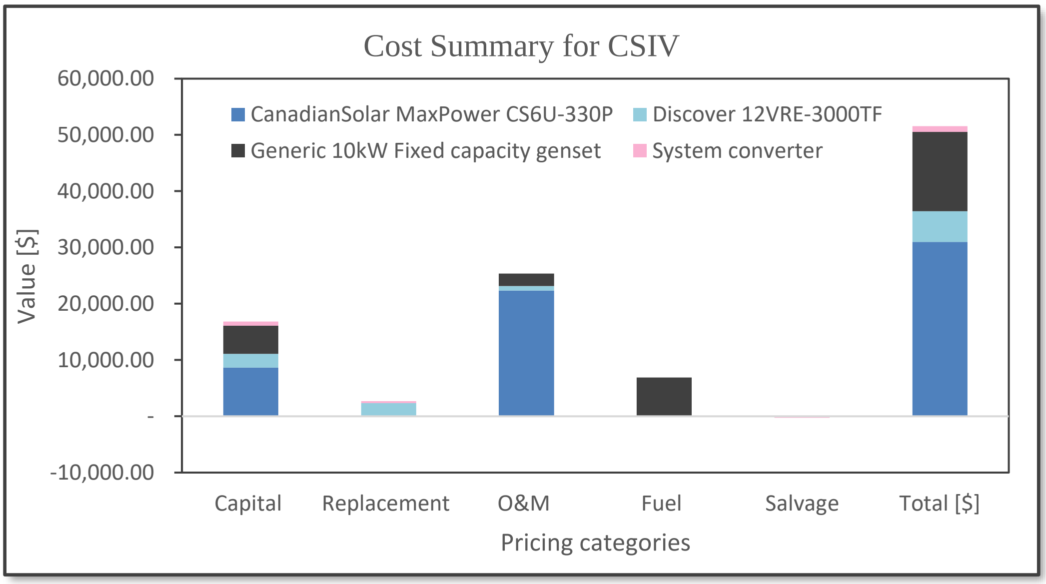

Figure 4.41: Cost summary for CSIV for Ngamiani

Electrical analysis:

The total yearly electrical production using a combination of both solar PV and generator was 6,285kWh/year with the AC primary load consumption standing at 5,920 kWh/year indicating an excess electricity of just 57.60 kWh/year (which is only 0.84 % of the total electrical production) as seen from Table 4.25. Furthermore, since this case study was largely based on solar PV but also had a diesel generator presence, the renewable fraction produced by this model was 75.50% and the unmet load percentage was 0% indicating that the system was reliable in meeting the load demands.

Quantity	Value
Total electrical production [kWh/year]	6825.00
AC primary load [kWh/year]	5920.00
Excess electricity [kWh/year]	57.60
Excess electricity [%]	0.84
Unmet Electric load [%]	0.00
Renewable fraction [%]	75.50

Table 4.25: Electrical summary for CSIV for Ngamiani

Figure 4.42 indicates that the monthly electric production using this combination was relatively constant throughout the year. It showed how the solar PV and the generator worked in tandem to supply the desired electric demand by the load. It also indicated that the majority of the electricity generated was from the PV module indicating a high presence of renewable resource.

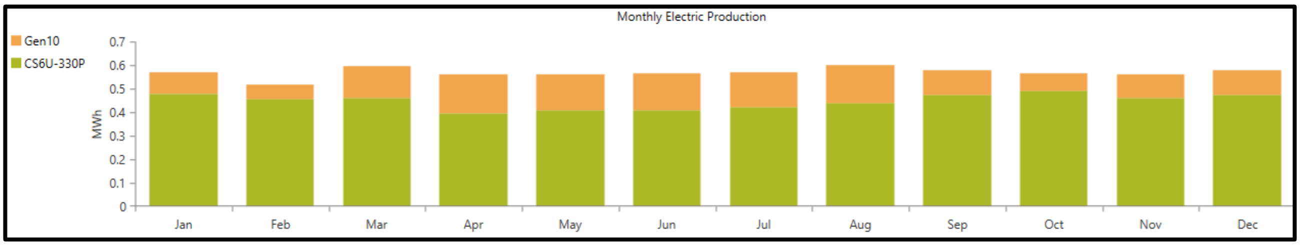

Figure 4.42: Monthly electrical production for CSIV for Ngamiani

Figure 4.43 and 4.44 on the other hand, displays the annual generator and PV power output capacity per hour respectively. From there, it was seen how both these components worked in tandem to meet the load demands. i.e. when the sun was out, it was mostly the solar PV generating power whereas at night and early mornings, it was the generator which was responsible to deliver power to the load.

