International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 • Website: www.ijfmr.com • Email: editor@ijfmr.com

Tecno-Economic analysis of Hybrid Renewable Energy on Telecommunication Industry in Zambia, Case Study in Mpulungu

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Abstract:
Renewable energies play vital role in telecommunication sectors where grid is neither accessible nor stable. Wind energy (WE) and photovoltaic energy (PVE) are energy sources which when properly used can enable telecommunication business to be lucrative. In the application of renewable energy on off-grid rural and back bone sites hybrid systems are most pragmatic. Combination of solar, wind and backup batteries to meet the load demand can enable the energy center for the telecommunication site to be highly sustainable. Therefore, this paper looks at the analysis of hybrid renewable energy in Zambia on telecommunication sites in Mpulungu area of Northern part of Zambia. The hybrid renewable energy sources proposed in this paper includes solar PV systems and wind turbines. Configurations of the energy systems are driven from practical loads on sites, solar radiation, wind speed and backup lithium-ion batteries. The renewable power systems are optimized using Hybrid Optimization Model for Electrical Renewable (HOMER) and PVsyst simulation tools.

Keywords: Photovoltaic energy (PVE), Wind energy (WE), Hybrid system, HOMER, PVsyst, Renewable Energy, Wind turbine, Batteries, Telecommunication.

1. Introduction

Globally telecommunication industries in their respective operations have direct impact on the environment, social and economic. The social impact is on the provision of jobs to the community. The economic impact field is on the provision of telecommunication services and products. The environmental field impact is the most significant on the telecommunication companies as it contributes directly and indirectly to the environment. Due to high energy consumption, by 2030 telecommunication companies will be responsible for 2% of the global greenhouse gas (GHG) emissions [1]. In the telecommunications system the main element in energy consumption and GHG emissions is the Base Transceiver station (BTS). Cost and GHG emissions can be reduced by evaluations and development of interventions and technical solutions like renewable energy basing on the energy requirements and the renewable energy source available [2].

In developing countries, but rapidly growing telecommunication industry like Zambia, it is vital to convert renewable energy found in biomass, wind and sunlight into electrical energy. Most countries around the globe are working towards reliable and feasible hybrid renewable energy systems. This is due to techno-economic advantage, fast depletion of fossil fuel and environmental friendship of renewable energy [3].

International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

In Zambia, use of hybrid renewable energy on telecommunication infrastructures within rural and urban set ups can enable sustainable communication in a lucrative and cleanly manner. The issues of oversizing, intermittent of renewable sources and reliability of supply can be sorted with proper design before implementation of combined system [4]. Hybrid systems improve load factors and help saving on maintenance and replacement cost as renewables complement each other [5]. To determine the average power generated by PV module and wind turbine, wind speed data, irradiance probability density function and manufacturer specifications on PV module and wind turbine is used [6].

2. System Description

Shown in figure 1 is the schematic diagram of the hybrid power plant for a telecommunication site. It consists of PV generator, wind turbine, DC to DC converters, AC to DC converters, battery energy backup, Inverter, DC load and AC load. This paper illustrates the renewable (wind/Solar) hybrid energy system for Mpulungu in Zambia. The system configuration is derived basing on the theoretical, Metro data, site load and sustainability of renewable energy sources.

