DESIGN OF A HYBRID POWER SYSTEM FOR A WIRELESS COMMUNICATION TOWER SYSTEM

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A thesis submitted in partial fulfilment for the Degree of Master of Science in Energy Management

2015

DECLARATION

I declare that this work has not been previously submitted for the award of a degree by this or any other University. To the best of my knowledge, this report contains no material previously published except where due reference is made.

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This thesis has been submitted for examination with our approval as University Supervisors.

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DEDICATION

I dedicate this thesis work to my family, Telkom Kenya workmates, church members and the MSc. Energy Management class of 2013, University of Nairobi.

ACKNOWLEDGEMENTS

My sincere thanks go to Prof. Mbuthia and Dr. Mwema for their continued support, listening, constructive ideas, patience and advice. Without them, this research work would not have come this far.

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	Alternating current
BTS	Base trans-receiver station
CAPEX	Capital expenditure
COE	Cost of energy
CRF	Capital recovery factor
DC	Direct current
Genset	Diesel generation set
GHG	Green House Gas
GMT	Greenwich Mean Time
HOMER	Hybrid Optimization Model for Electric Renewables
HPS	Hybrid Power Systems
IC	Initial cost
IEA	International Energy Agency
KES or S	Kenya shillings
KMD	Kenya Meteorological Department
KPLC	Kenya Power & Lighting Company
KVA	kilo volt ampere
KW	kilo watt
NASA	National Aeronautics and Space Administration
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
O & M	Operation and maintenance
OPEX	Operational expenditure
PV	Photovoltaic
PVPS	Photovoltaic Power Systems
REA	Rural Electrification Authority

RES	Renewable Energy Sources
Sim	simulation tool
SV	Salvage value
SWERA	Solar and Wind Energy Resource Assessment
TAC	Total Annualized Cost

SYMBOLS

C_{rep}	Replacement cost of component
i	Annual Real Interest Rate
R_{comp}	Life time of the component(s)
R_{rem}	Remaining life of component
R_{rep}	Replacement cost
t	Number of years
V	voltage
W	watts
Wh	watt-hour

ABSTRACT

Telkom Kenya tower systems, especially those located in rough terrain, are currently powered by diesel generator sets. Diesel power generation is associated with several disadvantages which do not make it the best option. Generally, Kenya is blessed with Renewable Energy Resources (RES) which can be utilized at such towers to supply power. This study carried out measurements for wind speeds and solar insolation at Aitong, Narok site and compared these with data from secondary sources. A prototype Hybrid Powered System (HPS) was assembled and installed to record the actual RES available on site.

A HPS system was designed based on the data collected. The design process basically involved selecting the best combination of HPS system components based on their cost and power characteristics. Finally, the study compared the designed power system and the current online system at the site in terms of cost of implementation and running.

The actual on site data indicates that there is abundant RES at this site. The obtained data agrees well with data from the secondary sources consulted. The correlation is particularly close in the case of National Aeronautics and Space Administration (NASA) data. The system design optimization shows that a Net Present Cost (NPC) cost of KES 2.6 million against that of the current system of KES 21 million can be expected. The simulated Cost of Energy (COE) for the month of October is approximately Kenya Shillings (KES) 10/kWh which is better than that of Kenya Power and Lighting Company (KPLC) at KES 21/kWh over the same period.

CHAPTER 1: INTRODUCTION

1.1 Background information

Energy is vital for development of a community and nation as a whole and thus it must be produced and utilized efficiently [1]. It is argued that energy is a basic requirement for the modern life-style [2]. The ever increasing cost and environmental concerns involving conventional sources of electrical energy have increased interest in RES [3]. Technologies should therefore be developed to produce energy in an environmentally friendly manner from all energy sources. Sufficient importance should also be given to the efficient conservation of energy resources [4].

Electrical power requirements for most communication towers installed in rural areas are met by diesel generator sets. The extension of the main grid to low population areas especially those in difficult terrains is associated with high capital outlays [1]. The use of a diesel generator however, induces several environmental issues and high Operation and Maintenance (O & M) costs as summarized in Table 1.1 [5].

Table 1-1: Comparison of RES with Diesel Generation[5]

Item	RES	Diesel Generation
Cost	Low O & M costs	High O & M cost
Pollution	No emissions	GHGs, sound, and oil spillage
Dependency	Depends on natural and RES	Depends on oil supply
Fuel transportation	No transportation costs	Costly to transport using tankers, losses and poor quality due to theft during transportation.
Maintenance	Low maintenance	Costly, losses due to theft, and oil spillage.
Life	Longer useful life	Seven years or shorter
Power supply	Depends on availability of RES	No guaranteed uninterrupted generation

Aitong, Rift Valley, Kenya (Latitude: 1.18^o; Longitude: 35.25^o) is hilly with an estimated terrain elevation of 1943m above sea level. Electricity consumed by the Telkom Kenya tower system in Aitong is currently supplied by two 8 kVA diesel generators, although RES are in abundance [6]. The Capital Expenditure (CAPEX) and annual Operational Expenses (OPEX) for the two diesel generators is approximately KES 5 million and KES 3.1 million respectively. Appendix 1 details the O & M for the current diesel generator. The average power demand for this tower system is approximately 1.5 kW.

In the current study, the feasibility of replacing diesel power generation in Aitong tower system with solar and wind HPS, supplemented with battery bank storage with the use of diesel generation as a back-up source, was investigated. A prototype was fabricated and installed at the site for actual data collection for comparison with secondary data from previous studies and weather stations. An HPS was then designed based on the solar and wind data collected and economic viability of the investigated system. Figure 1-1 shows the location of Aitong hill in the main Kenyan map context.

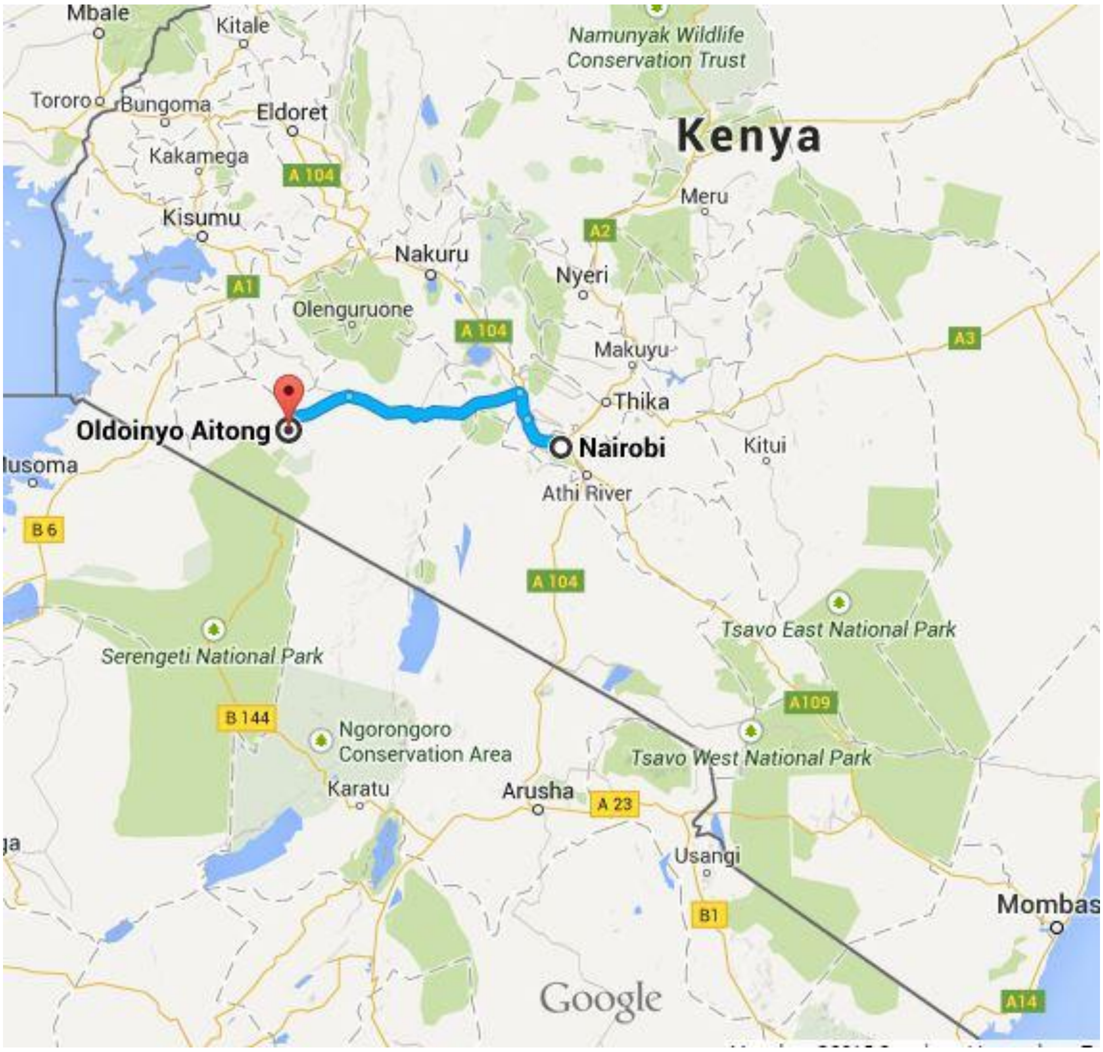


Figure 1-1: Location of Aitong from Nairobi (Google maps)

Results from the study represent additional power options to Telkom Kenya It is expected that the option suggested by these results will lead to lower O & M cost for communication towers. The cost savings realised can then be passed on to customers through reduction in calling charges leading to an increased market share and profits. An added benefit is a reduction in GHGs emission which will demonstrate the strong social responsibility characteristic of Telkom Kenya

1.2 Problem Statement

Electrical power generation using diesel engines is associated with environmental pollution while supplying power from the national grid to remotely located towers is costly. Therefore, a sustainable power supply system, which is environmentally friendly, cost effective and readily available is required.

1.3 Research Objectives

1.3.1 Main objective

The main objective of the study was to design a HPS consisting of Photovoltaic (PV), wind turbine and battery bank. The existing diesel generator set will be replaced by an optimized diesel generator which will act as a back-up power source in case the components for capturing RES are not available due to either breakdown, replacement, etc.

1.3.2 Specific objectives

1. To assess the solar and wind energy resource at the Aitong tower system site
2. To design and optimize a HPS for the communication tower system

3. To assess the economic viability of the HPS as a source of power for the tower system

CHAPTER 2: LITERATURE REVIEW

2.1 Renewable energy sources (RES)

Renewable energy comes from the sun and can be used directly as is the case with solar heating systems or indirectly as with hydroelectric power, wind power, and power from biomass fuels. RES includes solar energy, wind energy, hydroelectric power, geothermal energy, bioenergy, ocean energy, etc. There are other alternatives to sources of energy that are not renewable in nature. Although these are "alternative energy" rather than "renewable energy", they use the existing energy more efficiently than older technologies. The use of renewable and alternative energy sources can save funds, conserve energy, save the environment, and reduce over-dependence on energy supplies outside the country borders [9], [10].

2.2 Hybrid Power Systems (HPS)

Hybrid power system involves a combination of two or more modes of electricity generation devices or sources [2] such as wind turbines, PV, micro-hydro and/or fossil fuel generators. They are generally independent of centralized power grids and can be used in remote/rural areas [11], [12]. The use of RES in hybrid power generation systems reduces the reliance on expensive fuels while allowing for a cleaner generation of electrical power [13]. HPS addresses limitations in terms of fuel flexibility, efficiency, reliability, emissions and/or economics as well as elimination of fuel transportation costs [12]. Figure 2-1 shows the schematic diagram of a basic HPS involving various sources [11].

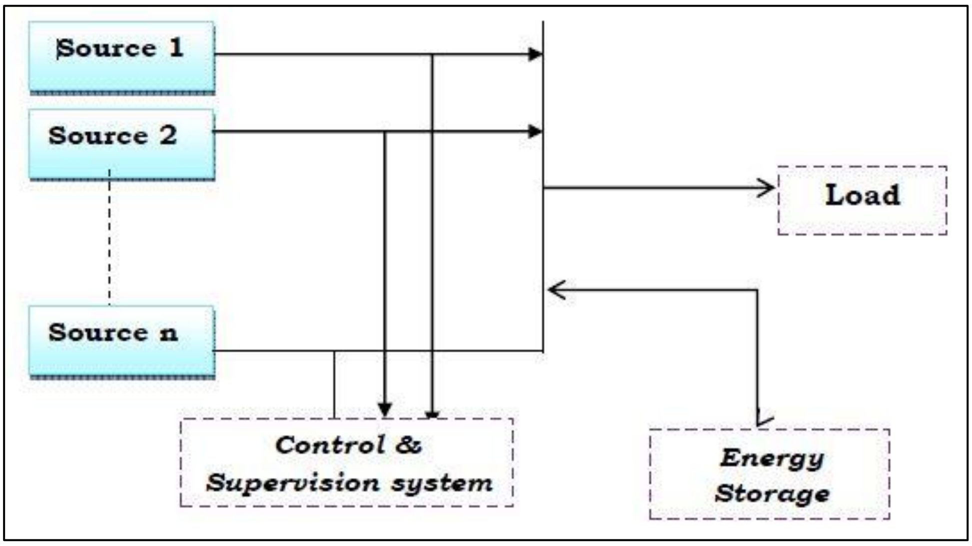


Figure 2-1: Basic HPS

In general a hybrid power system contains Alternating Current (AC) diesel generators, an AC distribution system, a Direct Current (DC) distribution system, loads, RES, energy storage, power converters, rotary converters, coupled diesel system, dump loads, load management options or a supervisory control system [14]. A schematic diagram of the possibilities available from a HPS is illustrated in Figure 2-2 showing the operation of each of these components and the interaction between them.