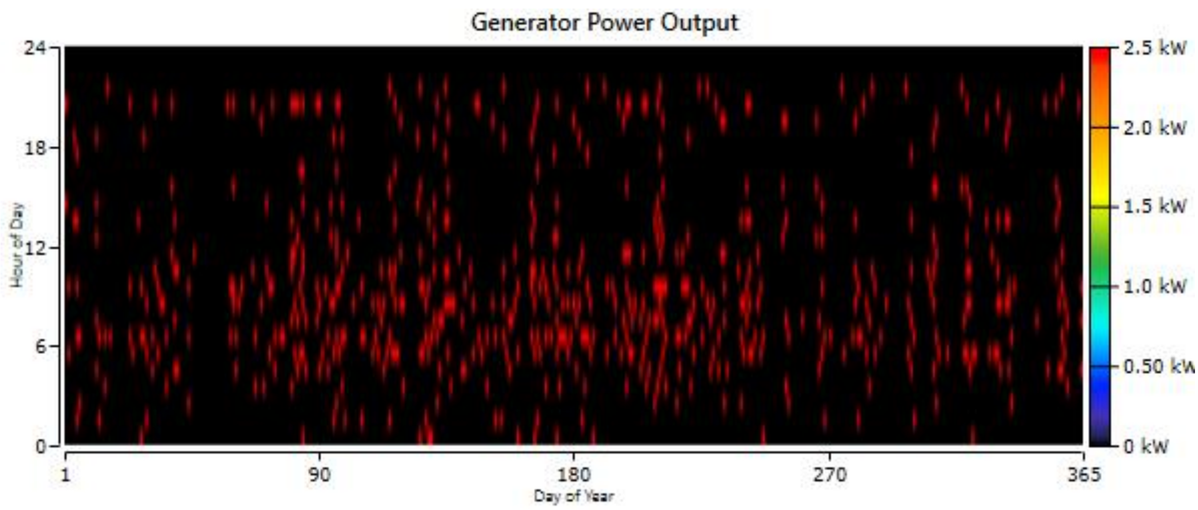

Figure 4.43: Generator power output for CSIV for Ngamiani

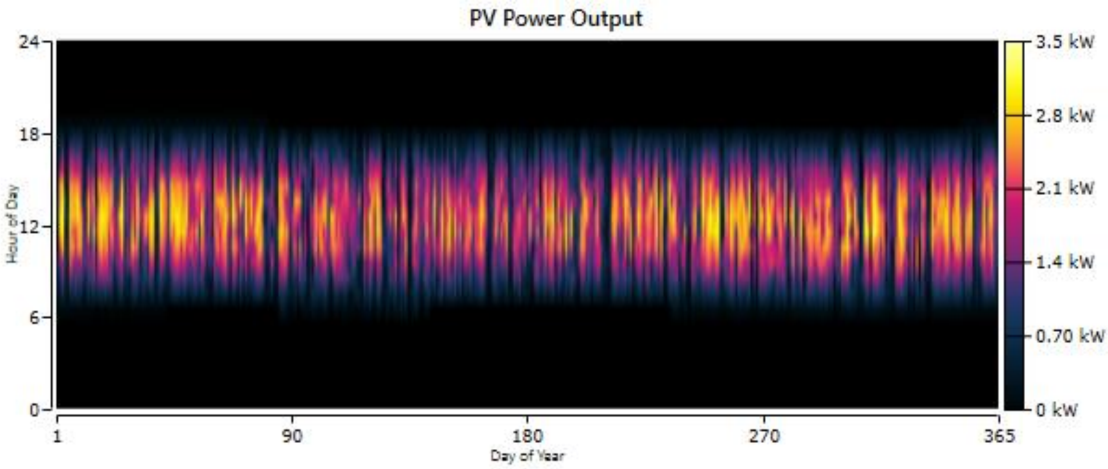

Figure 4.44: Solar PV power output for CSIV for Ngamiani

Emissions analysis:

From Table 4.25, it was seen that this system had a renewable fraction of 75.50% as most of it was run by solar PV which is a clean source of energy. The diesel generator on the other hand does produce emissions as its by product which harms the environment as seen from Table 4.26. The chosen diesel generator for this system on average had a total pollution quantity of 1,849.08 kg/year from which 98.10% was carbon dioxide emissions. Despite having pollutants, this system does ensure that these emissions are at a minimum by having as much dependence on solar as possible and only utilizing the generator during extreme load crisis.

Pollutant	Quantity [kg/year]
Carbon dioxide	1814.00
Carbon monoxide	13.70
Unburned hydrocarbons	0.50
Particulate matter	0.83
Sulphur dioxide	4.45
Nitrogen oxides	15.60
Total:	**1849.08**

Table 4.26: Emissions summary for CSIV for Ngamiani

4.3 Sensitivity Analysis

A nominal discount rate of 8% and an average diesel price of $0.767 per liter [18] were used as constant parameters for all the above optimization results. This section covered the effects of varying these diesel prices and nominal discount rates on the total NPC, COE, excess electricity and CO_2 emissions. The following diesel fuel rates and nominal discount rates were chosen as shown in Table 4.27 and the simulations were carried out for each of the chosen rates to determine their effects on the system. The system under consideration was that from Case study IV: Solar and diesel generator with storage. This case study was chosen as it would help to better view the changes in both fuel prices and discount rates.

Nominal discount rates [%]	6.00	7.00	8.00
Diesel fuel prices [$/liter]	0.74	0.77	0.78

Table 4.27: Sensitivity analysis parameters

4.3.1 Effects on NPC and COE with variations of nominal discount rates

Figure 4.45 indicates the relationship of NPC and COE with a change in the nominal discount rates for Upanga. An exact replicate relationship was also obtained for Ngamiani. It was clearly visible that the total NPC linearly decreased with an increase in the nominal discount rates whereas the COE linearly increased with an increase in discount rates. This seems correct as the total system cost would come down with an increased discount rate.

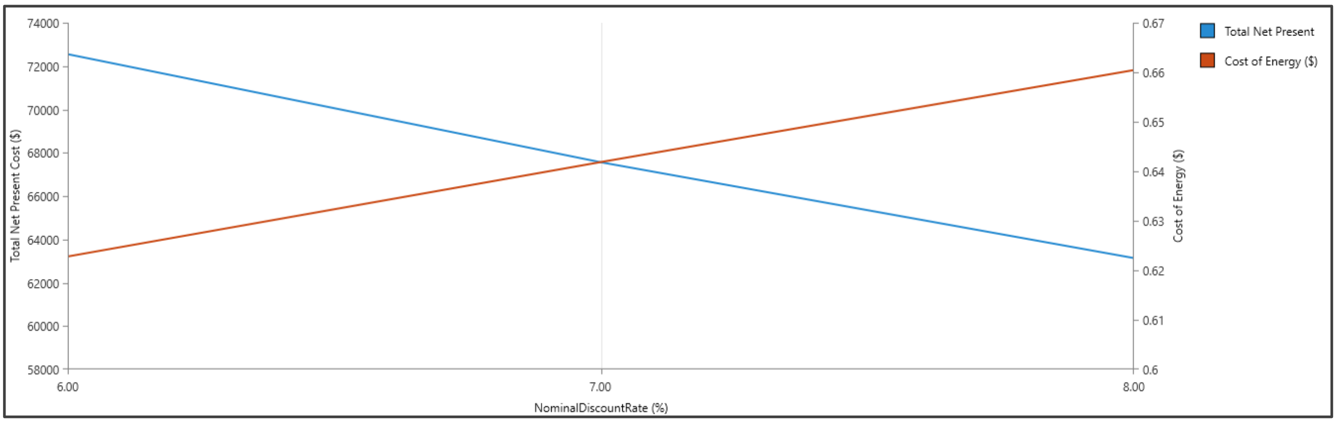

Figure 4.45: Effect of Nominal discount rate on NPC and COE

4.3.2 Effects on NPC and COE with variations of diesel fuel rates

Figure 4.46 indicates the relationship of NPC and COE with a change in the diesel fuel rates for Upanga. An exact replicate relationship was also obtained for Ngamiani. It was clearly visible that both the total NPC and COE linearly increased with an increase in the fuel rates. There was a steep increase up to $0.77 per liter and then the NPC and COE saw a less steep increase for an increase of fuel prices. This seems correct as the total system cost would increase with an increased nominal diesel fuel price.