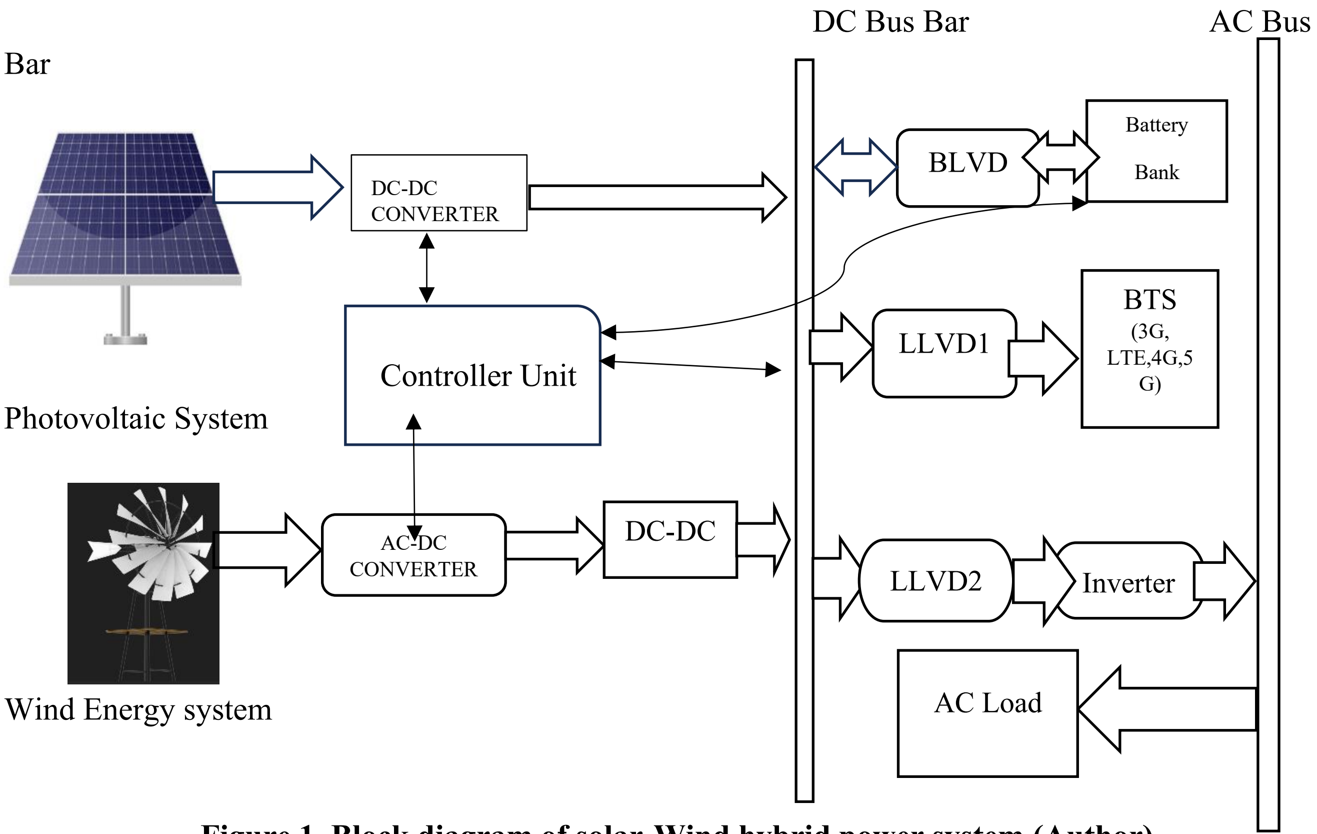


Figure 1. Block diagram of solar-Wind hybrid power system (Author)

The battery low voltage disconnect (BLVD) on the power system is set to disconnect the battery system when the battery voltage drops down to 43.2volts. Priority loads are also connected to the BLVD. Therefore, when the BLVD disconnects also priority loads are disconnected. Non-priority loads are connected to the low load voltage disconnect (LLVD), which is set at the voltage higher than BLVD setting. When the power generators start generation of voltage 5volts higher than active value LLVD and BLVD reconnects [7]. The controller plays the intelligence role in monitoring and regulation of the power required to mitigate the load demand [8].

2.1 Factors considered for sites selection

Factors considered for choosing the sites are as follows:

1. Sun irradiation
2. Wind speed
3. Temperature
4. Fossil diesel consumption
5. Site load
6. Sustainability (Environmental impact and Economic impact)
7. Grid availability

3. Data Collection

Data on Solar and wind was collected from reliable sources. Some of the sources where data was obtained include, IHS, INFRATEL NASA, National Renewable Energy Laboratory (NREL) database and Metrological database.