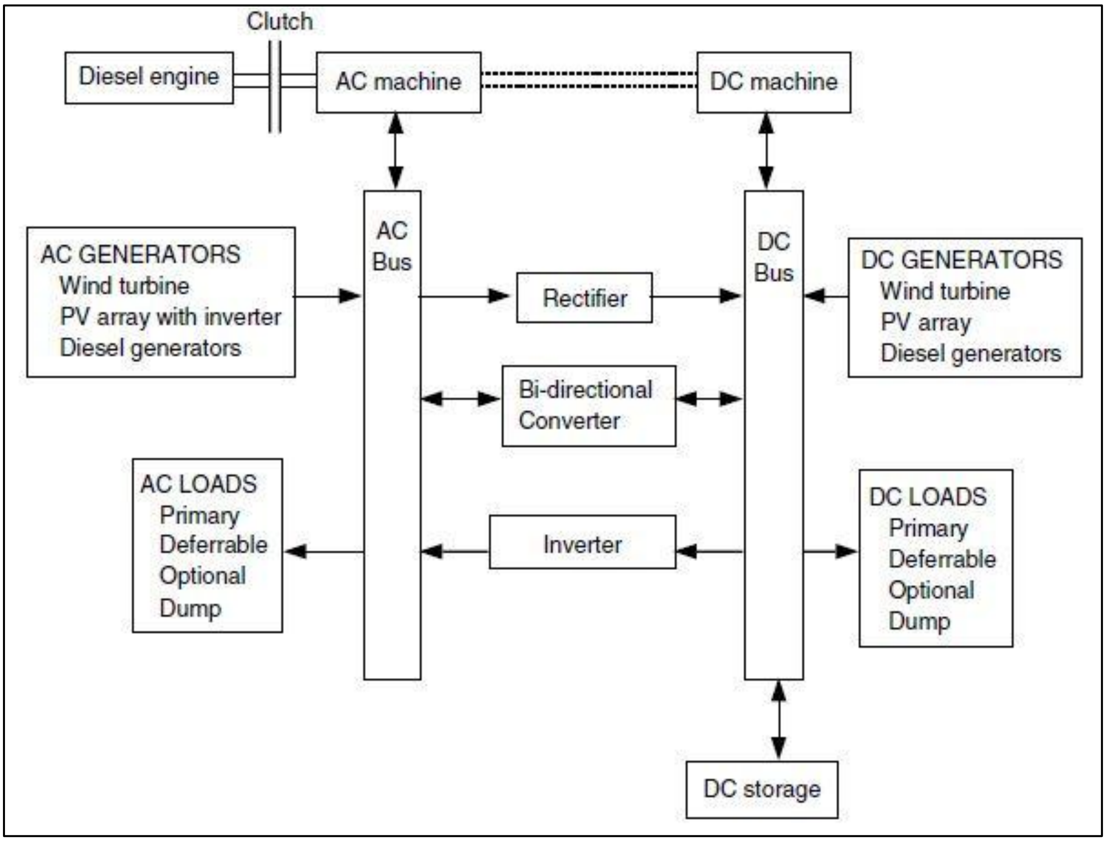


Figure 2-2: HPS possibilities [15]

In a HPS, a diesel power generator acts as a back-up system in circumstances which may render RES capturing components unavailable. The system is usually modified so that the diesel generator is not always required, but in that case other components must be added. There are a number of wind turbines that supply DC power as their principal output. These machines are typically in the smaller size range of 10kW or less. With suitable controls or converters they can support both AC and DC loads. PV panels represent a useful complement to wind turbines in some hybrid power systems. PV panels inherently generate DC power and therefore usually operate in conjunction with storage and a separate DC bus. In larger systems they may be coupled with a dedicated inverter and act as a de facto AC power source in this case.

A dump load is used to dissipate excess electrical power in the network. Such an excess could arise during times of high renewable contribution and low load and can lead to power supply instability. There are two types of power conversion functions of particular significance for hybrid power systems: rectifying and inverting, to charge batteries from AC sources or supply AC loads from DC sources, such as batteries and photovoltaic panels.

Most hybrid power systems incorporate a wide variety of control functions. Some control functions are carried out by dedicated controllers that are integral to the system components. Overall system control is accomplished by the system supervisory control (SSC).

A stand-alone HPS consisting of wind and solar PV is a suitable hybrid combination for most applications, taking care of seasonal changes [16]. They also complement each other during lean periods in that they are both seasonal in nature. Figure 2-3 shows a HPS consisting of wind and solar PV and other components.

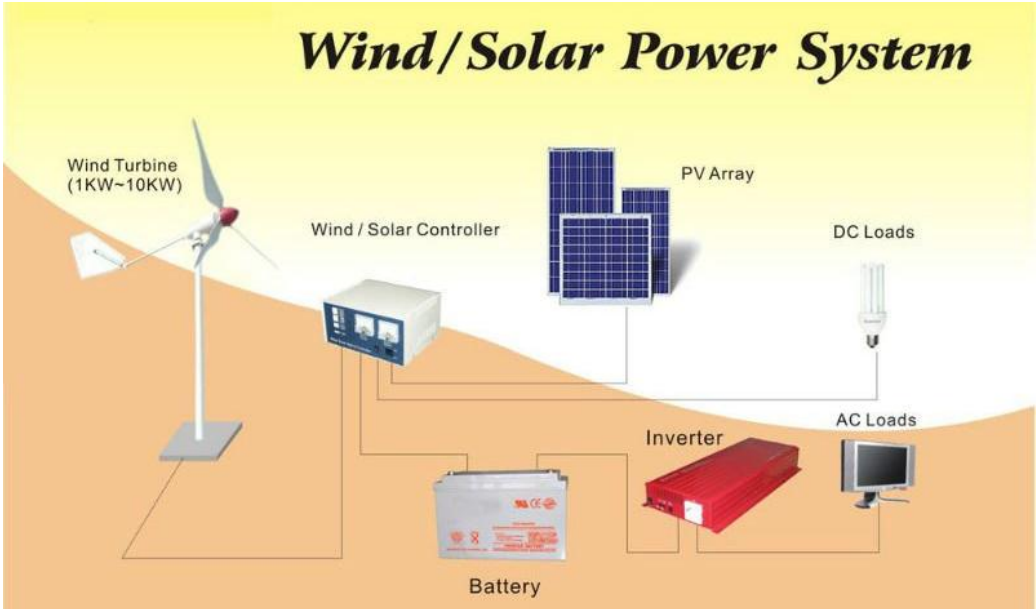


Figure 2-3: Solar-wind hybrid power system[1]

2.2.1 HPS design

There are different configurations of renewable and conventional energy sources being deployed for telecommunication purposes: Diesel-Battery; Solar-Diesel-Battery; Diesel-Battery-Wind; Solar-Diesel-Battery-Wind or Solar-Battery. The configuration of a HPS depends on three factors namely, RES availability, load, and costs (i.e. CAPEX and OPEX) [11]. Thus, the HPS is selected to optimize the available resources vis-à-vis various constraints to improve performance, economy and reliability.

2.2.2 HPS Design Optimization

Optimization of a HPS looks into the process of selecting the components based on NPC, Total Annualized Costs (TAC), and Salvage Costs (SV). The RES components are then sized to provide efficient, reliable and cost effective energy [17]. There are

[1] http://sunfadgroup.com/Wind-Solar%20Hybrid%20System.html (Accessed on 26th March, 2016)

several tools used in hybrid systems design such as dimensioning tools, simulation tools, research tools, and mini-grid design tools although a manual design approach is also possible. However, the manual design approach is both tedious, time consuming, and prone to errors.

A dimensioning tool (also referred to as a sizing tool) is capable of dimensioning HPS system, i.e. for a given energy requirement, this tool can be used to determine the optimal size of each component in the system based search space. Search spaces consists of optional number of components and ratings as specified by the designer. With the simulation tool, as opposed to a dimensioning tool, the designer must specify the nature and size of each component. The tool then provides a detailed analysis of the behaviour of the system. Performing Research and Development (R&D) at component and system level requires a high level of flexibility in the interaction of the components. While traditional simulation tools can perform extensive sensitivity analyses, they generally do not permit the user to modify the algorithms that determine the behaviour and interactions of the individual components and research tools must therefore be resorted to. Mini-grid design tools assist with the design of the mini-grid electrical distribution network[18]. Table 2-1 gives a summary of some of these tools category-wise.

Table 2-1: Overview of simulation tools [18]

Tool	Type
RETScreen	Dimensioning tool
HOMER	Simulation/dimensioning tool
Hybrid2	Simulation tool
Vipor*	Design tool
Jpelec*	Design tool

2.3 HOMER and NPC

Hybrid Optimization Model for Electric Renewables (HOMER) software has been developed and is continually improved from time to time by National Renewable Energy Laboratory (NREL) [19]. HOMER is primarily an optimization software package which simulates various RES system configurations and scales them on the basis of NPC [20]. HOMER calculates the available renewable power and compares it to the required electrical load. Any constraints on the system imposed by the user are then assessed; e.g. the fraction of the total electrical demand served or the proportion of power generated by renewable sources.

NPC represents the life cycle cost of a system. The calculation assesses all costs occurring within the project lifetime, including initial set-up costs, component replacements within the project lifetime, maintenance and fuel. Future cash flows are discounted to the present. HOMER calculates NPC according to

$$NPV = \frac{TAC}{CRF} \qquad (2.1)$$

where Capital recovery factor (CRF) in equation 2.1 is defined as

$$CRF = \frac{i}{1-[1+i]^{-t}} \qquad (2.2)$$

HOMER assumes that all prices escalate at the same rate, and applies an 'annual real interest rate' rather than a 'nominal interest rate'. NPC estimation in HOMER also takes into account salvage costs, which is the residual value of the power system components at the end of the project lifetime. The salvage value (SV) is given as

$$SV = C_{rep} * \frac{R_{rem}}{R_{comp}} \qquad (2.3)$$

Annual savings are estimated by subtracting the annualized costs from the annualized gains, giving the overall saving or loss for each year. Published payback times for grid-connected small-scale systems range from seven years (IC aided by large rebates) to 11.2 years, 15 years or as high as 30 years [20].

2.4 Summary

Renewable energy is free in nature, continuously replenished, and does not pollute the environment, while reducing dependence on the non-renewable and polluting sources of energy. In addition, use of RES saves funds for the investors. There are various types of RES which have been used over the world successfully. Most of the Telkom Kenya tower systems in the remote areas are powered by diesel generation, although such may be located in RES abundant areas, which is a polluting source. To design a HPS system, information about the RES availability is required. The system is then optimized based on various costs. The final decision is determined from the expected savings to be made by implementing the designed HPS system. This triggered objectives and the order in which they were carried out in this study.

CHAPTER 3: MATERIALS AND METHODS

3.1 Energy demand and renewable resources availability

The starting point in the design phase of the HPS treated in the work was the assessment of the availability of the respective renewable resources at the site. Solar insolation and wind speeds were accessed and sizing of the various components of the HPS then based on the energy demand of the tower and the average RES available on site.

A HPS prototype was assembled and installed at the site for the purposes of measuring the RES potential. The HPS consisted of 50W wind turbine, 20W solar panel and 40AH battery as well the measuring meters. The RES potential was based on the actual percentage of generation from each component over a period of time. After installing the prototype, the respective amount of energy generated from each source was read from the energy meters and noted. This was to represent the actual performance of the system and act as a baseline for similar systems which may be installed at this site irrespective of their ratings.

3.1.1 Load/demand assessment

The energy demand for the tower components was based on the rating of the current energy consuming equipment of the tower system. The total energy consumption in kW was computed and used as the basis for the HPS design. The monthly peak power demand was then used in HOMER as this has to be met continually by the HPS.

3.1.2 Wind Resource Assessment

The data pertaining to the wind resource available at the location was required to estimate the power output [1]. The wind resource data for this project was based on secondary sources which included latest published studies, for the last 15 years, such Kenya Meteorological Department data, and NASA weather data. Actual data collection, using an anemometer, and analysis was performed to verify documented data.

Most secondary sources provide wind speeds measured at different heights above the ground. To draw valid conclusions, the prototype height of 3m above the ground was adopted in the current work and all readings therefore normalized to this height using the wind shear logarithmic law shown in equation 3.1.

$$V_z = V_{z_{ref}} \left[\frac{\ln\left(\frac{z}{z_o}\right)}{ln\left(\frac{z_{ref}}{z_o}\right)} \right] \quad \ldots\ldots\ldots\ldots\ldots \quad (3.1)$$

where: V_z is the wind speed at the current height "z" above ground (3 m)

$V_{z,ref}$ is the wind speed at the reference height "z_{ref}"

$Z_o = 0.01$ m is the roughness length [6]

3.1.3 Solar Resource Assessment

Kenya straddles the equator and therefore generally receives consistently high solar radiation. Solar insolation data in kWh/m^2 was used to assess the site-specific solar availability and these values then used to determine the amount of photovoltaic energy output [1].

3.2 Hybrid power system design

In the front end, HOMER calculations on size of the wind, solar and battery systems was carried out following an iterative scheme based on the respective average monthly data of the measured RES according to the procedure provided in [4], [20]. Various HPS components were then sourced from various manufacturers and their cost and power characteristics compared.

3.3 Cost-Benefit-Analysis

It is pertinent that economic justification should be made while attempting to optimize the size of integrated power generation systems [4]. The economic analysis of the HPS was performed and the cost aspects taken into account for optimization of the size of the systems. Using the HOMER model developed, various costs, namely, NPC, COE, SV and TAC were computed considering the life period and replacement costs of the individual systems as highlighted in [4], [20].

The HPS configurations in this study consisted of wind energy, solar energy, battery bank, and optimized diesel generator to act as back-up energy source when RES capturing components are not available. These configurations were then modelled and analysed to determine the most viable configuration based on the NPC of the system over its lifetime and diesel fuel consumption. HOMER software assisted the researcher in assessing the technical feasibility of each system design and the NPC of the system. While RETScreen and Hybrid2 software can do simulation just like HOMER, HOMER has the dimensioning capability and thus it was chosen in this project. In addition, it could be accessed for free.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Tower system BTS and Transmission load

The energy consuming equipment for Aitong station as follows:-

The power needed for radio site depends on BTS type, generation, traffic and output power and the power consumption ranges from 1000 -1200 watts for a S222 BTS configuration and power consumption of a microwave radio link depends on capacity and ranges from 200 to 300watts and this is according to manufacturer's specifications. The security and aviation warning tower lights range from 20 to 25 watts according to manufacturer's specifications and the lights works during the night.

The daily average energy consumption of the tower BTS and the transmission load was found to be approximately 36 kWh with an errors of +ve (positive) or –ve (negative) 10%.