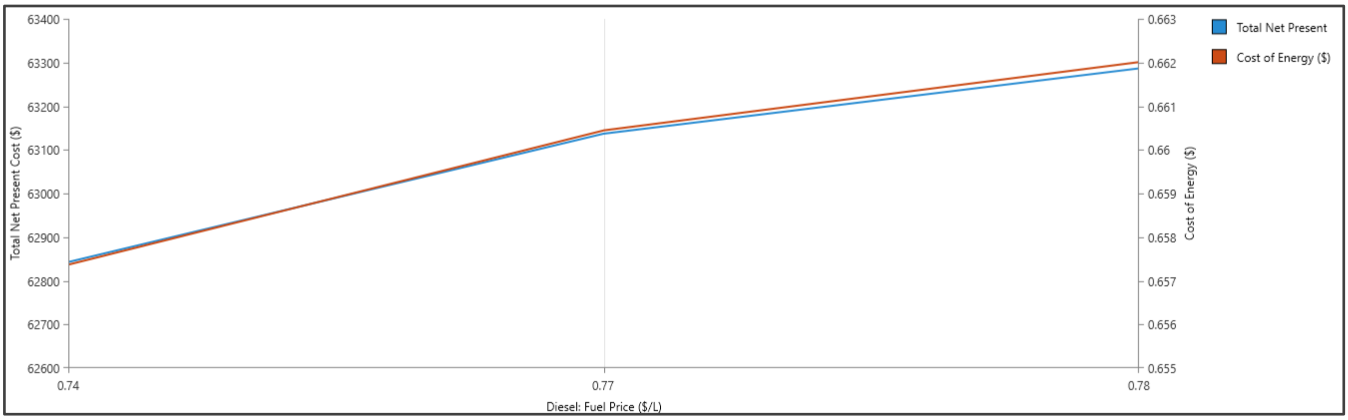

Figure 4.46: Effect of diesel fuel rate on NPC and COE

4.3.3 Effects on excess electricity and CO_2 emissions with variations of nominal discount rates

Figure 4.47 indicates the relationship of excess electricity and CO_2 emissions with a change in the nominal discount rates for Upanga. An exact replicate relationship was also obtained for Ngamiani. It was evident that the total excess electricity linearly increased with an increase of up to a discount rate of 7% and then linearly decreased with an increase in discounts. A vice versa plot was visible for the CO_2 emissions, which showed an initial decrease but then increased in the weight of emissions produced once the discount rate crossed 7%.

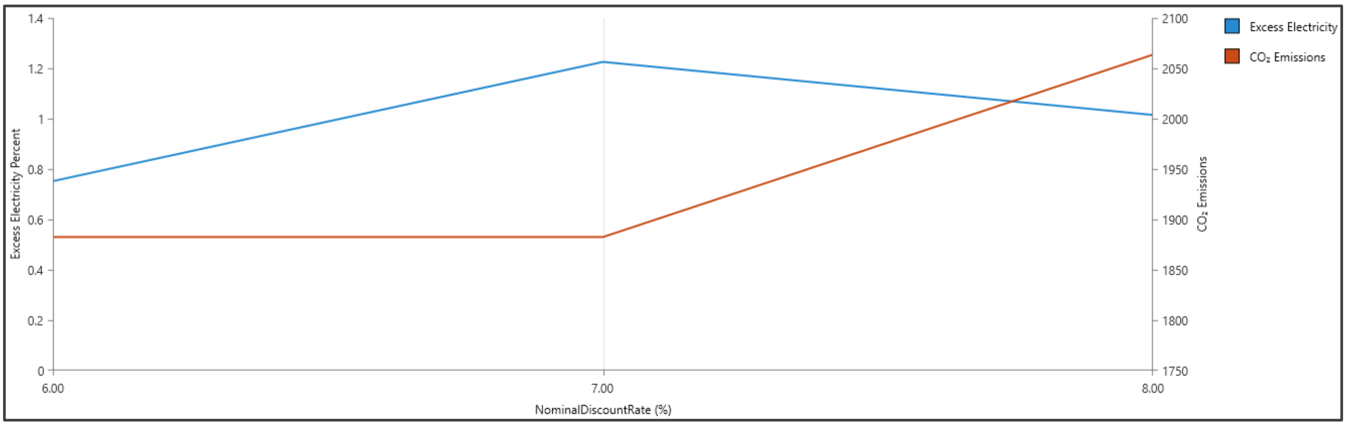

Figure 4.47: Effect of Nominal discount rate on excess electricity and CO2 emissions

5. Discussion

In this section, a comparison was conducted between the cost, electrical and emissions parameters from both the Upanga and Ngamiani locations. These comparisons would then aid in determining the most optimal HRES configurations for both the locations respectively.

5.1 Comparison analysis for Upanga

5.1.1 Cost comparison

The total system costs obtained from all the case study optimizations conducted in chapter 4 for Upanga were plotted together in Figure 5.1 to provide for a visual comparison of the most cost-efficient system.

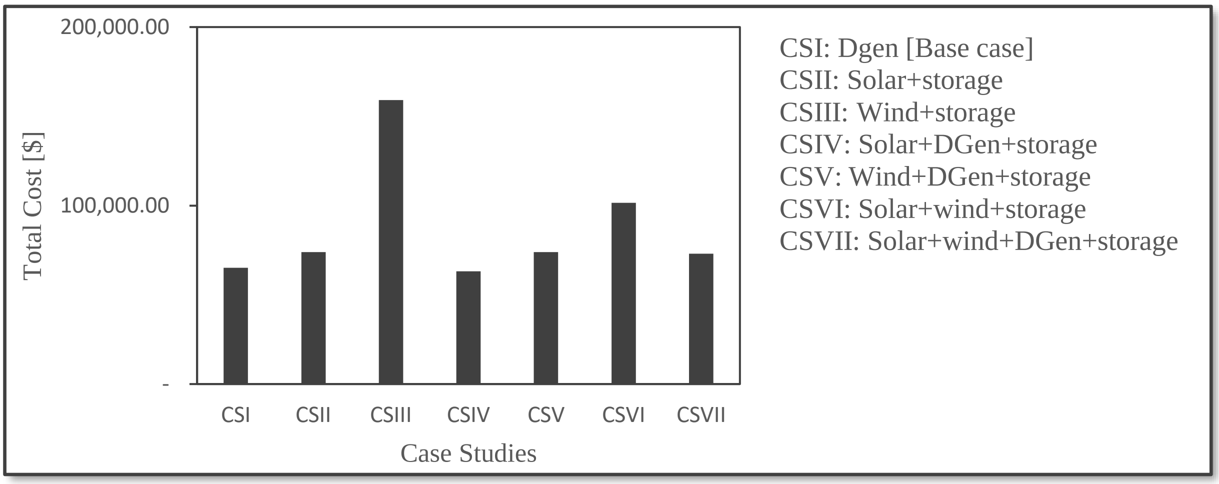

Figure 5.1: Cost comparison for case studies for Upanga

From the above figure, it was seen that CSIV: Solar PV and diesel generator with storage had the lowest system cost of just $63,136.93 with a total COE of only $0.66. This was due to the heavy reliance on solar PV which compensated for the high diesel fuel prices. It should also be noted that having just a standalone diesel generator as seen in CSI or a standalone solar PV as seen in CSII would have an increased total system cost than both of them combined as seen in CSIV. This is because both the solar PV and generator work in tandem to not only support the load demands of the location but also to equally share the system costs amongst themselves as contrary to CSI and CSII, where all the generation costs were directed to a single component.