3.1 Solar Energy

The solar irradiation levels in Zambia are suitable for solar harvesting for conversion to electricity. The irradiation levels of solar in Zambia ranges from 1981kWh/m^2 to 2281kWh/m^2 [9]. On average, Zambia's solar radiation is estimated at 5.5kWh/m^2/day, with highest value ranging around 7.53kWh/m^2/year [10]. The solar irradiation in Zambia can be utilized for power generation, and the telecommunication sector can highly benefit from harnessing of solar electricity. PV output depends on radiations. Basing on the hourly data,output power of PV system for fixed surfaces can be evaluated as shown in equation 1 [3]. **PV** specifications used in Mpulungu is as shown in table 3.

$$P_{pv,each} = \begin{cases} P_{RS}\left(\frac{R\hat{}2}{RsrsRcr}\right) & 0 \le R < R_{CR} \\ P_{RS}\left(\frac{R}{Rsrs}\right) & R_{CR\le R} < R_{SCS} \\ P_{RS} & R_{SrS} \le R \end{cases}$$

Eq 1

$P_{pv,each}$= Power generated by PV system

P_{RS} = PV Panel rated power

R = solar radiation factor

R_{CR} = Certain radiation at 150w/m^2

R_{srs} = standard solar radiation at 1000w/m^2

3.2. Wind Energy

Wind energy is the electrical energy produced by harnessing the wind with wind turbines. This energy is environmentally friendly, and the energy has the potential to be used in future energy supply worldwide. Wind power depends on the air volume, velocity of the air, air density (mass) and swept area [11].The global growing market of wind energy technology will lead to more improvements like larger wind turbines and new system applications [12]. The output wind power of the turbine is given by equation 2 [13]

$$\mathbf{Pw} = \frac{1}{2} \mathbf{A} \, \mathbf{V}^3 \, \mathbf{C}_{\mathbf{p}\,(\lambda,\,\beta)} \rho \quad \ldots\ldots\ldots\ldots.. \text{Eq 2}$$

A = Turbine swept area (m^2)

Cp = Power coefficient of the turbine

V = Wind velocity (m/s)

ρ = Air density (kg/m^3)

λ = Tip speed ratio of the rotor speed

β= Blade pitch angle (degrees)

Table 1. Site data for Mpulungu and Kasongole Museshya

No	Site Name	Region	Number of ternants	Latitude	Longitude	Site Topology	SOLAR Capacity (KW)	Gen-1 Capacity (KVA)	Transformer Capacity (KVA)	Battery Brand	Battery Capacity (AH)	Battery DOD (%)	Rectifier Capacity	Actual AC Load (KW, for last quarter period)	Actual DC Load (KW, for last quarter period)
1	MPULUNGU	Northern	2	31.11240	-8.76410	Grid-Gen	N/A	20	50	Lithium	300	60	24	7.8	6.1
2	KASONGOLE_Museshya	Northern	2	29.38290	-8.97830	Solar - Gen	9.9	20	N/A	Lithium	400	60	24	2.3	2.3

On Mpulungu site the key issue underpointing to this site is long hours of load shedding resulting in high diesel consumption and high carbon emissions. Grid tarriffs are also extremely high. Owing to this, three solution analyzed were PV based hybrid system , wind based hybrid system and PV-Wind based hybrid system.

Due to very good solar irradiance simulations of a stand-alone solar with backup batteries scenario was done followed by a combination of solar and wind with backup batteries. Figures 2 shows the location of Mpulungu in the Northern part of Zambia.

Figure2: Map showing location of Mpulungu in Zambia (HOMER)

This area is located in the northern part of Zambia and has an avarage yearly wind speed of 5.97m/s and yearly average temperature of 20.2 °C (Metro data).