The daily average energy consumption of the tower BTS and the transmission load was found to be approximately 36 kWh with an errors of +ve (positive) or –ve (negative) 10%. This was based on the power consumption maintenance monitoring data for Telkom Kenya sites for the last 15 years. This translated to 1.5 kW of power requirements for the tower system. The security lights and aircraft warning light at the top of the tower represented a night-time average load of 50 W as from historic data recorded over a long time by the maintenance technicians at the site. Figure 4-1 shows the hourly BTS load pattern while Figure 4-2 shows the lighting load pattern of the telecom tower as modelled by HOMER software.

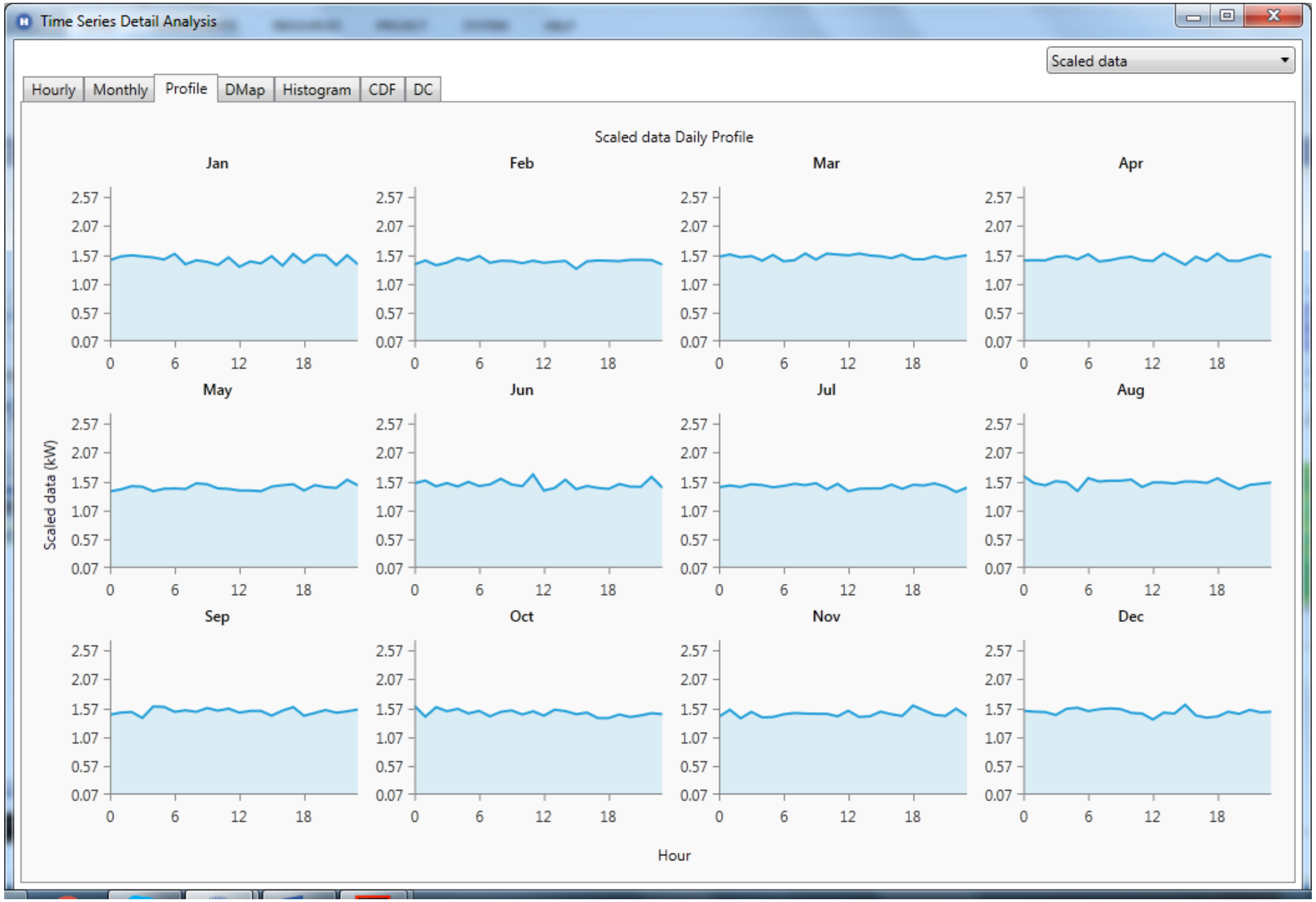


Figure 4-1: Hourly BTS load pattern for the tower

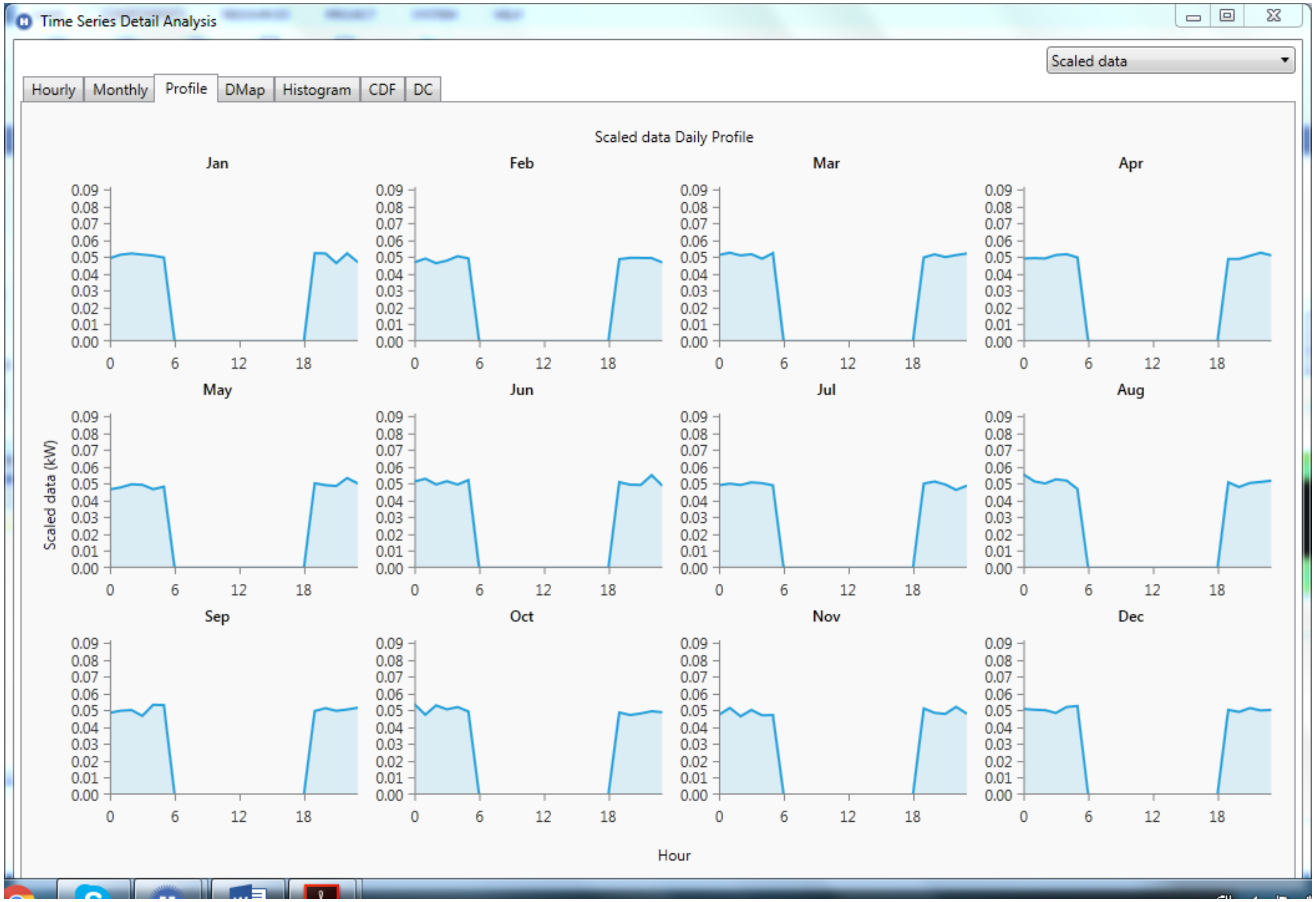


Figure 4-2: Hourly lighting load pattern for the tower

4.2 Renewable energy sources availability

RES availability in the study area was categorised into secondary data and actual data. The secondary data was based on the published NASA historical data, Kenya Meteorological Department (KMD) published data from KMD library, and previous studies on the availability of RES in the Aitong area [6], [21][22], [23] and [23]. Actual data was the data collected by use of a prototype HPS installed at the study site. From the analysis of the two sets of data, conclusions on average RES potential were drawn and the HPS designed based on these findings.

4.2.1 Secondary data collection and analysis

4.2.1.1 Wind energy potential

Data collected, documented and published by NASA Data atmospheric centre for the last 35 years for Aitong area, are shown in Table 4-1. These indicate an average wind speed of 4.97 m/s at 50m above ground level (agl) (source: NASA[2]).

[2] https://eosweb.larc.nasa.gov/cgi-in/sse/grid.cgi?email=skip%40larc.nasa.gov&step=1&lat=-1.18&lon=35.25&submit=Submit (Accessed on 26th March, 2016)

Table 4-1: Monthly averaged wind speed at 50 m agl

Month	Average wind speed (m/s)
January	4.58
February	4.80
March	4.76
April	4.81
May	4.95
June	5.16
July	5.28
August	5.50
September	5.39
October	5.13
November	4.76
December	4.49
Average	**4.97**

A study carried out for Ministry of Energy (MoE) Republic of Kenya in 2013 showed that average wind speeds in Narok, where the current site is located, is 5.55 m/s at 40 m height [22].

A study carried out by [23] as shown in Figure 4-3 presents wind data in Kenya which places Narok region in the 4.5 to 5.5 m/s wind speed zone measured at 80 m height.

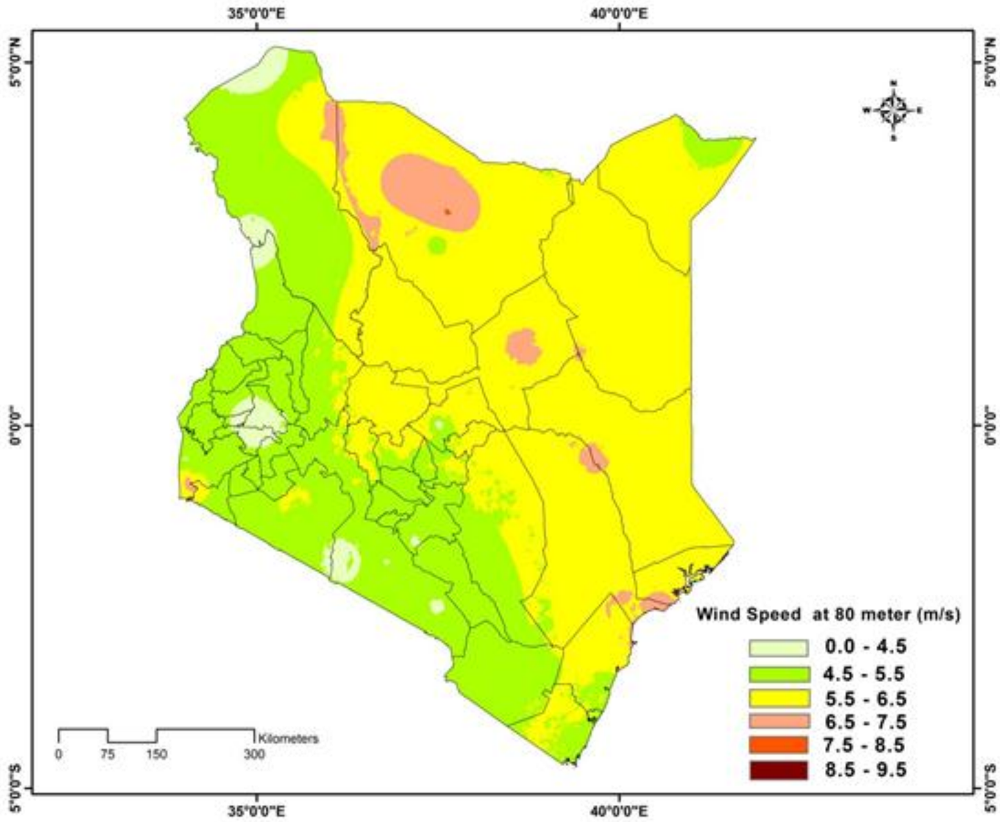


Figure 4-4: Kenyan wind speed map at 80m altitude [23]

A study by [6], [21] shows that the wind energy potential in the Kenyan Rift Valley region stands at 3.36-5.5 m/s measured at 20m above the ground level (agl).

The daily wind speeds as recorded and published by KMD between 1964 and 1980 are presented in Appendix 2. This is the only reliable and well documented data by KMD. The average wind speeds at 0600 GMT is 4 knots (equivalent to 2.06 m/s) while at 1200 GMT it is 9 knots (equivalent to 4.63 m/s) at 10 m above ground level (agl). Table 4-2 shows the summary of the wind speeds extracted from Appendix 2.

Table 4-2: Summary of wind speeds extracted from Appendix 3

Average wind speed @10m above ground level				
Month	**knots**		**m/s**	
	Wind speeds	**Wind speeds**	**Wind speeds**	**Wind speeds**
	0600 GMT	**1200 GMT**	**0600 GMT**	**1200 GMT**
January	3	9	1.54	4.63
February	3	10	1.54	5.14
March	3	10	1.54	5.14
April	4	10	2.06	5.14
May	5	9	2.57	4.63
June	4	8	2.06	4.12
July	5	9	2.57	4.63
August	5	9	2.57	4.63
September	6	9	3.09	4.63
October	7	10	3.60	5.14
November	5	9	2.57	4.63
December	3	9	1.54	4.63
Average	**4**	**9**	**2.06**	**4.63**

These readings were then normalized to the height of the prototype (3m) using the wind shear logarithmic law stated by Equation (3.1). The resulting data is shown in Table 4-3.