It was also seen that the study with the highest system cost was CSIII: Wind turbine with storage which had a total of NPC of $159,028.00 and a high COE of $1.66. The reason for such a high cost was due to the system having to use three wind turbines to meet the load demands for the Upanga.
A single standalone wind turbine would be insufficient to power the entire location and thus in order to reduce costs and meet the load demands at the same time, the wind turbines would need to hybridize with either the diesel generator, the solar PV modules or a combination of both as evident in CSV, CSVI and CSVII respectively. The major cutdowns in system costs were clearly visible once the wind turbines were used in tandem and not as a standalone.

5.1.2 Electrical comparison

The total excess electricity values obtained from all the case study optimizations conducted in chapter 4 for Upanga were plotted together in Figure 5.2 to provide for a visual comparison of the most energy-efficient system.

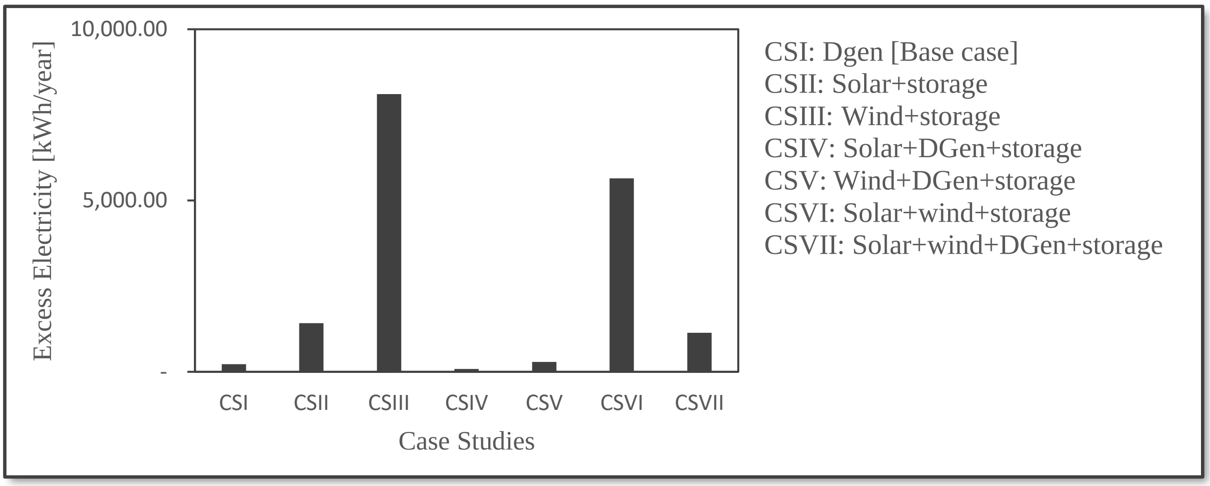

Figure 5.2: Electrical comparison for case studies for Upanga

For designing and modelling of the optimal HRES system, energy efficiency was one of the topmost priorities and to quantify such a constraint, this study made use of the excess electricity parameter which is a measure of surplus energy neither used up the load nor the storage options. Thus, having a minimal percentage of excess electricity would indicate that the HRES configuration is suitable and well designed. For Upanga, any case study having an excess electricity of less than 30% or 3,000 kWh/year would be termed as suitable due to the nature of priority loads which require a constant supply of energy even during power outages.

Thus, from the above figure, CSI, CSII, CSIV, CSV and CSVII, all qualify as energy-efficient systems due to their excess electricity measure being less than 3,000kWh/year. The lowest from these five studies however was from CSIV: Solar PV and diesel generator with storage, having an excess electricity value of just 86.30 kWh/year which was only 1.01% of the total energy produced.
CSIII and CSVI did not qualify as energy-efficient systems due to their excess energy values with CSIII: Wind turbine with storage having a value of 8,106 kWh/year which was around 49.90% of the total energy produced. This excess amount of energy would further increase system costs and make it both energy and cost inefficient.

5.1.3 CO_2 emissions comparison

The total CO_2 emission values obtained from all the case study optimizations conducted in chapter 4 for Upanga were plotted together in Figure 5.3 to provide for a visual comparison of the most environmentally friendly system.

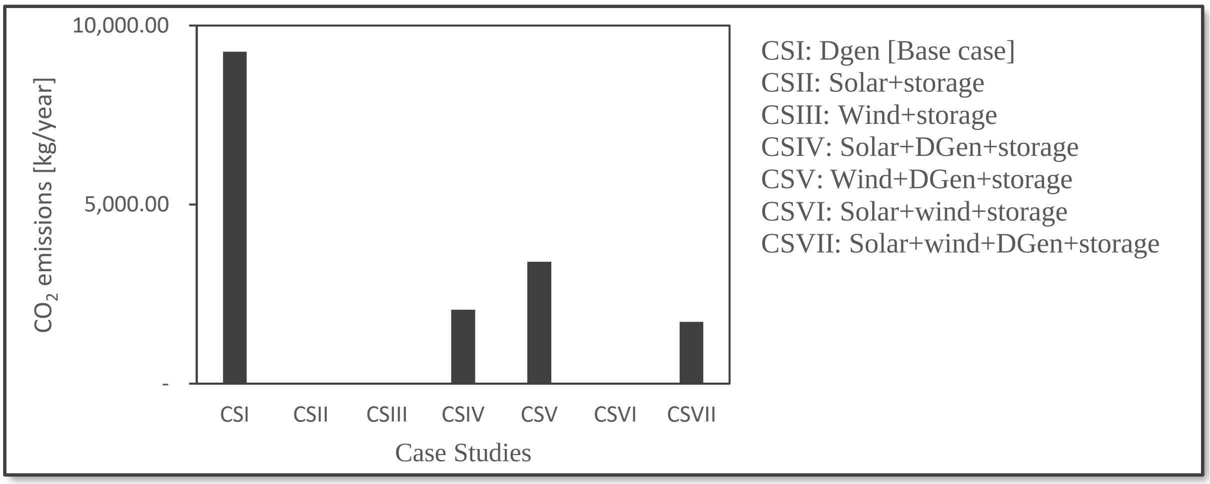

Figure 5.3: CO_2 emissions comparison for case studies for Upanga

Another crucial aspect for determining an optimal system was the amount of pollutants it emitted. The lesser the emissions, the more optimal the HRES configurations. Since CSII, CSIII and CSVI were all completely based on renewable resources, they had no CO_2 emissions making them entirely eco-friendly. CSIV, CSV and CSVII on the other hand, were partially based on diesel generators and hence had some amount of CO_2 emissions. These amounts however were fairly small with the maximum just being at 3,401 kg/year. Hence, these three case studies were also deemed suitable as environmentally friendly systems.