Table 2. Solar Irradiation and Clear index Metro data for Mpulungu

	Global Horizontal irradiation	Horizontal diffuse Irradiation	Global Horizontal irradiation	Horizontal diffuse Irradiation	Temperature	Wind Velocity	Linke turbidity	Relative humidity
	$kwh/m^2/day$	$kwh/m^2/day$	Ratio	Ratio	°C	m/s	[-]	%
January	5.35	2.65	0.492	0.243	20.3	3.8	3.412	79.7
February	5.41	2.73	0.498	0.252	20.2	3.2	3.35	79.6
March	5.53	1.83	0.527	0.223	20.6	4.1	3.196	76.4
April	5.87	1.83	0.607	0.189	20.2	6.8	2.827	74.2
May	6.12	1.43	0.697	0.163	19.6	7	2.794	65.6
June	6.08	0.99	0.736	0.12	17.7	7.4	2.733	60.5
July	6.18	1.14	0.734	0.135	18	8	2.864	55.1
August	6.38	1.52	0.695	0.166	19.7	8	3.213	50.3
Septemb	6.6	1.84	0.656	0.183	21.8	7.5	3.856	41.8
October	6.31	2.44	0.592	0.229	22.8	6.6	4.109	48.5
Novembe	5.7	2.59	0.526	0.239	21.4	5	3.483	65.8
Decembe	5.3	2.87	0.489	0.265	20.5	4.2	3.254	73.4
Average	**5.9**	**2.03**	**0.596**	**0.205**	**20.2**	**5.97**	**3.258**	**64.2**

From table 2, Solar irradiance the clear index for Mpulung at the location -8.76410,31.11240 is very good for solar energy use in the generation of electrical enery required for telecommunication equipmen

Table 3: PV specifications

Solar PV Specifications		
Maximum power	M_p	455W
Voltage at Maximum	V_m	35.8V
Open Circuit Voltage	V_{oc}	53.3V
Maximum Current	I_m	11.0875A
Short Circuit Current	I_{sc}	11.8A

Table 4: yearly PV position for average Maximum power collection

Fixed tilt plane for Mpulungu		
	Value	Unit
Average Year fixed Angle of tilt	16	degree
Azimuth	0	degree
Transposition Factor	1.04	
Loss with respect to Optimum	0	%
Power on collector plane	2231	kwh/m^2

In order to determin the best optimal results Homer and Pvsyst simulation sofwares were used. Figure 3 shows HOMER schematic model used.