Table 4-3: Summary of secondary data scaled at the 3 m height

Source	Average wind speed (m/s)	Wind speed at 3m above the ground (m/s)
NASA for the last 35 years	4.97 m/s @50m	3.33
A study by [22] for MoE republic of Kenya in 2013	5.5 m/s @40m	3.78
A study by [23] in 2007	5 m/s @80m	3.17
A study by [6] in 2013, [21] in 2008	4.43 m/s @20m	3.32
Kenya Meteorological Department (KMD), between 1964-1980	3.345 m/s @10m	2.76
Average wind speed at 3 m above the ground		3.27

The average wind speed for the site location from secondary data and previous studies was found to be 3.27 m/s. Figure 4-4 is a graphical illustration of the secondary data in Table 4-3.

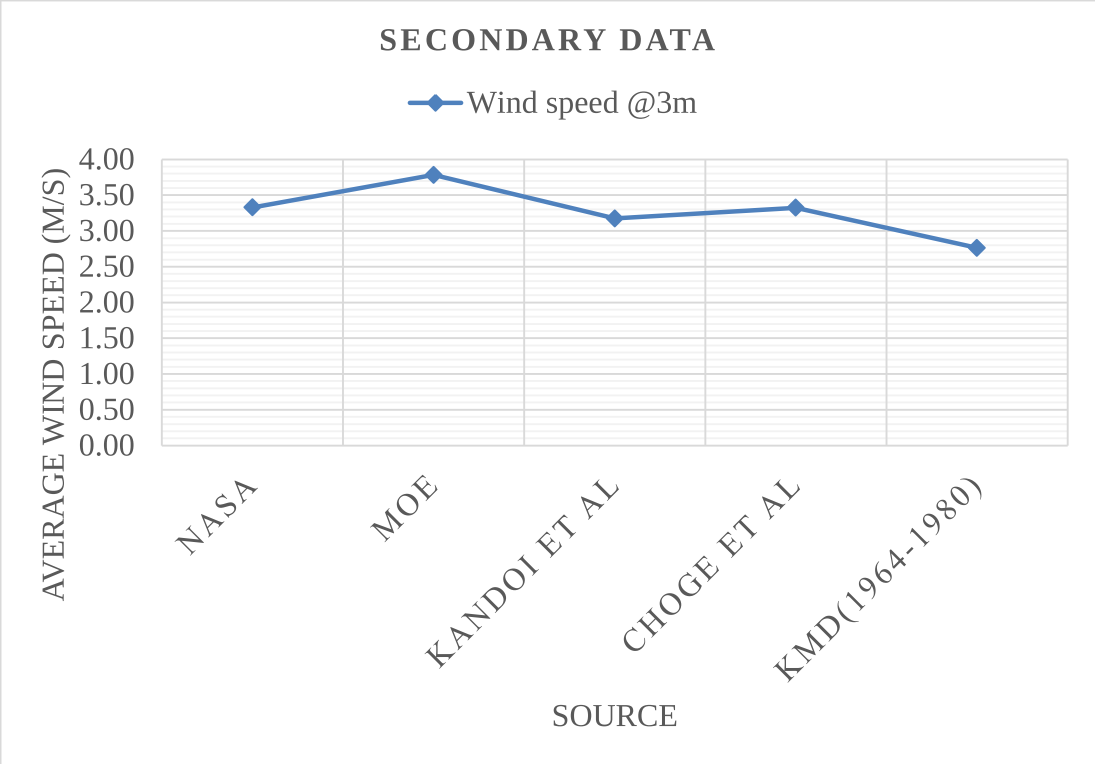


Figure 4-5: A summary of secondary data

4.2.1.2 Solar insolation

Data collected, documented and published by NASA Data atmospheric centre over the last 35 years for Aitong area, shown in Table 4-4 shows that the average insolation incident on a horizontal surface is 5.95 kWh/ m^2/day.

Table 4-4: Monthly averaged insolation incident on a horizontal surface

Month	($kWh/m^2/day$)
January	6.10
February	6.58
March	6.49
April	5.95
May	5.69
June	5.53
July	5.48
August	5.81
September	6.30
October	6.08
November	5.60
December	5.82
Average	5.95

The daily average solar insolation of 476 langleys (equivalent to 5.54 $kWh/m^2/day$) as recorded and published by KMD between 1964 and 1980 are presented in Appendix 2. This is the most reliable documented data. Based on the secondary data, Table 4-5 shows the summary of the solar potential for the site.

Table 4-5: Summary of solar energy potential from secondary sources

Source	Solar power potential (kWh/sq. m/day)
NASA	5.95
A study by (Theuri, 2008)	5.12
Kenya Meteorological Department (KMD), between 1964-1980	5.54
Average solar potential	**5.54**

4.2.2 Primary data collection and analysis

4.2.2.1 HPS prototype assembly

Figure 4-5 shows the HPS prototype block diagram while Appendix 3 shows the circuitry of the same. Appendix 4 highlights the specifications of the HPS prototype components.

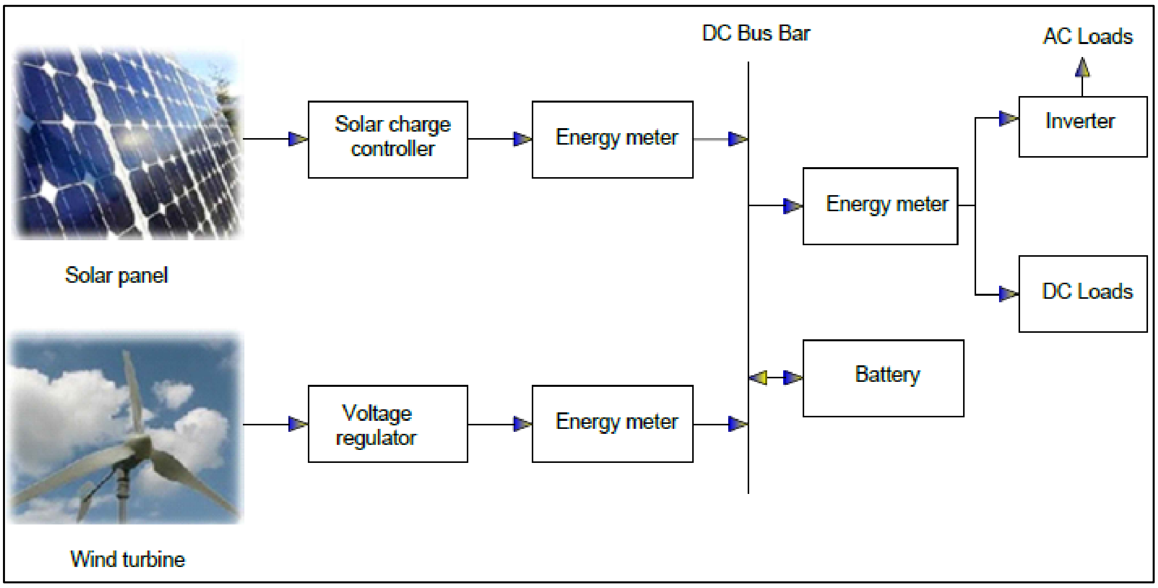


Figure 4-6: Prototype HPS

4.2.2.2 Data analysis

The testing period was divided into seven periods labelled 1 to 7, each covering 21 days as shown in Table 4-6. The full actual data is shown in Appendix 5. After every 21 days, the system was reset for checks and maintenance carried out where necessary. The most important data are the insolation levels and wind speed. The purpose of the consumption loads was to make sure that there was continuous loading of the RES. Figures 4-6 and 4-7 show a representation of the solar insolation and average wind speed for the site respectively. The actual average wind speed for the site was found to be 3.37 m/s while the average solar insolation for the site is 6.0 kWh/ m^2/day.

Table 4-6: Set of data averages

Item	Set of data averages								Avg.
	1	2	3	4	5	6	7	8	
Irradiance (Wh/m^2/ day	5537.43	5959.53	5892.04	6375.52	6731.23	6135.44	5257.66	5357.97	5984.12
Wind Speeds (m/s)	3.99	3.69	3.31	3.04	3.23	3.22	2.74	3.27	3.31
Solar potential (Wh/m^2/day)	475.02	477.63	479.03	479.03	487.49	357.25	303.98	279.71	417.39
Wind potential (Wh/m^2/day)	97.72	97.80	97.74	97.74	59.78	96.10	94.10	94.10	91.89
Consumption (Wh/day)	105.42	107.03	106.82	107.03	66.40	94.00	37.00	37.00	82.59

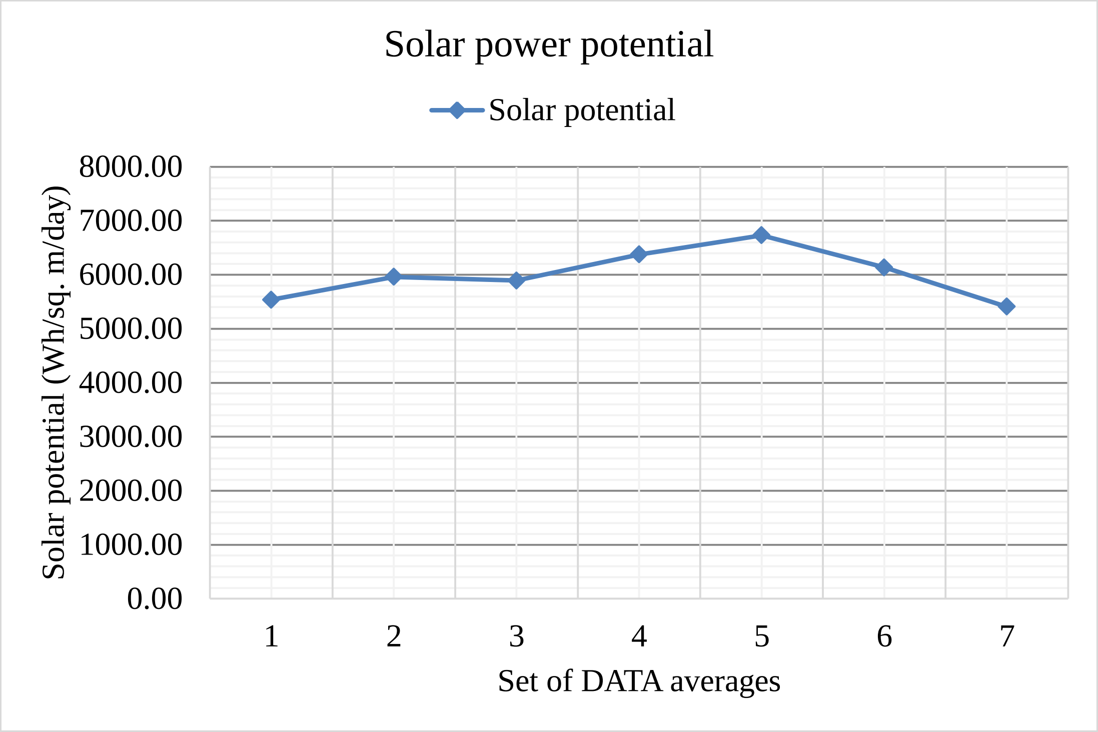


Figure 4-7: Actual solar insolation

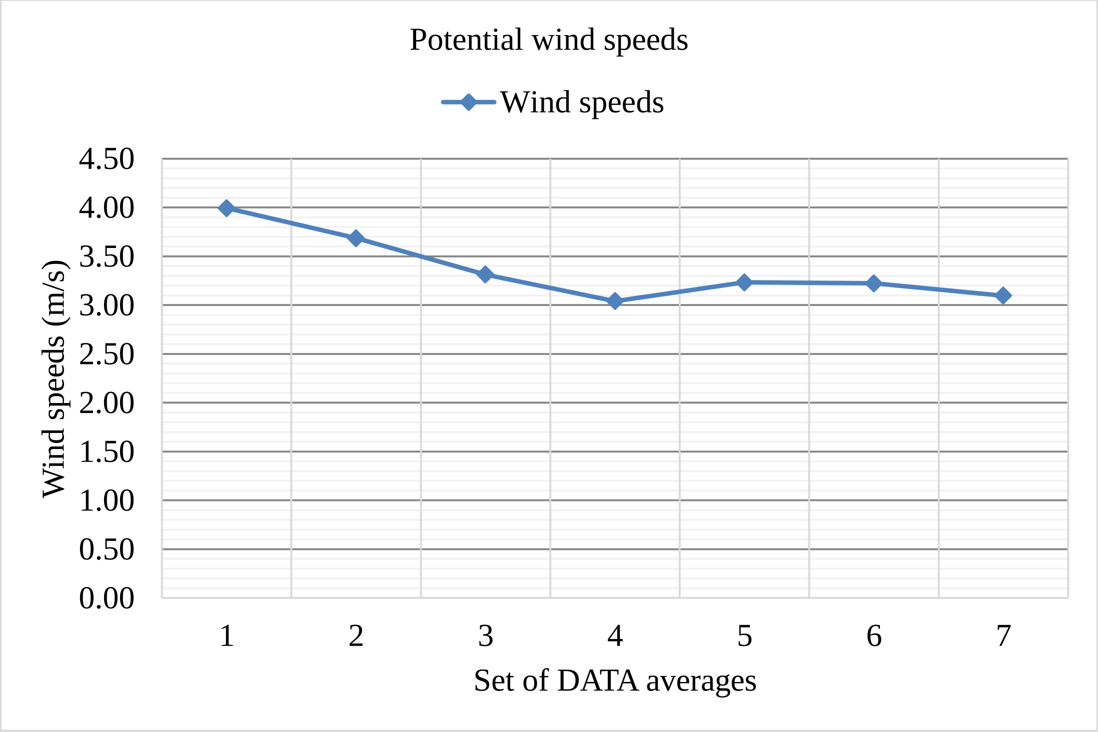


Figure 4-8: Actual wind speeds

4.3 HPS design

The HPS was modelled using HOMER. The RES data was based on NASA data uploaded directly to the software from the NASA website. The optimization was based on various sensitivity analyses including the cost and the available RES.

4.3.1 HPS modelling

The model consists of a XL6R wind turbine, PV, FB10-130 batteries, BDI converter, and an auto sized diesel generator as shown by Figures 4.8-4.15 which represents the HOMER simulation results. Table 4-7 shows the eight (8) best combinations based on NPC (of both CAPEX and OPEX) for various components from the HOMER simulation results. Figures 4-16 to 4-21 shows the designed HPS daily profiles.