The base case i.e. CSI, however had very large emissions totalling to up to 9,266 kg/year of CO_2 making it a non-eco-friendly system. This large amount of emissions was due to the system only relying on diesel fuel (which is derived from fossil fuels and emits greenhouse gases depleting the Earth's ozone layer) [20] as their primary source of energy.

5.2 Comparison analysis for Ngamiani

5.2.1 Cost comparison

The total system costs obtained from all the case study optimizations conducted in chapter 4 for Ngamiani were plotted together in Figure 5.4 to provide for a visual comparison of the most cost-efficient system.

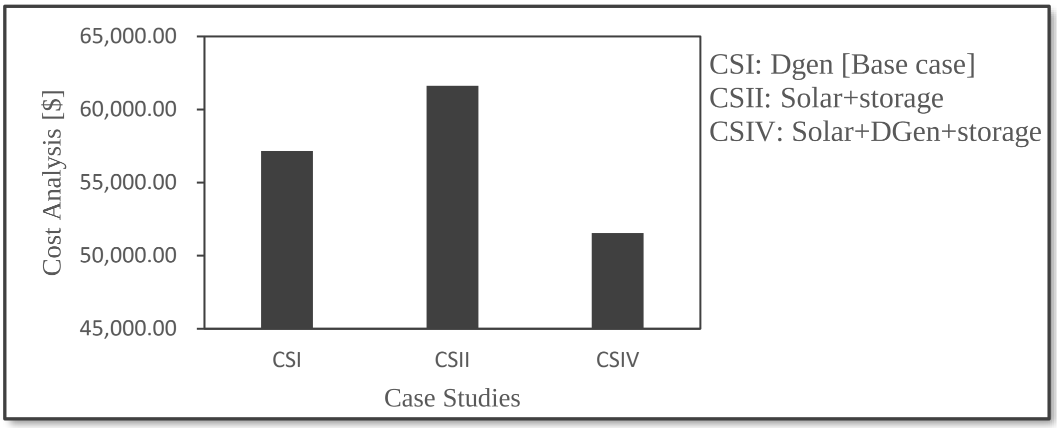

Figure 5.4: Cost comparison for case studies for Ngamiani

From the above figure, it was seen that CSIV: Solar PV and diesel generator with storage had the lowest system cost of just $51,544.75 with a total COE of only $0.673. This was due to the heavy reliance on solar PV which compensated for the high diesel fuel prices. It should also be noted that having just a standalone diesel generator as seen in CSI or a standalone solar PV as seen in CSII would have an increased total system cost than both of them combined as seen in CSIV. This is because both the solar PV and generator work in tandem to not only support the load demands of the location but also to equally share the system costs amongst themselves as contrary to CSI and CSII, where all the generation costs were directed to a single component.

5.2.2 Electrical comparison

The total excess electricity values obtained from all the case study optimizations conducted in chapter 4 for Ngamiani were plotted together in Figure 5.5 to provide for a visual comparison of the most energy-efficient system.

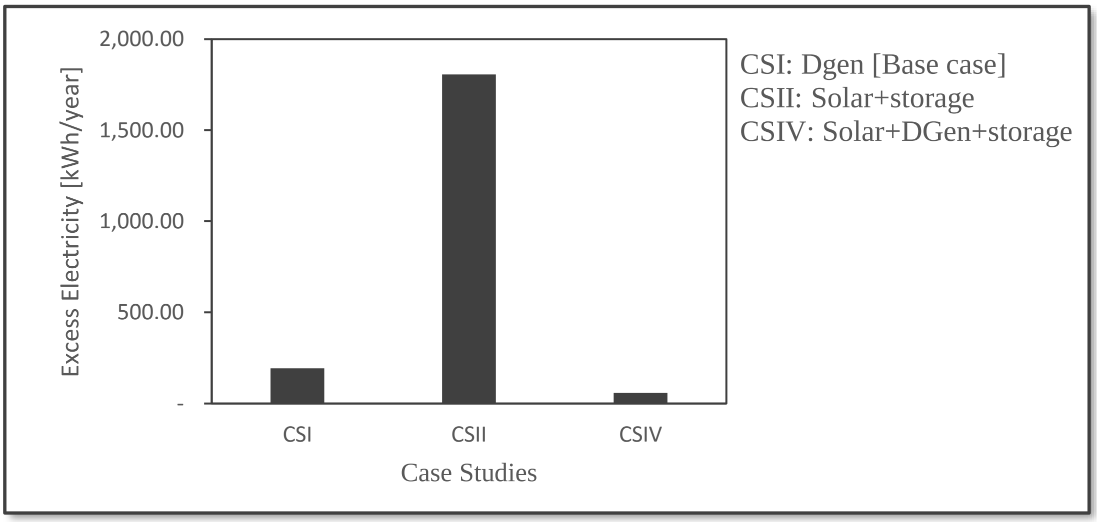

Figure 5.5: Electrical comparison for case studies for Ngamiani

For designing and modelling of the optimal HRES system, energy efficiency was one of the topmost priorities and to quantify such a constraint, this study made use of the excess electricity parameter which is a measure of surplus energy neither used up the load nor the storage options. Thus, having a minimal percentage of excess electricity would indicate that the HRES configuration is suitable and well designed. For Ngamiani, any case study having an excess electricity of less than 1,000 kWh/year would be termed as suitable due to the nature of priority loads which require a constant supply of energy.

Thus, from the above figure, CSI and CSIV, both qualify as energy-efficient systems due to their excess electricity measure being less than 1,000kWh/year. The lowest from these two studies however was from CSIV: Solar PV and diesel generator with storage, having an excess electricity value of just 57.60 kWh/year which was only 0.84% of the total energy produced.
CSII did not qualify as an energy-efficient system due to its excess energy value of 1,806 kWh/year which was around 21.10% of the total energy produced. This excess amount of energy would further increase system costs and make it both energy and cost inefficient.

5.2.3 CO_2 emissions comparison

The total CO_2 emission values obtained from all the case study optimizations conducted in chapter 4 for Ngamiani were plotted together in Figure 5.6 to provide for a visual comparison of the most environmentally friendly system.