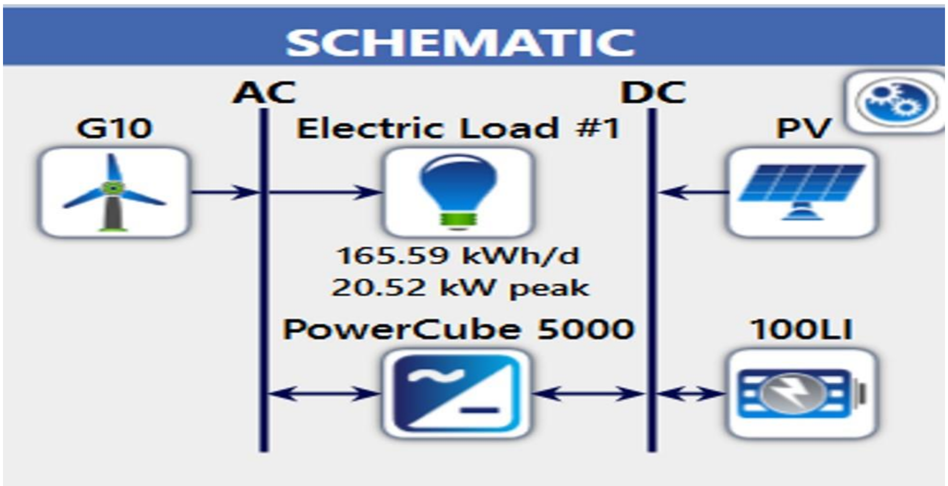
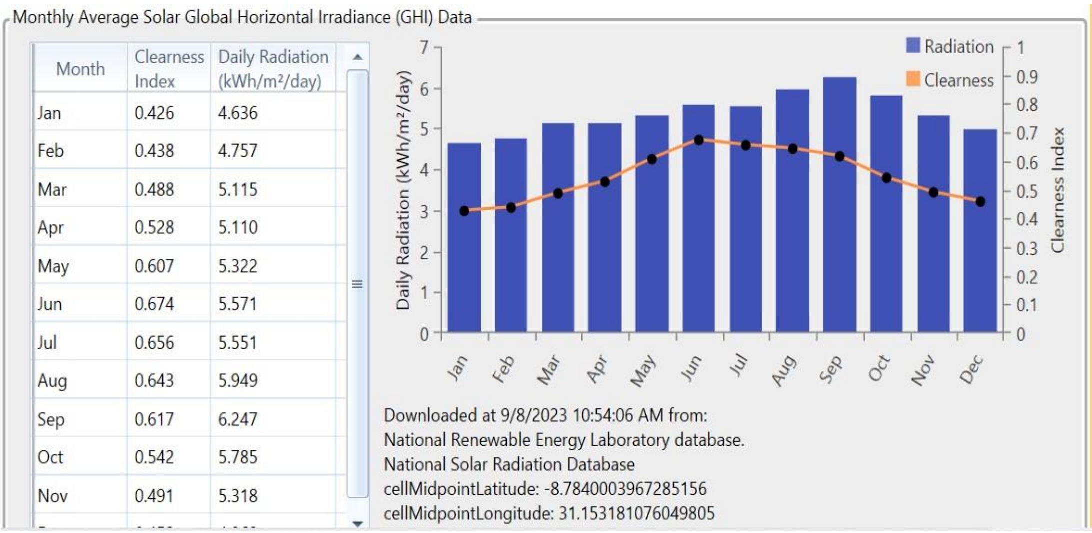


Figure 3; Schematic HOMER model diagram for solar-wind hybrid and backup batteries



Month	Clearness Index	Daily Radiation (kWh/m²/day)
Jan	0.426	4.636
Feb	0.438	4.757
Mar	0.488	5.115
Apr	0.528	5.110
May	0.607	5.322
Jun	0.674	5.571
Jul	0.656	5.551
Aug	0.643	5.949
Sep	0.617	6.247
Oct	0.542	5.785
Nov	0.491	5.318

Figure. 4 : Monthly Average Solar Horizontal Irradiance for Mpulungu Site (NREL data download).