Table 4-7: The eight (8) best simulation results

No.	Architecture						Cost (KES)				System	Auto Genset
	PV (kW)	**XL6R**	**Auto Genset (kW)**	**FB10-130**	**BDI 3P (kW)**	**Dispatch**	**COE**	**NPC**	**Operating cost**	**Initial capital**	**RES Fraction (%)**	**Hours**
1	6	1	3.4	4	15	CC	10	2,600,080	27,410	2,067,500	100	0
2	10		3.4	4	15	CC	10	2,658,371	30,410	2,067,500	100	0
3		1	3.4	32	15	CC	34	8,776,689	319,563	2,567,500	57	1695
4	7	1	3.4		15	CC	37	9,583,642	389,401	2,017,500	47	5686
5	8		3.4		15	CC	40	10,434,250	456,338	1,567,500	33	6033
6		1	3.4		15	CC	46	11,864,990	560,852	967,500	21	8379
7			3.4		15	CC	53	13,725,680	687,495	367,500	0	8760
8			3.4	4	15	CC	54	13,925,360	687,478	567,500	0	6031

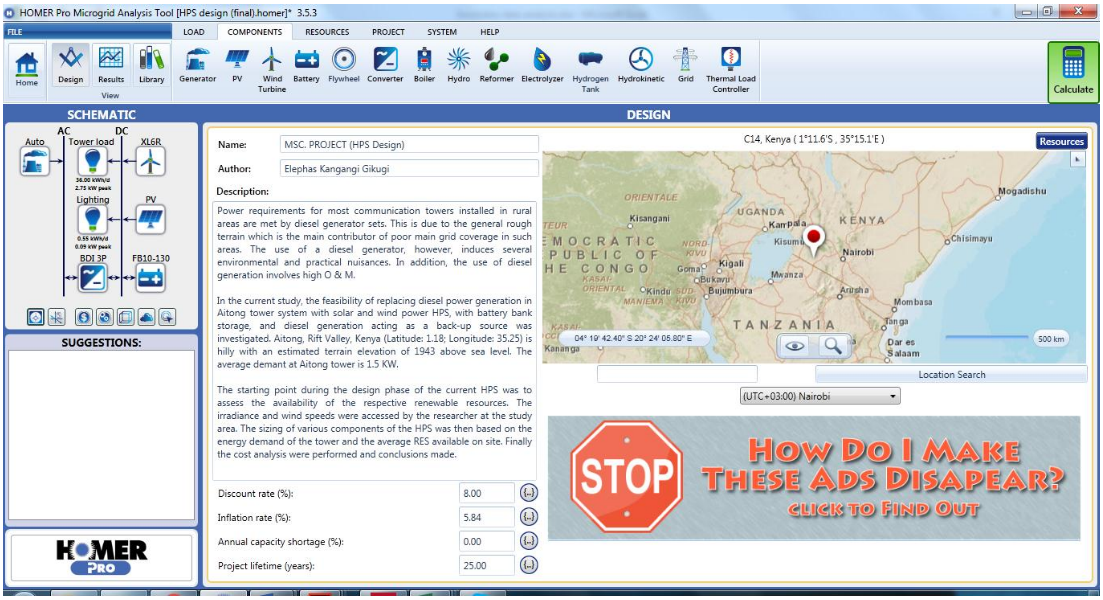


Figure 4-9: HPS schematic screen shot

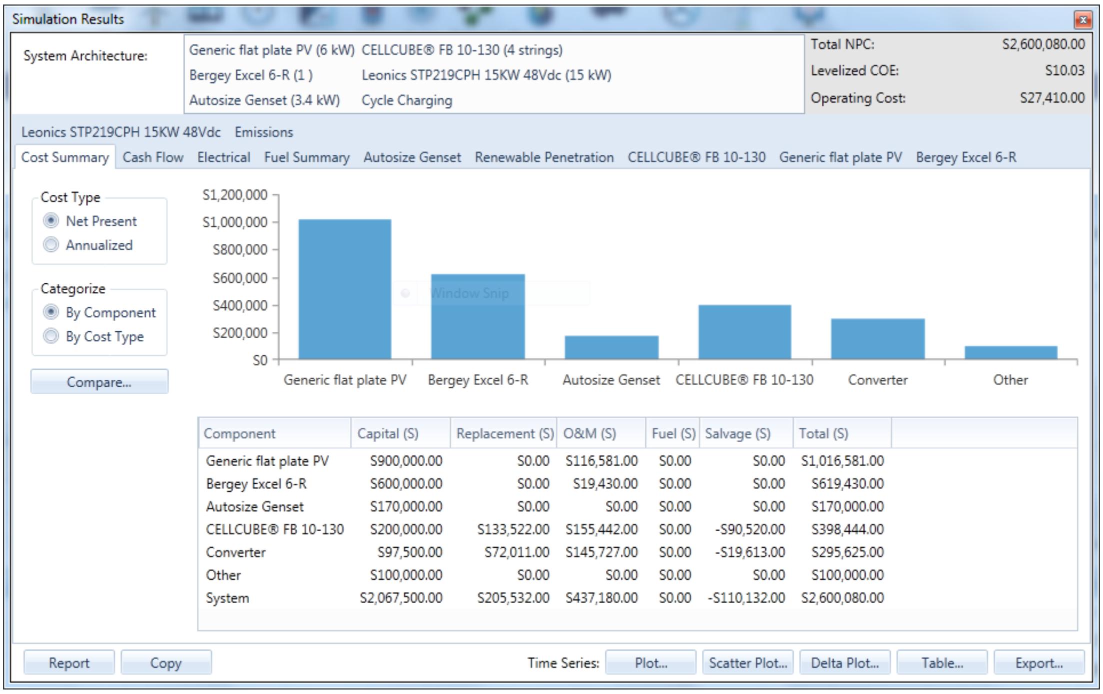


Figure 4-10: Cost summary

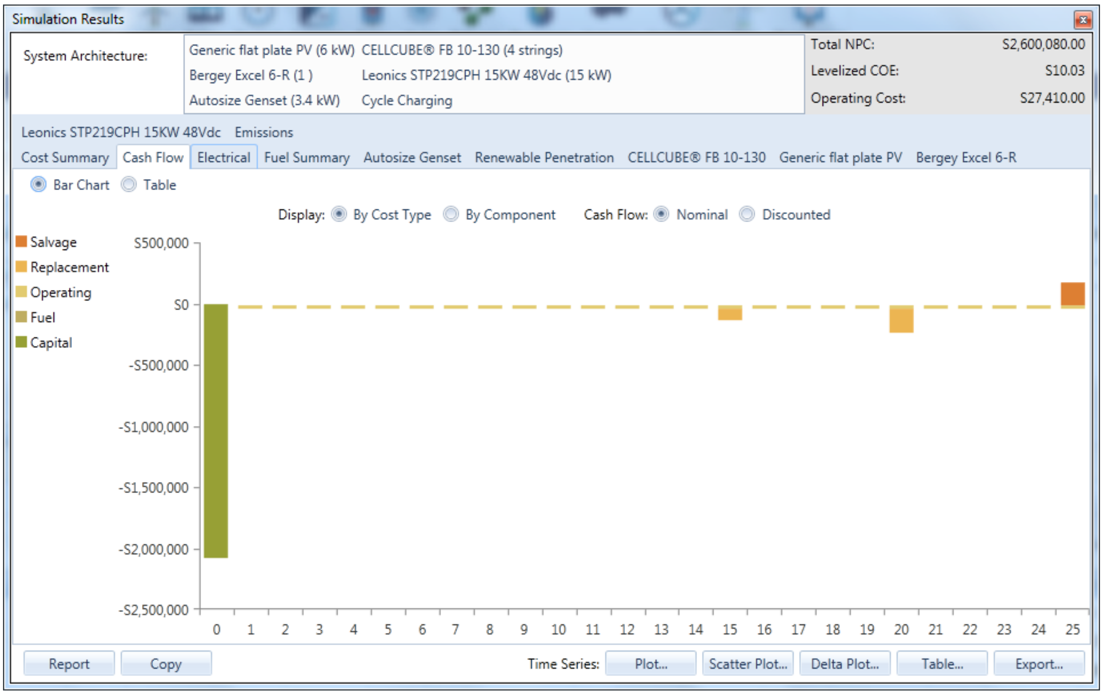


Figure 4-11: Cash flow

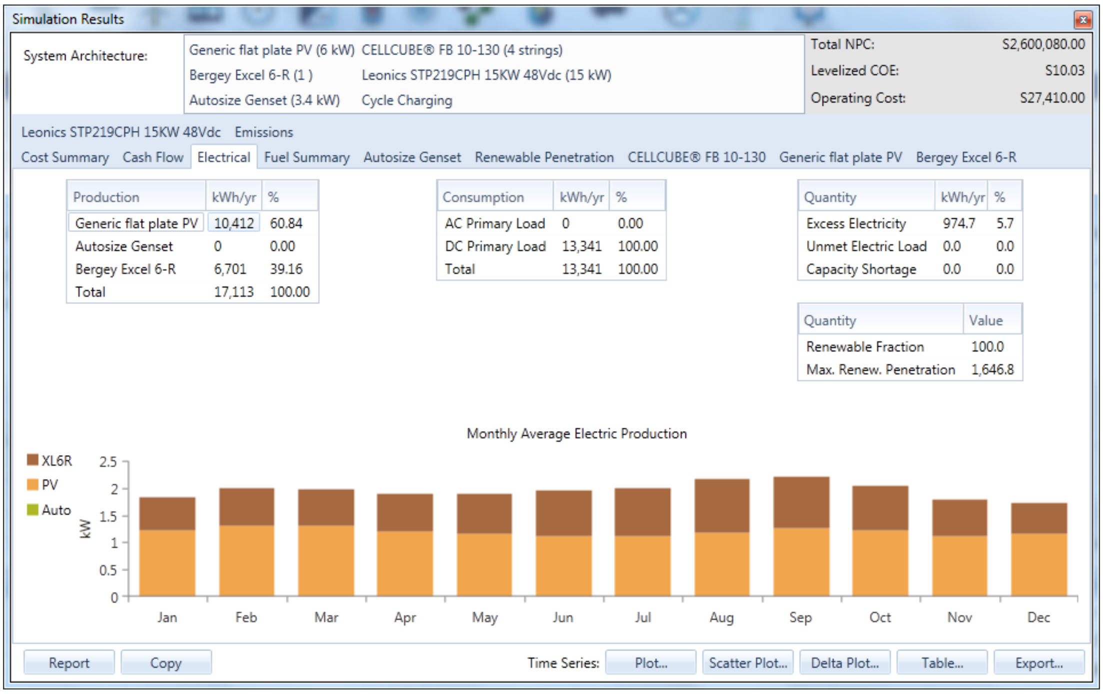


Figure 4-12: Electrical production

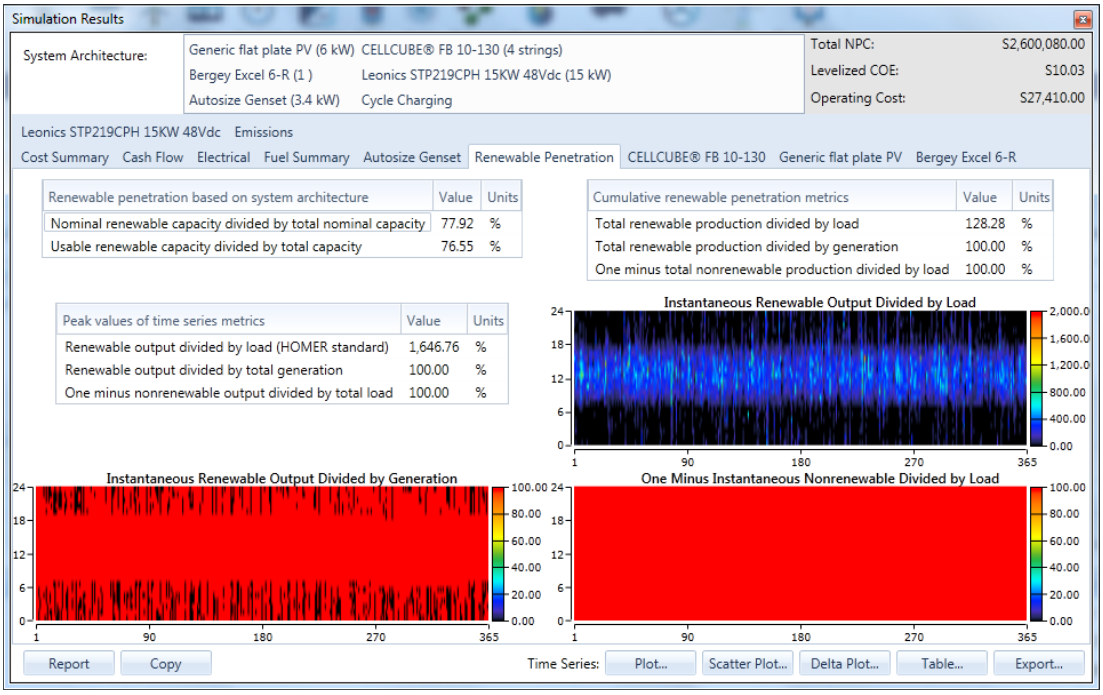


Figure 4-13: RES penetration

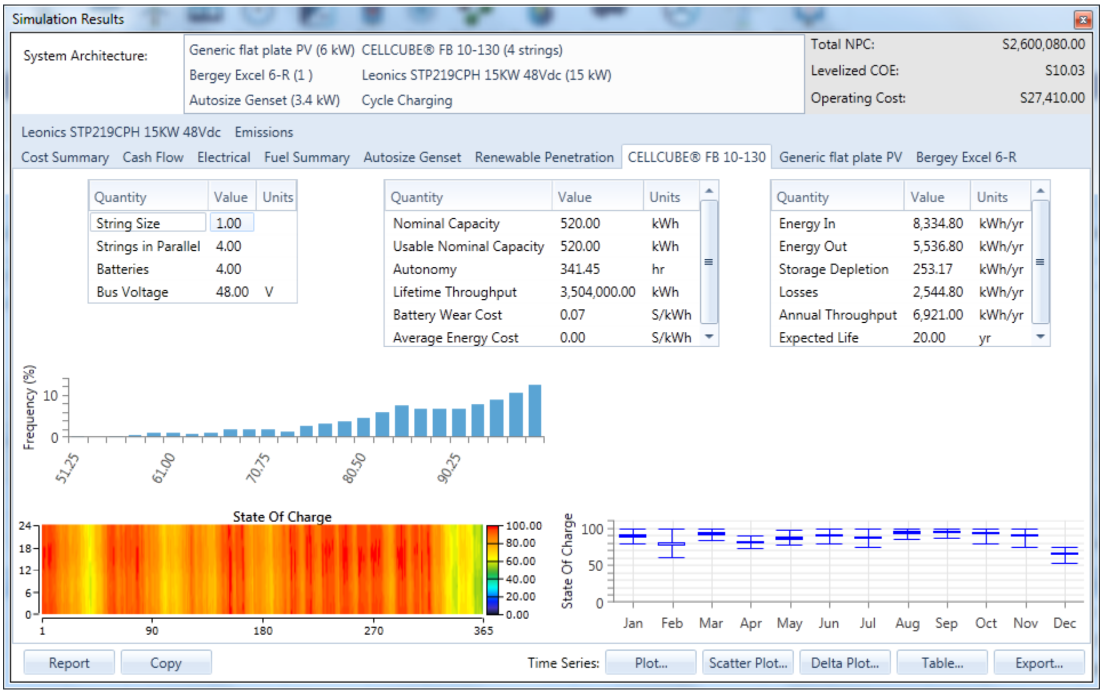


Figure 4-14: Battery operation

Figure 4-15: PV output

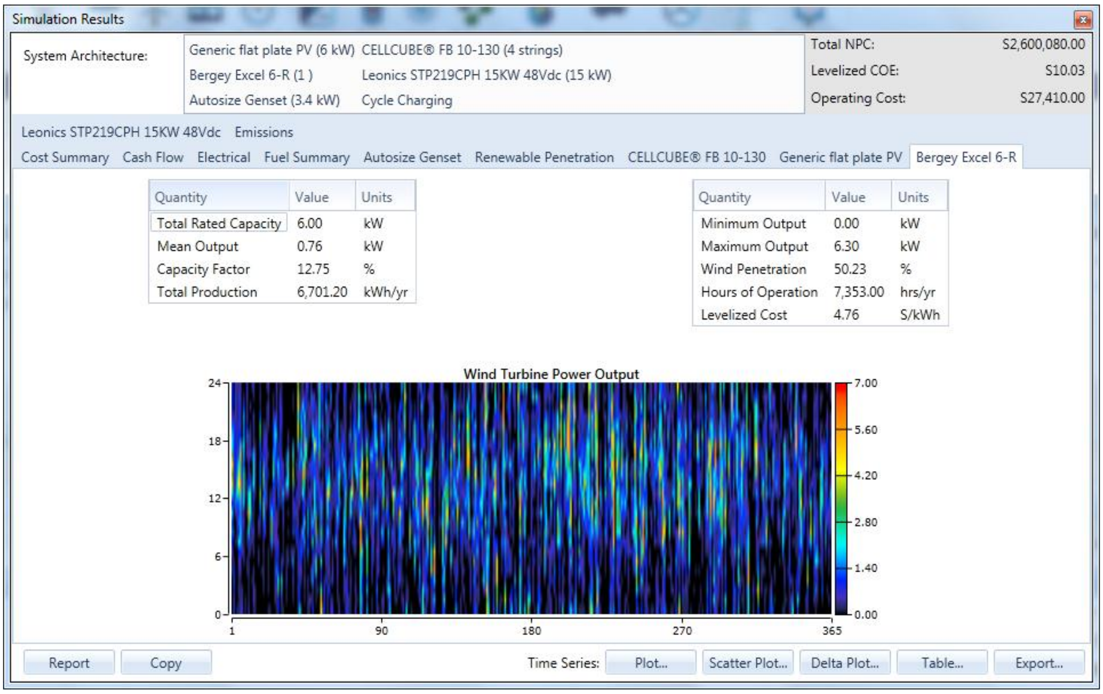


Figure 4-16: Wind turbine output

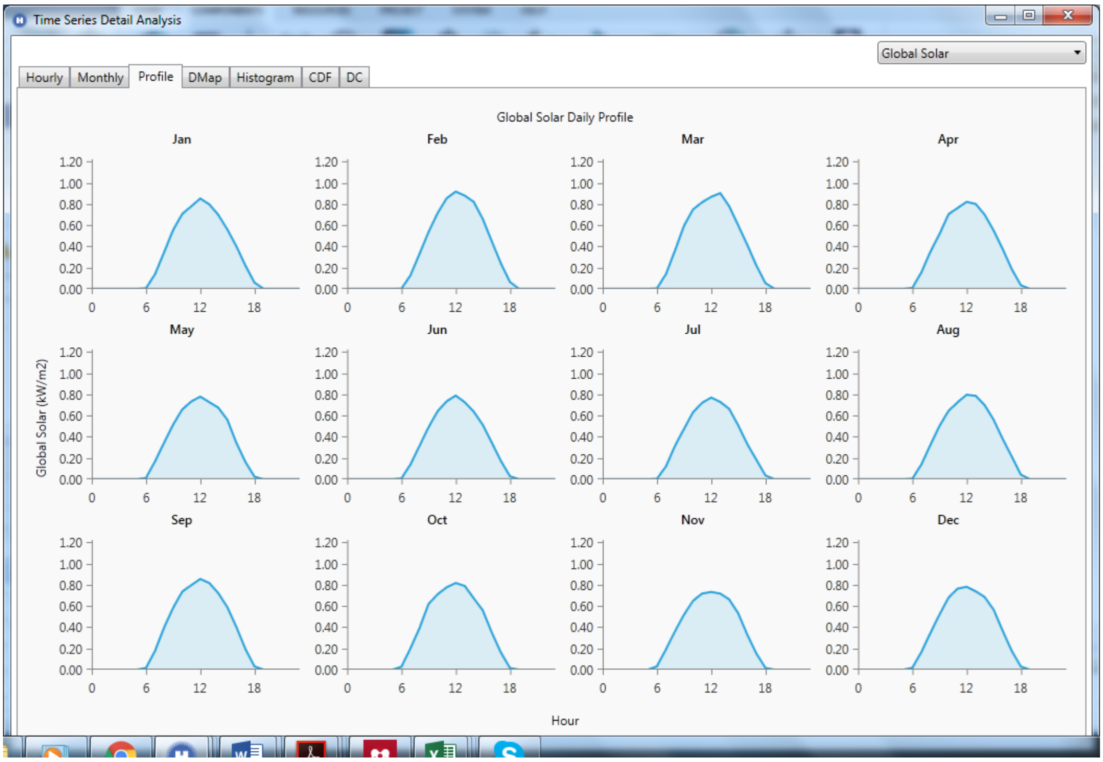


Figure 4-17: Global solar daily profile

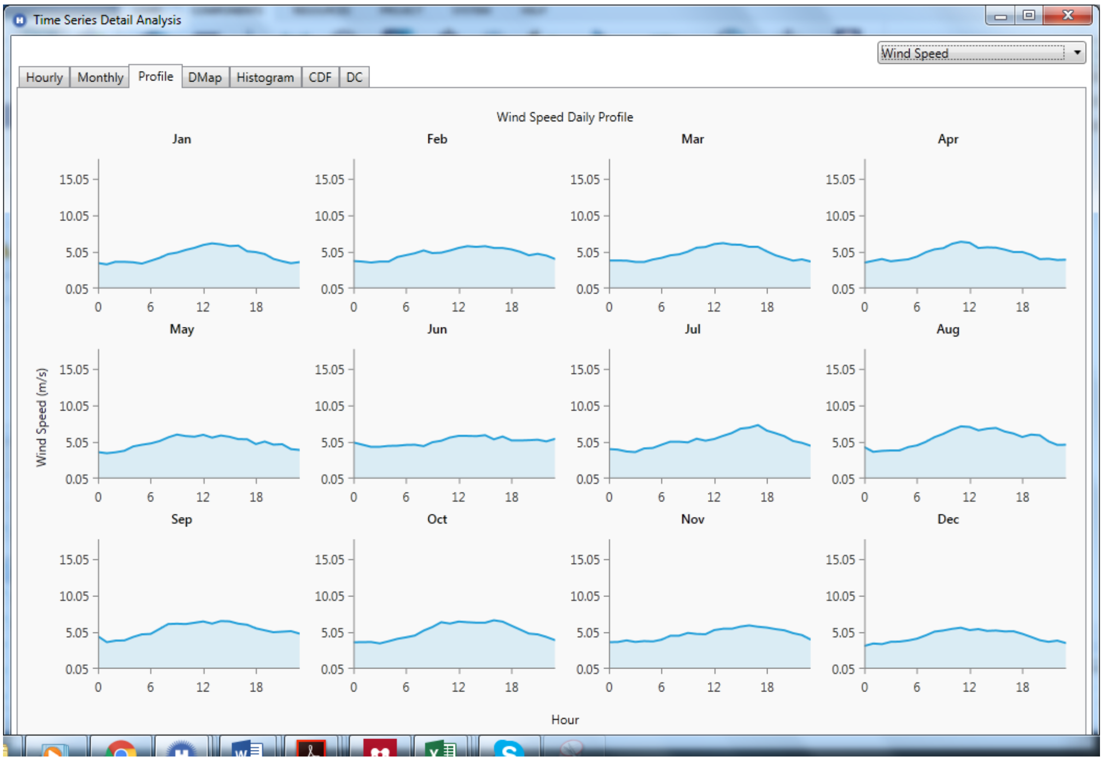


Figure 4-18: Wind speed daily profile

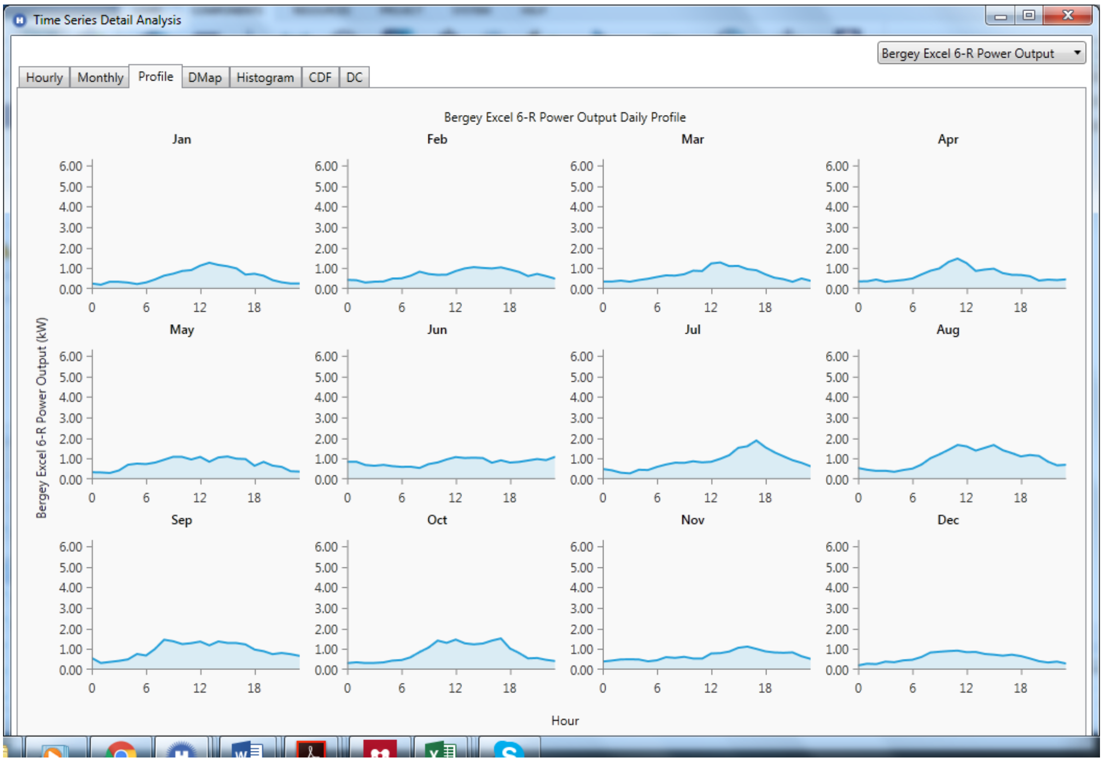


Figure 4-19: Wind turbine output daily profile

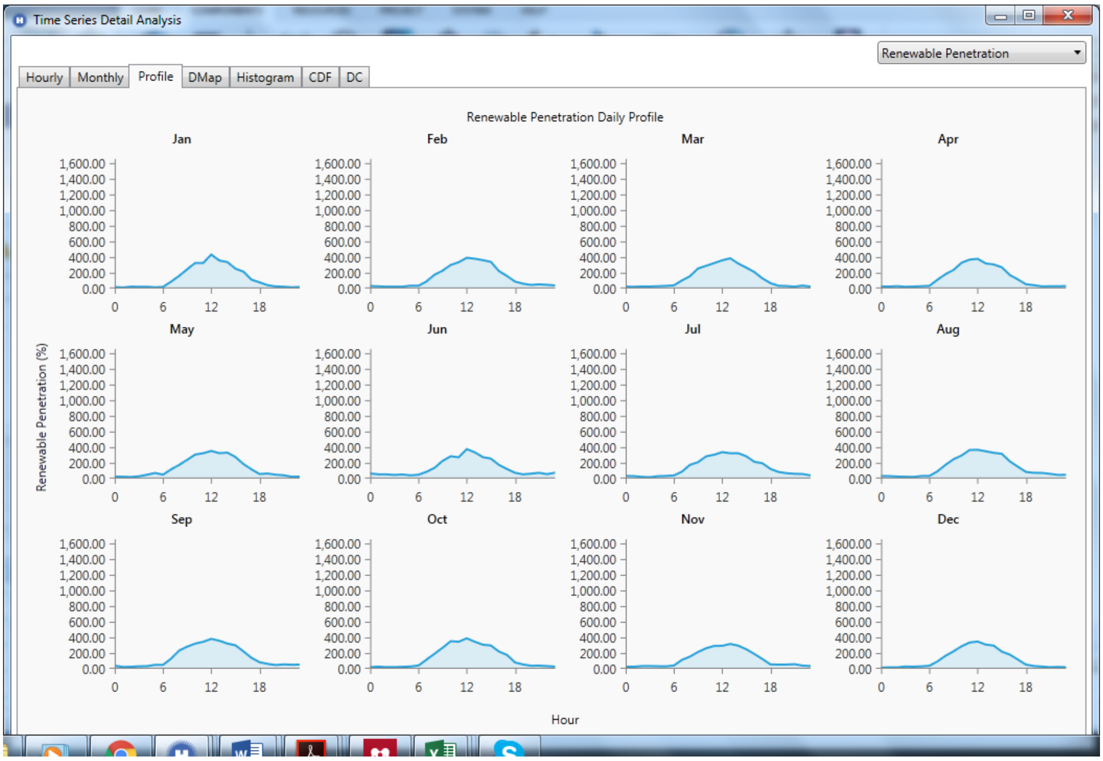


Figure 4-20: RES penetration daily profile

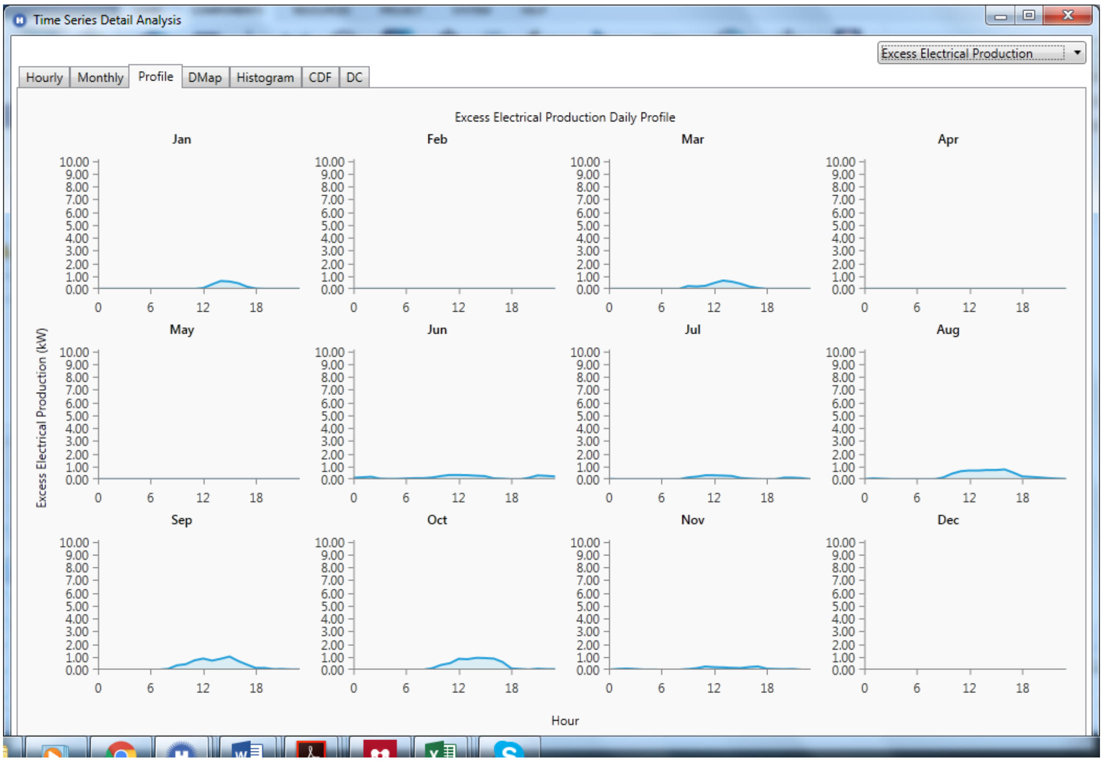


Figure 4-21: Excess electrical production

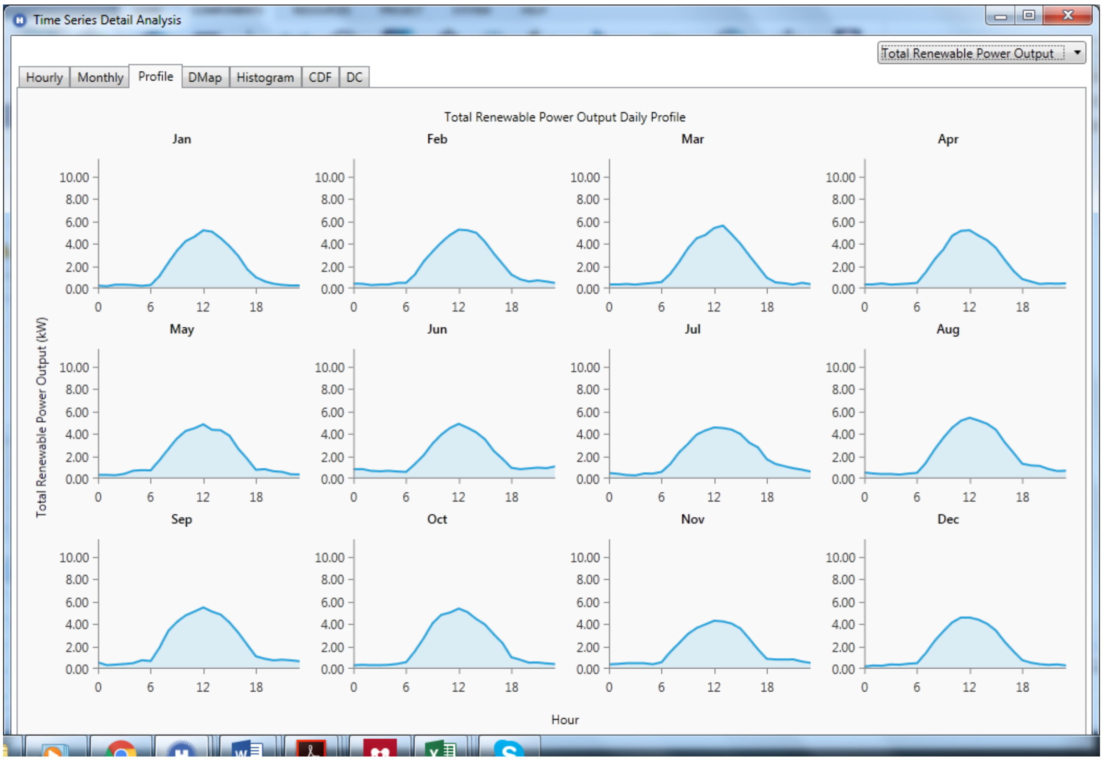


Figure 4-22: Total RES output daily profile

The HPS annual production from the best combination of different components is as shown in Figure 4-11. PV is expected to account for 61%, and the wind turbine to generate the rest of the energy consumed. There will be no production from the Genset and thus, under normal circumstances, this will act as a back-up system in the case of RES or components for capturing RES becoming unavailable.

4.4 Economic viability of the HPS

The various costs involved in this HPS are the CAPEX, OPEX, COE, and the NPC generated by HOMER and used to make the decision on the best combination of various components. These costs are as a result of the current cost of the components and the discounted cost over the whole life of the HPS.