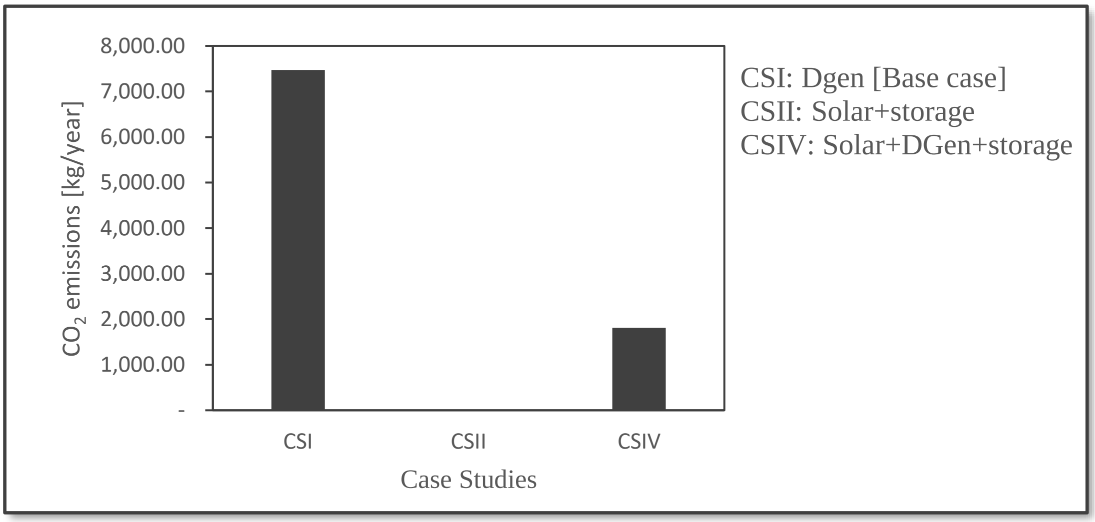

Figure 5.6: CO_2 emissions comparison for case studies for Ngamiani

Another crucial aspect for determining an optimal system was the amount of pollutants it emitted. The lesser the emissions, the more optimal the HRES configurations. Since CSII was completely based on renewable resources, it had no CO_2 emissions making it entirely eco-friendly. CSIV on the other hand, was partially based on diesel generator and hence had some amount of CO_2 emissions. This amount however was fairly small at just 1,814 kg/year and hence this system was deemed suitable as an eco-friendly system.
The base case i.e. CSI, however had very large emissions totalling to up to 7,473 kg/year of CO_2 making it a non-eco-friendly system. This large amount of emissions was due to the system only relying on diesel fuel (which emits greenhouse gases) [20] as their primary source of energy.

6. Conclusions

This research presented a thorough economical, technical and environmental analysis for designing a standalone hybrid renewable energy system with storage for supplying priority loads in two off-grid communities in Tanzania namely Upanga and Ngamiani. Both these locations were selected based on several different criterions as discussed in Chapter 3 of Methodology alongside component selection, data collection, renewable resource assessments and software selection and optimization. Upanga was rich in both solar and wind resources whereas Ngamiani had an abundance of only solar resources. Also, since the prioritized loads required immediate electricity access even in cases of power failures, a continuous back up system such as the battery storage system was an essential component in providing a reliable optimal HRES combination and was hence used in all case studies as a fixed component. Thus, a total of seven case studies for Upanga, and three case studies for Ngamiani, were analysed and the results obtained were presented in Chapter 4 followed by a detailed discussion in Chapter 5. The following conclusion was built up from these previous sections.

6.1 Optimal HRES configuration for Upanga

The load profile for Upanga indicated an average energy consumption of 20.26 kWh per day with a peak power consumption of 2.96kW. The optimal HRES configuration chosen from the case studies analysed was CSIV which involved a hybrid combination of solar PV and diesel generator with a storage option. This system consisted of a 6.34kW CS6U-330P solar PV module with an 8-string battery option, a 10-kW fixed capacity diesel generator and a 2.77kW converter, combining to an initial cost of $20,111.47 and a relatively low COE of $0.66. It had a total NPC of just $63,136.93 or TZS 146,400,650.55 Tanzanian Shillings (taking an exchange rate of 2318.78 TZS per 1 US dollar as of 07/11/2020) [19]. The fuel cost was at a minimum of only 12.3% of the overall system cost which indicated that the system was largely running on the renewable solar resource as a primary source of energy. The system costs were relatively low with savings worth of $1,520.31 making it economically feasible.

The total yearly electrical production using a combination of both solar PV and generator was 8,503 kWh/year with the AC primary load consumption standing at 7,395 kWh/year indicating an excess electricity of just 86.30 kWh/year (which was only 1.01 % of the total electrical production) as seen from Table 4.9. Furthermore, since this case study was largely based on solar PV but also had a diesel generator presence, the renewable fraction produced by this model was 77.70% and the unmet load percentage was 0% indicating that the system had both the solar PV and generator working in tandem to meet the load demands.

The chosen diesel generator for this system on average had a total pollution quantity of 2064.00 kg/year from which 98.11% was carbon dioxide emissions. Despite having pollutants, this system does ensure that these emissions are at a minimum by having as much dependence on solar as possible and only utilizing the generator during extreme load crisis.

Despite having CSIV as the optimal configuration, CSVII [solar PV, wind turbine, generator and storage] could also be used as a backup option. This system consisted of a 1.58kW CS6U-330P solar PV module, a 3.3kW AWS wind turbine, a 10kW fixed capacity diesel generator with a 6-string battery option and a 3.55kW converter having an initial cost of $37,481.57 and a total NPC of $73,122.02 or TZS 169,553,877.54 Tanzanian Shillings (taking an exchange rate of 2318.78 TZS per 1 US dollar as of 07/11/2020) [19]. The fuel cost was at a minimum, it had a lower excess electricity percentage of 12.3% and it was also environmentally friendly.

6.2 Optimal HRES configuration for Ngamiani

The load profile for Ngamiani indicated an average energy consumption of 16.22 kWh per day with a peak power consumption of 2.37kW. The optimal HRES configuration chosen from the case studies analysed was CSIV which involved a hybrid combination of solar PV and diesel generator with a storage option. This system consisted of a 3.46kW CS6U-330P solar PV module with a 6-string battery option, a 10-kW fixed capacity diesel generator and a 2.53kW converter, combining to an initial cost of $16,861.25 and a relatively low COE of $0.673 with a total NPC of just $51,544.75 or TZS 119,520,935.41 Tanzanian Shillings (taking an exchange rate of 2318.78 TZS per 1 US dollar as of 07/11/2020) [19]. The fuel cost was at a minimum of only 13.35% of the overall system cost which indicated that the system was largely running on the renewable solar resource as a primary source of energy. The system costs were relatively low making it economically feasible.

The total yearly electrical production using a combination of both solar PV and generator was 6,285kWh/year with the AC primary load consumption standing at 5,920 kWh/year indicating an excess electricity of just 57.60 kWh/year (which was only 0.84 % of the total electrical production) as seen from Table 4.25. Furthermore, since this case study was largely based on solar PV but also had a diesel generator presence, the renewable fraction produced by this model was 75.50% and the unmet load percentage was 0% indicating that the system had both the solar PV and generator working in tandem to meet the load demands.