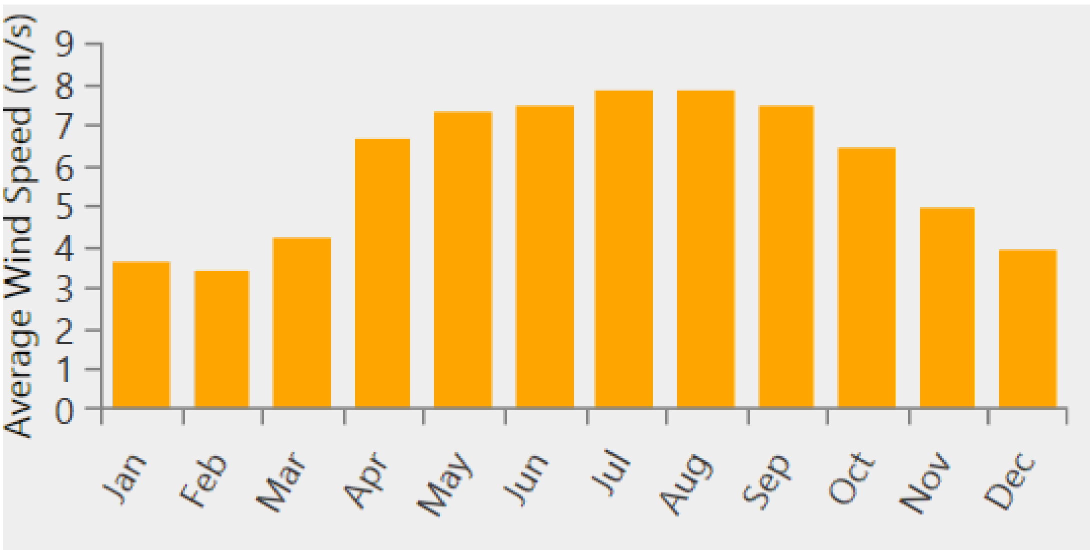


Figure. 5: Monthly Average wind speed for Mpulungu site (NASA data download).

In this model, the output power charecteristic of the wind turbine used is as shown in figure 6 .

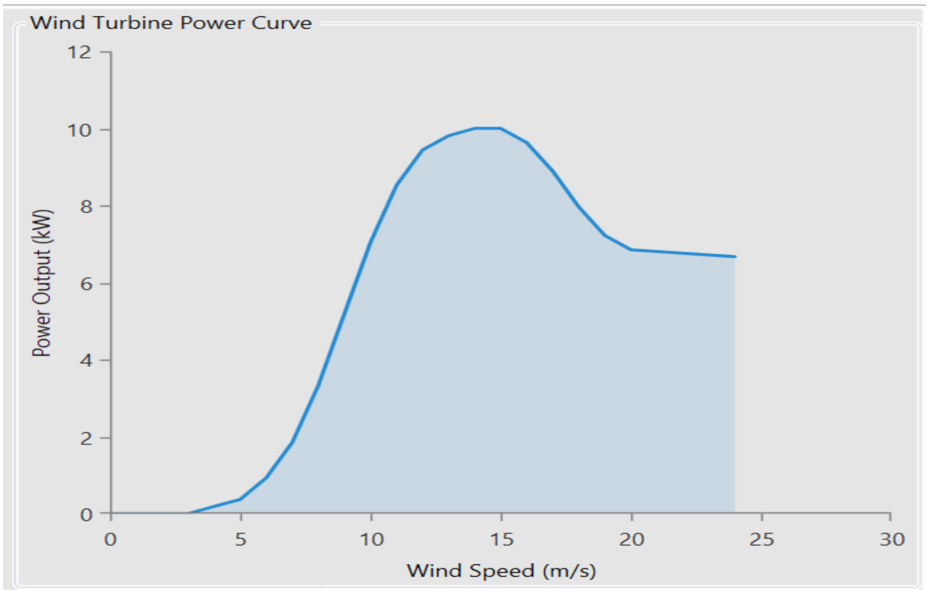


Figure 6: Power curve of wind turbine generated by HOMER Program

3.3 Simulation using Pvsyst

Using Pvsyst simulations to get the best optmum requirement for PV/ battery system were done. Figure 7 shows the best requirements which were used on a load of 6kw in Mpulungu.