It can be noted from Figure 4-9, which shows the summary of the costs based on the best combination of the HPS components, that a 5% excess energy generation can be expected. The total annual energy generation is expected to be 17,133 kWh with a NPC of KES 2.6 million. A COE (cost of energy) of KES 10/kWh and a total operating cost of KES 437,180. The entire load can therefore be met fully with the two renewable energy resources.

The CAPEX of the current power system in the tower system was estimated as KES 5 million and the annual operating cost (OPEX) as KES 3 million. The breakdown of the O & M is tabulated in Appendix 1. Considering a discount interest rate of 17.5%[3], a life-cycle of 15 years and applying Equation (2.1), the NPC of the OPEX is approximately KES 16 million. If an investment of the current system was to be made today, a total of KES 21 million (NPC of OPEX and CAPEX) will be required

[3] https://www.centralbank.go.ke/ (Accessed on 26th March, 2016)

against a KES 2.6 million for the HPS in this study. Based on the same argument, the COE of the existing system will be much higher than the COE in this study. The current O&M for the existing system is KES 3 million while the O&M for the HPS system is KES 27,410. The net savings if the current system is replaced with the HPS is therefore, KES 2,972,590. Based on this, the return of investment will be approximately 9 months.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

This study has demonstrated that there is sufficient RES at the Aitong site to power the Telkom Kenya BTS system. The RES measured and reported at the site during the testing period compares well with the NASA documented data and other secondary sources consulted during this study. It will be worth noting that data from NASA was used in the design of the HPS since it agreed closely with the collected data. The average wind speed for the site as documented by NASA was 3.33 m/s while the actual average speed as measured during this study was 3.27 m/s. The average insolation by NASA was 5.95 kWh/m^2/day against the actual average insolation of 6.0 kWh/m^2/day recorded in the study. It can also be concluded that NASA data can be applied at other sites to drive decisions on whether to substitute current power sources with economically efficient source(s) of power.