The chosen diesel generator for this system on average had a total pollution quantity of 1,849.08 kg/year from which 98.10% was carbon dioxide emissions. Despite having pollutants, this system does ensure that these emissions are at a minimum by having as much dependence on solar as possible and only utilizing the generator during extreme load crisis.

7. Recommendations

7.1 Elaborative cost analysis

Although a fairly decent cost analysis was conducted using the NPC and COE based on the initial capital cost, replacement cost, maintenance cost and salvage values, a more detailed approach involving other relatable costs such as shipping and transportation costs could have been added to the HOMER optimizer to obtain better and more accurate results than the ones already gathered in this study.

7.2 Detailed electrical analysis

The technical feasibility analysis for the case studies in this report were determined from the amount of excess electricity produced which was not sufficient to provide conclusive evidence. Adding additional parameters such as the system electrical efficiency would be a better option to test the model's technical feasibility.

7.3 Added emissions

The current emissions analysis conducted through the HOMER optimizer was already detailed enough having almost six different types of pollutants with their respective weights of emissions per year. The software however does not take into account the entire life cycle of the component. For example, although having a system solely run on solar shows a 100% energy efficient system without any pollutions, the system however would have emitted a lot of pollutants when manufacturing the solar PV arrays and the individual cells mounted on it. Thus, in order to obtain more accurate results, a detailed Life Cycle Assessment (LCA) must have been taken into consideration.

7.4 Numerous sensitivity analysis

The sensitivity analysis carried out for this report only took variations from nominal discount rates and diesel fuel prices. There are however numerous other sensitivity parameters such as variations in the annual solar irradiance, average wind speed and annual average temperatures for both the locations. Alongside these, only three discount rate values and three diesel fuel price values were chosen for the sensitivity analysis, which seems less and thus a bulkier range of values must have been used in order to obtain much more accurate results.

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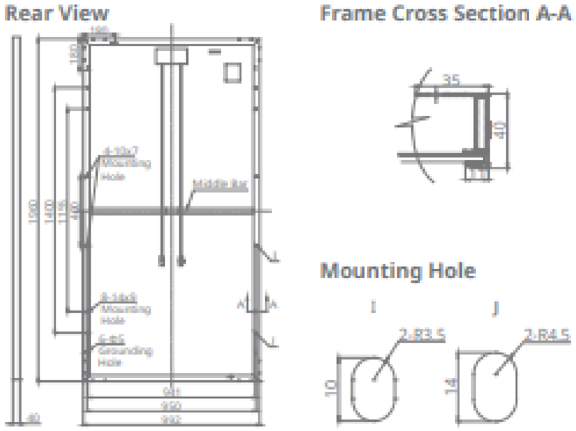
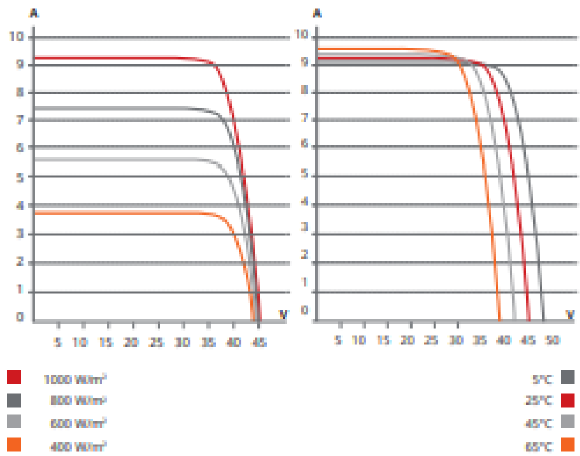
9. Appendix

9.1 Solar PV datasheet

ENGINEERING DRAWING (mm)



CS6U-320P / I-V CURVES



ELECTRICAL DATA / STC*

CS6U	315P	320P	325P	330P
Nominal Max. Power (Pmax)	315 W	320 W	325 W	330 W
Opt. Operating Voltage (Vmp)	36.6 V	36.8 V	37.0 V	37.2 V
Opt. Operating Current (Imp)	8.61 A	8.69 A	8.78A	8.88 A
Open Circuit Voltage (Voc)	45.1 V	45.3 V	45.5 V	45.6 V
Short Circuit Current (Isc)	9.18 A	9.26 A	9.34 A	9.45 A
Module Efficiency	16.20%	16.46%	16.72%	16.97%
Operating Temperature	-40°C ~ +85°C			
Max. System Voltage	1000 V (IEC) or 1000 V (UL)			
Module Fire Performance	TYPE 1 (UL 1703) or CLASS C (IEC 61730)			
Max. Series Fuse Rating	15 A			
Application Classification	Class A			
Power Tolerance	0 ~ + 5 W			

* Under Standard Test Conditions (STC) of irradiance of 1000 W/m², spectrum AM 1.5 and cell temperature of 25°C.

MECHANICAL DATA

Specification	Data
Cell Type	Poly-crystalline, 6 inch
Cell Arrangement	72 (6 × 12)
Dimensions	1960 × 992 × 40 mm (77.2 × 39.1 × 1.57 in)
Weight	22.4 kg (49.4 lbs)
Front Cover	3.2 mm tempered glass
Frame Material	Anodized aluminium alloy
J-Box	IP67, 3 diodes
Cable	4 mm² (IEC) or 4 mm² & 12 AWG 1000V (UL), 1160 mm (45.7 in)
Connector	T4 (IEC/UL)
Per Pallet	26 pieces, 635kg (1400lbs)
Per container (40' HQ)	624 pieces

ELECTRICAL DATA / NOCT*

CS6U	315P	320P	325P	330P
Nominal Max. Power (Pmax)	228 W	232 W	236 W	239 W
Opt. Operating Voltage (Vmp)	33.4 V	33.6 V	33.7 V	33.9 V
Opt. Operating Current (Imp)	6.84 A	6.91 A	6.98 A	7.05 A
Open Circuit Voltage (Voc)	41.5 V	41.6 V	41.8 V	41.9 V
Short Circuit Current (Isc)	7.44 A	7.50 A	7.57 A	7.66 A

* Under Nominal Operating Cell Temperature (NOCT), irradiance of 800 W/m², spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s.