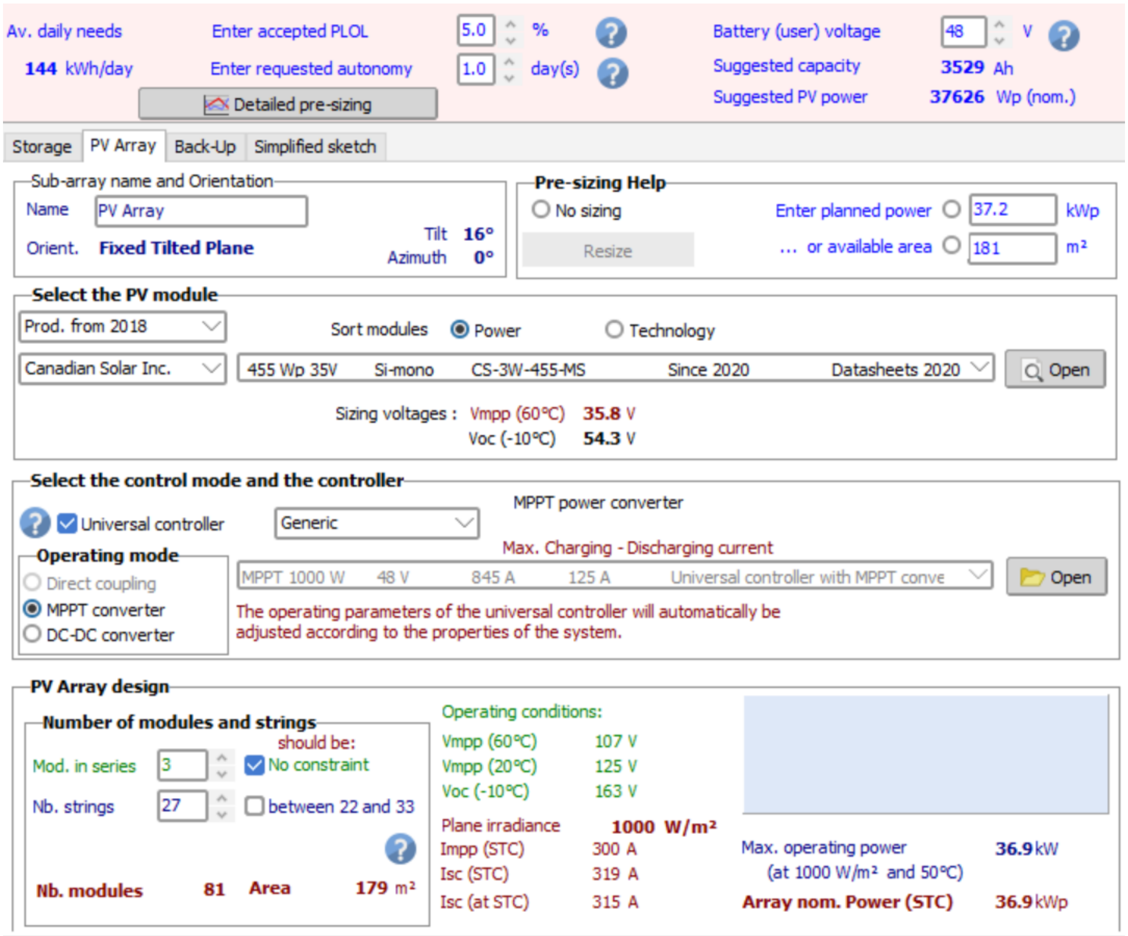


Figure7: PV/ batteries Simulation needs (PVsyst)

Figure 7 shows the simulation components required for a 144Kwh/day maximum load of a site in Mpulungu. The aim of this simulation is to archive an optimal simulation which can give a backup time of 24hrs.

4 Results and Discussion

In this section optimal results using HOMER and PVsyst are analyzed. In the analysis economical, environment and sensitivity results are also analyzed.