The design of the HPS system was aided by the use of HOMER. It included sourcing for the costs of various HPS components in the market and analysis of the best combination from a cost perspective. The design also factored in future modification for the tower loads in terms changes in technology. In particular, changes in technology will involve use of power saving BTS equipment. The HOMER optimization model was chosen based on the attractive NPC cost of the system.

The NPC for the current system was found to be KES 2.6 million compared to KES 21 million for the current system employed in the tower system. The COE was found to be KES 10/kWh which is better than the KPLC rate for October, 2015 at KES 21/kWh for other Telkom Kenya similar sites. It should be noted that the cost analysis in this study did not include the environmental cost and the actual per unit kWh cost is likely to be considerably lower than the calculated cost. The return on investment was found to be favourable at 9 months.

It was noted that the simulation software results varies according to RES components' prices. This is due to the fact that HPS components prices vary from region to region. This does not allow for automatic updates of changes in cost and other characteristics of the various HPS components. Consequently, this was identified as a weakness of HOMER software.

5.2 Recommendations

The following are the recommendations based on the study:

a) Based on the study, there is a good regime of RES at the study area which can be utilized as a source of power for remotely located tower system.

b) Finally, it is recommended that mapping of RES in all other sites be carried out to ensure that the best system(s) are selected for each tower system.

APPENDICES

Item	Item Description	Unit	Annual Consumption Rate	Unit Cost (KES)	Overall O&M Cost (KES)
Preventive Maintenance	Air Element	Each	24	4,500.00	**108,000.00**
	Oil Filter	Each	24	1,500.00	**36,000.00**
	Oil	Liters	7*24	300.00	**50,400.00**
	Fuel Filter	Each	24	1,600.00	**38,400.00**
	Starter Battery	Each	1	9,000.00	**9,000.00**
	Fan Belt	Each	1	1,000.00	**1,000.00**
	Coolant	Liters	2	1,000.00	**2,000.00**
	Transport	100km	24	2,000.00	**48,000.00**
	Labour	2 Tech	24	3,000.00	**72,000.00**
Collective Maintenance	Labour, Transport And Minor Spares	Per Call	12	5,000.00	**60,000.00**
Site Fueling	Supply And Delivery Of Fuel	Liters	3*24*365	100.00	**2,628,000.00**
Total					**3,052,800.00**

Appendix 1: O & M for the existing two 8kVA Dual plant (recorded data)