TEMPERATURE CHARACTERISTICS

Specification	Data
Temperature Coefficient (Pmax)	-0.41 % / °C
Temperature Coefficient (Voc)	-0.31 % / °C
Temperature Coefficient (Isc)	0.053 % / °C
Nominal Operating Cell Temperature	45±2 °C

Figure 9. 1: Solar PV datasheet

9.2 Wind turbine datasheet

MODEL	AWS—HC 3.3kW
RATED OUTPUT	3300W
RATED WIND SPEED m/s / mph	10.5 / 24
PEAK OUTPUT	3650W
CUT IN m/s / mph	2.7 / 6
YAW SYSTEM	Passive by tail Vane
YAW / TOWER CABLE	N x 360° Freedom
GENERATOR	PM 3 phase alternator (variable speed)
INSULATION CLASS & EFFICIENCY	Class "H" > 87%
STATOR SKEW	1 slot pitch
MAX STATOR CORE TEMPERATURE	180°C
POLES	16
RPM—50hz/60hz	375 / 450
OVER SPEED LIMIT RPM / Hz	525 / 70
MONTHLY KWH 10mph / 4.5 m/s PLF %	352 kWh (18%)
MONTHLY KWH 12mph / 5.4 m/s PLF (%)	568 kWh (25%)
ROTOR DIAMETER	4.65m / 15ft
NUMBER OF BLADES	3
BLADE MATERIAL & COMPOSITION	Carbon fibre composite ~ 0.37
SWEPT AREA	6.4 sq.m / 175 sq.feet
MINIMUM TIP CLEARANCE cm / in	36 / 14
TIP SPEED RATIO (TSR)	8.5
LATERAL THRUST (MAX)	3200 nts
GOVERNOR / OVER SPEED LIMIT	Uptilt tilt (Hydraulic assisted)
GOVERN SPEED	27mph
GOV. SHUT-DOWN / OPTIONAL STOP	Electro-dynamic Switch
UNIT WEIGHT (TOWER TOP)	77Kg
TOWER TOP PIPE / YAW ADAPTOR	P 2.5" Shd 40
VOLTAGE OPTIONS	12 to 48 LV / 60—140 HV

Figure 9. 2: Wind turbine datasheet

9.3 Battery storage datasheet

12VRE-3000TF

FEATURES

TUBULAR TECHNOLOGY

- Positive plates provide 20% more capacity than flat plate batteries
- Encapsulated active material avoids plate shedding extending cycle life

POLYPROYLENE CONTAINER

- Impact resistant suitable for high heat environments

BENEFITS

ENHANCED RUNTIME

- Ultra-high Amp Hour capacity
- 50% DoD to 12.0V

EXTENDED SERVICE LIFE

- 2,000 cycles to 50% DoD

RESILIENCE

- Intense duty cycling superior to flat plate lead-acid
- Partial Stage of Charge operation superior to flat plate lead-acid
- Deep discharge recovery

CERTIFIED QUALITY

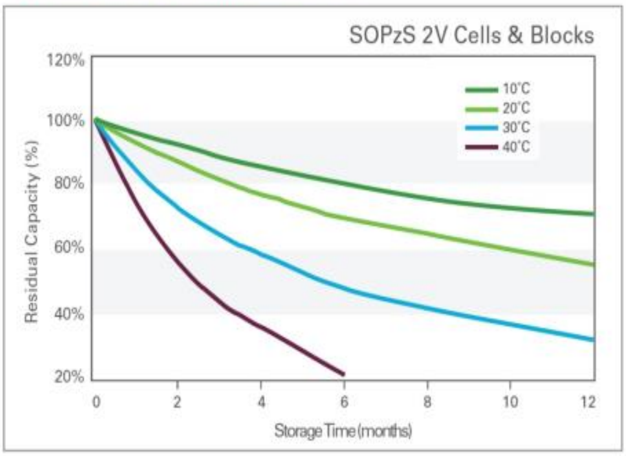
Discover® manufacturing facilities are fully certified to ISO 9001/14001 and OSHA 18001 standards.
Designed in accordance with and published in compliance with applicable standards, including:

- IEC 60896-11 (SOPzS) for stationary applications
- IEC 61427 for PV energy systems

SHIPPING CLASSIFICATION

- UN 2794

SELF-DISCHARGE CHARACTERISTICS



CAPACITY VS. TEMPERATURE

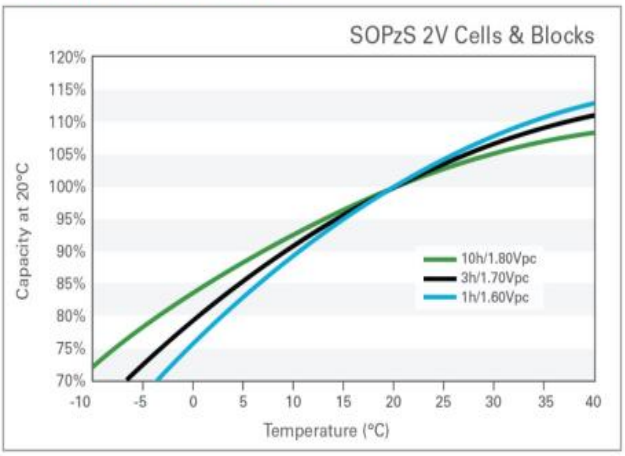


Figure 9. 3: Battery storage datasheet

ETHICS APPLICATION FORM

Please Note:
Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form **before** collecting or analysing data. The objective of submitting this application *prior* to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the **EBE Ethics in Research Handbook** (available from the UCT EBE, Research Ethics website) prior to completing this application form: http://www.ebe.uct.ac.za/ebe/research/ethics1

APPLICANT'S DETAILS		
Name of principal researcher, student or external applicant		RONAK MEHTA
Department		ELECTRICAL ENGINEERING
Preferred email address of applicant:		ronn_mehta@hotmail.com
If Student	Your Degree: e.g., MSc, PhD, etc.	BSc. in Mechatronics Engineering
	Credit Value of Research: e.g., 60/120/180/360 etc.	40
	Name of Supervisor (if supervised):	A/PROF. SUNETRA CHOWDHURY
If this is a researchcontract, indicate the source of funding/sponsorship		-
Project Title		DESIGN OF AN OPTIMAL STAND ALONE HYBRID RENEWABLE ENERGY SYSTEM WITH STORAGE FOR SUPPLYING PRIORITY LOADS IN A TYPICAL OFF GRID COMMUNITY

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

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

APPLICATION BY	Full name	Signature	Date
Principal Researcher/ Student/External applicant	RONAK MEHTA	RMehta	06/08/2020
SUPPORTED BY	Full name	Signature	Date
Supervisor (where applicable)	A/PROF. SUNETRA CHOWDHURY	S.Chowdhury	07/08/2020

APPROVED BY	Full name	Signature	Date
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section 1; and for all Undergraduate research (Including Honours).	A/Prof F Nicolls pp J Buxey	JBuxey Dept. Manager: Elec Eng Authorised to sign obo HOD	7.09.2020
Chair: Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the questions in Section 1.			