STATION NAME NAROK MET. STATION

LATITUDE 01° 08'S LONGITUDE 35° 50'E

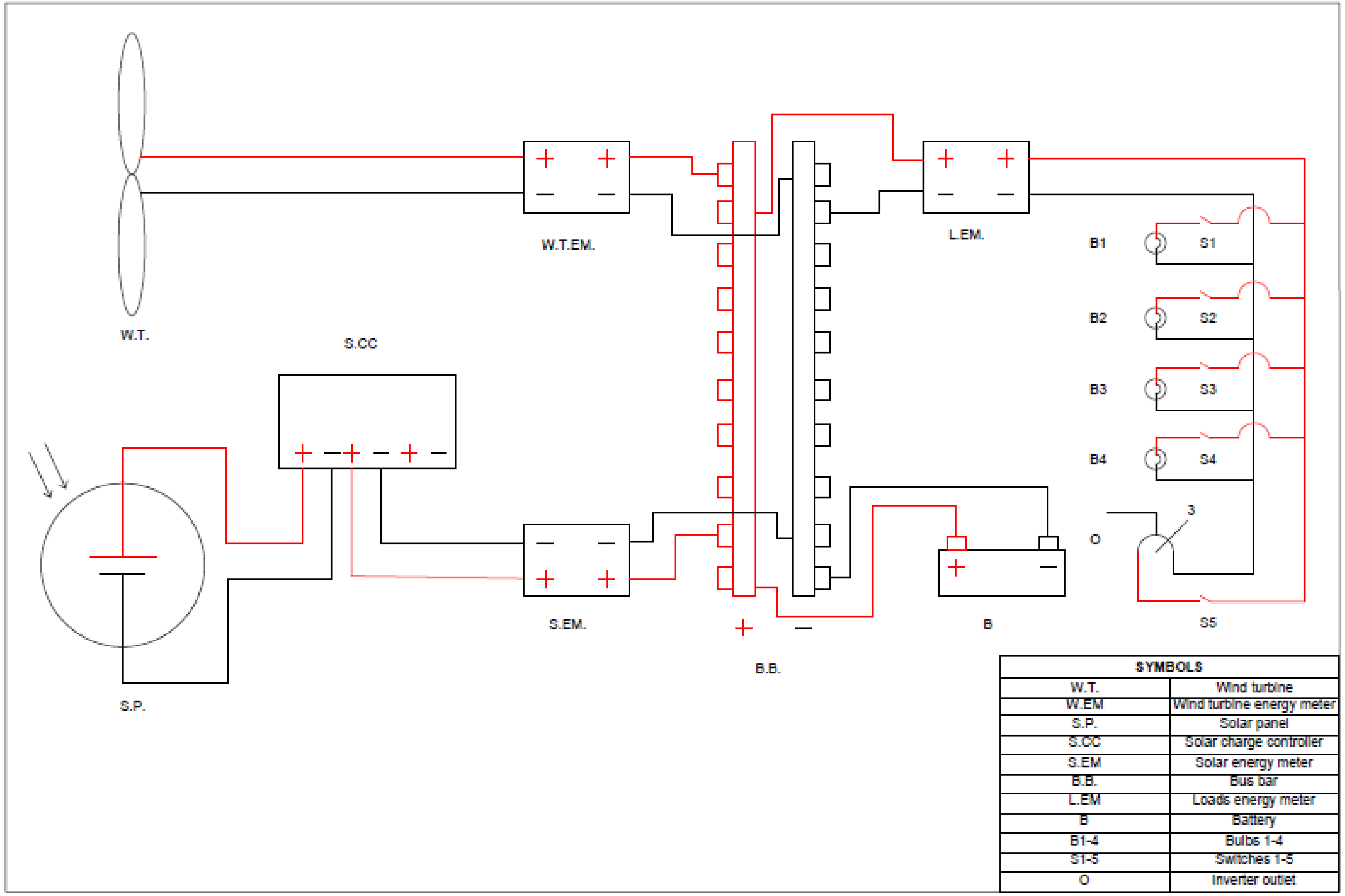
STATION NUMBER 91.35/001

ALTITUDE 6200 FEET 1890

MONTH	ATMOSPHERIC PRESSURE (1966-80) 0600 GMT	1200 GMT	TEMPERATURE (1939-80) MEANS MAX.	MIN.	RANGE	EXTREMES HIGHEST	LOWEST	DRY BULB 0600 GMT	1200 GMT	DEW POINT 0600 GMT	1200 GMT	RELATIVE HUMIDITY 0300 GMT	0600 GMT	1200 GMT	RAINFALL (1913-8 MEAN	HIGHEST	LOWEST
	mb.	mb.	°C	°C	°C	°C	°C	°C	°C	°C	°C	%	%	%	mm	mm	mm
January	814.3	810.7	26.7	7.7	19.0	32.7	0.1	15.2	24.9	10.7	9.9	91	75	40	75	328	0
February	814.3	810.9	26.9	7.9	19.0	32.1	0.3	15.2	25.4	10.8	10.0	90	75	39	81	224	3
March	814.4	811.0	26.4	8.5	17.9	31.0	0.5	15.9	25.2	11.9	11.3	91	77	43	102	369	1
April	814.6	811.5	24.6	10.7	13.9	30.2	1.2	16.4	23.5	13.7	13.0	94	84	53	144	420	11
May	815.7	811.3	22.7	11.2	10.5	27.1	1.8	15.8	21.8	13.5	13.4	95	87	60	93	293	7
June	816.4	814.0	21.8	8.9	12.9	27.3	0.4	14.4	20.9	11.8	11.9	94	84	56	28	182	0
July	816.5	814.2	21.6	7.7	13.9	26.7	0.1	13.4	20.7	10.5	10.5	92	82	53	16	74	0
August	816.4	813.4	22.6	7.5	15.1	28.0	1.1	14.0	21.4	10.5	10.2	91	80	49	21	130	0
September	815.9	812.6	24.8	7.1	16.7	30.6	0.2	15.4	23.4	10.9	9.6	92	75	42	23	110	0
October	815.3	811.7	26.0	7.5	18.5	29.6	0.4	17.2	24.7	11.5	9.4	92	70	39	26	118	0
November	814.8	811.4	25.5	7.8	17.7	30.5	0.2	17.3	23.7	12.1	10.9	93	73	45	63	289	4
December	814.5	811.1	25.8	7.8	18.8	30.9	0.4	16.2	24.1	11.7	11.1	93	75	45	71	372	0
Year	815.3	812.0	24.6	8.4	16.2	32.7	0.1	15.5	23.4	11.6	10.9	92	78	47	743	1359	351

MONTH	NUMBER OF DAYS OF RAIN	THUNDER	DAILY SUNSHINE (1963-80) MEAN	MAX. MEAN	MIN. MEAN	DAILY RADIATION (1964-80) INSTRUMENT GB MEAN	MAX. MEAN	MIN. MEAN	MONTHLY EVAPORATION (1959-80) PAN TYPE A MEAN	HIGHEST	LOWEST	CLOUD AMOUNT (1939-80) TOTAL 0600 GMT	TOTAL 1200 GMT	LOW 0600 GMT	LOW 1200 GMT	DAILY WIND RUN	WIND SPEED 1939-80 0600 GMT	1200 GMT	CALMS 1966-80 0600 GMT	1200 GMT	VISIBI (1961- FOG 0600 GMT	1200 GMT
	>1mm	days	hours	hours	hours	langleys	langleys	langleys	mm	mm	mm	oktas	oktas	oktas	oktas	miles	knots	knots	days	days	days	days
January	9	8	8.6	10.1	5.3	535	664	402	153	200	109	4.3	5.9	1.9	4.7		3	9	11	2	1	0
February	10	9	8.2	9.8	6.2	523	605	458	146	174	111	4.4	5.7	2.0	4.8		3	10	12	3	0	1
March	12	11	8.0	9.8	4.8	534	623	404	159	209	98	5.4	6.1	3.0	4.9		3	10	10	1	0	0
April	13	9	7.1	9.1	5.1	473	566	421	133	163	103	6.7	6.4	5.1	5.4		4	10	5	2	0	0
May	12	5	7.0	8.4	5.0	436	521	360	117	147	102	6.9	6.2	6.2	5.3		5	9	6	2	0	0
June	4	3	6.7	8.7	5.4	408	495	329	100	132	76	6.5	6.1	4.8	4.7		4	8	6	2	0	1
July	3	2	6.1	7.4	4.8	387	429	349	101	144	76	6.5	6.2	5.0	4.7		5	9	5	3	1	0
August	3	3	6.5	7.8	5.0	424	474	355	112	130	83	6.3	6.0	4.9	4.7		5	9	5	2	0	0
September	4	3	7.6	8.8	5.9	489	562	381	133	161	94	5.7	5.6	4.1	4.2		6	9	4	1	0	0
October	4	4	8.4	9.3	6.2	513	621	447	158	213	126	5.6	6.1	3.9	4.8		7	10	3	1	0	1
November	9	7	7.4	9.3	6.0	477	601	412	133	169	90	5.5	6.5	3.6	5.5		5	9	4	2	0	0
December	8	7	8.0	9.2	6.1	507	607	410	140	198	96	4.8	6.2	2.4	5.3		3	9	8	2	0	0
Year	91	71	7.5	8.2	6.8	476	574	416	1585	1847	1337	5.7	6.1	3.9	4.9		4	9	79	23	2	3

Appendix 2: Climatological statistics recorded at Narok Met. Station (KMD)



SYMBOLS	
W.T.	Wind turbine
W.EM	Wind turbine energy meter
S.P.	Solar panel
S.CC	Solar charge controller
S.EM	Solar energy meter
B.B.	Bus bar
L.EM	Loads energy meter
B	Battery
B1-4	Bulbs 1-4
S1-5	Switches 1-5
O	Inverter outlet

Appendix 3: HPS prototype circuit

NO:	Component	Specifications/purpose in the system	Number of components
1	Solar panel	20W, 18V, with 1.28 m tower	1
2	Wind turbine	50W, 12V DC, with 3m tower	1
3	Energy meter(s)	60V 100A Digital LCD Display Voltage, Current, Power, Battery Voltage Analysis: Voltage: (0) V-4V-60V 0.01V (Resolution); Current: 0-100 A peak 0.01A (Resolution); Power: 0-655.4 W 0.1W (Resolution); Charge: 0-65 Ah 0.001Ah (Resolution); Energy: 0-655.4 Wh 0.1 Wh (Resolution); Measurement Update period: 400mS; Signal Sampling Rate: sample/s; Data Queue Sequence time: 2 seconds; In Circuit Resistance: 0.001 Ohms; Operation Current: 7 mA; Auxiliary Power Voltage : 4.0V ~ 60V; Size : 8.3 x 4.7 x 2cm / 3.27 x 1.85 x 0.79inch; Display Screen : 1602 STN LCD	3
4	Battery	12V, 40AH deep cycle, maintenance free	1
5	Solar charge controller	Solar Panel Regulator Charge Controller 10A 12V/24V Auto Switch Safe	1
6	Loads	Three 9W DC bulbs and one 11W DC bulb. Total of 38W of DC loads	4 DC bulbs
7	Inverter	30 A inverter	1
8	Bus bar	Twin strip for +ve and –ve sides.	1

Appendix 4: Components specifications

Month, year	June, 2015											July, 2015										Avg
Date	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7	8	9	10	
Irradiance (Wh/m^2/ day	5480	5436	6110	6647	5740	5587	5466	5922	5518	4446	5644	5627	4689	5129	5213	5588	5271	5207	5761	5755	6050	5537
Wind Speeds (m/s)	4	4	4	4	4	4	4	4	4	4	4	4	4	3	4	4	4	4	4	4	4	4
Solar potential (Wh/m^2/day)	541	627	568	507	404	661	521	519	529	313	378	338	269	299	492	456	535	554	471	541	453	475
Wind potential (Wh/m^2/day)	161	148	118	136	121	135	145	131	50	41	45	39	66	45	53	56	91	120	54	119	177	98
Consumption (Wh/day)	279	97	136	199	149	99	168	136	87	85	15	9	94	57	15	0	124	112	168	77	109	105

Month, year	July, 2015																					Avg
Date	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
Irradiance (Wh/m^2/ day	6404	6602	6676	6841	7875	7205	6536	7027	5583	5802	5714	4997	4948	4602	4944	4387	6373	5820	5138	6366	5312	5960
Wind Speeds (m/s)	4	5	4	4	4	4	4	4	3	4	4	3	3	3	3	2	3	4	4	4	5	4
Solar potential (Wh/m^2/day)	524	643	578	497	519	543	567	479	515	332	360	353	286	296	522	395	586	545	443	476	569	478
Wind potential (Wh/m^2/day)	161	151	125	132	115	135	147	128	52	39	79	46	29	47	65	43	88	120	55	117	179	98
Consumption (Wh/day)	285	92	138	200	146	99	170	133	86	86	14	9	96	55	15	0	124	112	173	78	137	107

Month, year	August, 2015																					Avg
Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	

Irradiance (Wh/m^2/ day	5605	6710	6480	6069	7518	6636	6573	6655	5916	3714	5204	3771	3704	4479	5188	5404	6484	7134	6688	6691	7114	5892
Wind Speeds (m/s)	4	4	4	4	4	4	4	4	3	2	2	2	3	2	3	2	3	4	3	4	5	3
Solar potential (Wh/m^2/day)	546	601	570	524	522	546	594	450	512	288	438	329	255	356	492	409	591	524	503	486	527	479
Wind potential (Wh/m^2/day)	161	151	114	138	119	138	144	130	57	34	46	38	68	44	59	52	91	120	54	118	178	98
Consumption (Wh/day)	280	97	134	202	143	104	165	138	88	84	14	9	95	57	15	0	121	128	160	81	130	107

Month, year	August, 2015										September, 2015											Avg
Date	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5	6	7	8	9	10	11	
Irradiance (Wh/m^2/ day	6283	6867	6802	7239	8350	7997	7521	7989	6230	3814	5204	3743	3380	4479	5213	5744	7427	7614	7089	6933	7967	6376
Wind Speeds (m/s)	4	4	4	3	3	3	3	3	2	2	2	1	2	2	3	3	3	4	3	4	4	3
Solar potential (Wh/m^2/day)	552	623	572	509	517	568	557	457	522	268	444	334	250	357	503	397	591	524	517	472	527	479
Wind potential (Wh/m^2/day)	162	152	114	137	121	136	145	141	41	38	46	38	67	45	59	52	91	120	54	119	177	98
Consumption (Wh/day)	285	92	138	200	146	99	169	134	88	84	14	9	96	55	15	0	125	124	160	80	134	107

Month, year	August, 2015																October, 2015					Avg
Date	12	13	14	15	16	19	20	21	22	24	25	26	27	28	29	30	1	2	3	4	5	

Irradiance (Wh/m^2/ day	6673	7012	7765	7174	0	7804	7437	7384	7571	6498	5377	7033	8403	6886	7268	6682	6107	6166	7353	7502	7260	6731
Wind Speeds (m/s)	4	3	3	1	0	6	8	6	4	2	2	3	4	2	1	1	1	1	4	6	7	3
Solar potential (Wh/m^2/day)	508	537	540	473	434	519	546	553	470	352	430	406	500	512	458	442	335	362	952	479	432	487
Wind potential (Wh/m^2/day)	71	80	72	130	88	69	15	7	6	0	0	0	0	0	0	0	0	0	0	0	0	60
Consumption (Wh/day)	110	114	128	128	182	81	65	59	23	44	41	72	10	37	21	26	76	120	18	40	0	66

Month, year	October, 2015																				Avg
Date	6	7	8	9	10	11	12	13	14	15	16	17	18	19	22	23	24	25	26	27	28	
Irradiance (Wh/m^2/ day	6872	5448	7526	7645	6438	6925	6994	4758	7530	6743	8194	4790	6164	6095	5427	5101	6616	5611	3866	3490	6612	6135
Wind Speeds (m/s)	3	6	6	5	2	2	4	5	2	4	3	4	3	2	1	1	3	3	2	3	5	3
Solar potential (Wh/m^2/day)	400	427	547	464	385	372	445	340	349	367	431	269	422	349	307	245	380	248	192	213	350	357
Wind potential (Wh/m^2/day)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	96
Consumption (Wh/day)	12	0	0	0	2	0	24	0	15	18	32	10	0	1	0	0	0	0	0	0	0	94

Month, year	October, 2015			November, 2015																	Avg
Date	29	30	31	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	

Irradiance (Wh/m^2/ day	4287	4608	6149	6115	5298	6080	6585	4191	6115	7400	4401	4343	4743	4421	7281	6334	4779	6070	4572	2268	4372	5258
Wind Speeds (m/s)	7	1	3	1	2	2	6	6	5	4	1	2	2	2	3	5	2	3	2	1	1	3
Solar potential (Wh/m^2/day)	215	282	364	322	218	352	421	293	394	397	298	193	321	280	397	385	338	288	241	174	209	304
Wind potential (Wh/m^2/day)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	94
Consumption (Wh/day)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37

Month, year	November, 2015												December, 2015									Avg
Date	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7	8	9	
Irradiance (Wh/m^2/ day	5184	6149	4771	5453	7065	7050	3690	3231	2002	5640	6869	4074	6808	7026								5358
Wind Speeds (m/s)	4	3	1	2	3	3	3	2	3	3	6	6	3	3								3
Solar potential (Wh/m^2/day)	252	355	204	330	328	376	241	181	151	286	315	235	333	331	NO DATA COLLECTED							280
Wind potential (Wh/m^2/day)	0	0	0	0	0	0	0	0	0	0	0	0	0	0								94
Consumption (Wh/day)	0	0	0	0	0	0	0	0	0	0	0	0	0	0								37

Appendix 5: Actual data

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