Using multicriterial decision analysis results are as shown in table 5

Table 5: Results from simulations using HOMER

Configuration	Unit	Scenario 1	Scenario 2	Scenario3
Wind Turbine (10kw)	Number	1	______	3
Solar PV Rated capacity	kw	174	212	___________
PV maximum output	KW	24	24	___________
Backup Batteries	AH	3900	4200	9300
Converter (Power cube 5000)	KW	25	24	35.8
Additional solar converter (MPPT)	KW	24	24	____________
Total Capital	K	1,243,234.01	1,257,187.11	2,753,421.86
Total Net present Value	K	1,784,133.00	1,824,928.00	3,816,682.00
Total Operation & Maintenance	K	810,950.50	83,726.25	156,802
Cost of Energy (COE)	K/KWh	4.35	4.45	9.31
Wind Production	KWh/yr	24,133	_________	651,604
Percentage wind production	%	21.3	______	100
PV Production	KWh/yr	89,182	91,734	89,182
Percentage PV Production	%	78.7	100	78.7
Total Electrical Production	KWh/yr	113,315	91,734	113,315
AC Primary Load	KWh/yr	60442	60442	60442
Renewable Fraction	%	100	100	100
Capacity shortage	KWh/yr	59.9	56	59.5
Unmet load	KWh/yr	0	0	0
Excess Electricity	KWh/yr	184,403	208072	589,726
Present worth	K	K34,125	0	0
Annual Worth	K/YR	K5, 032	0	0
Return on Investment	%	302.8	0	0
Internal rate of Return	%	231.3	N/A	N/A
Simple payback	YR	0,43	N/A	N/A
Discounted payback	YR	0.49	N/A	N/A

4.1 Optimal output Results

In this case study, using HOMER the optimal combinational electrical power is required is 34KW of which 24kw is from PV and 10 KW from Wind turbine. The capacity of the storage batteries required is 3900AH and the optimal system converter rating of 24KW. From the simulation results, the net present cost (NPC) is K1,784,133.00 and the levelized cost of electricity (COE) is K4.35. The capital required for system implementation is K1,234,234.01. Three scenarios considered were PV/battery, wind/battery and PV/wind/battery. System architecture parameters and cost summary is as shown in tables 7 and 8.

Table 6. System architecture parameters

System Architecture			
			Unit
1	Site Load	6	KW
2	PV array maximum output	24	KW
3	Wind turbine	10	KW
4	Backup Battery (Lithium)	3900	AH
5	Converter	24	KW
6	External Solar Supply Unit	24	KW

Table7. Cost Summary

Cost Summary		
1	Total NPC	K1,784,133.00
2	Levelized COE	K4.35
3	Operating Cost	K81,095.05

Table 8 Optimal Electrical Production per year

Electrical		
Component	Production kwh/year	%
PV array	89,182	78.7
Wind Turbine	24,133	21.3
Total	113,315	100

4.2 Economics Results

The results from HOMER simulations shows that the project has positive indicators. The economic comparison is as shown in Table 9.

Table 9. Economic Comparison

No	Metric	Value
1	Present worth (k)	K34,125
2	Annual Worth (k/yr)	K5, O32
3	Return on Investment (%)	302.8
4	Internal rate of Return (%)	231.3

5	Simple payback (yr)	0,43
6	Discounted payback (yr)	0.49

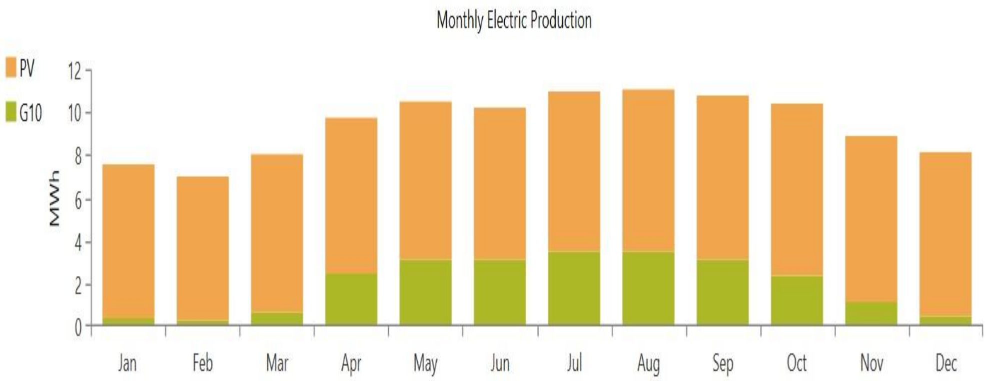


Figure 4.1 Monthly average electrical output for Mpulungu

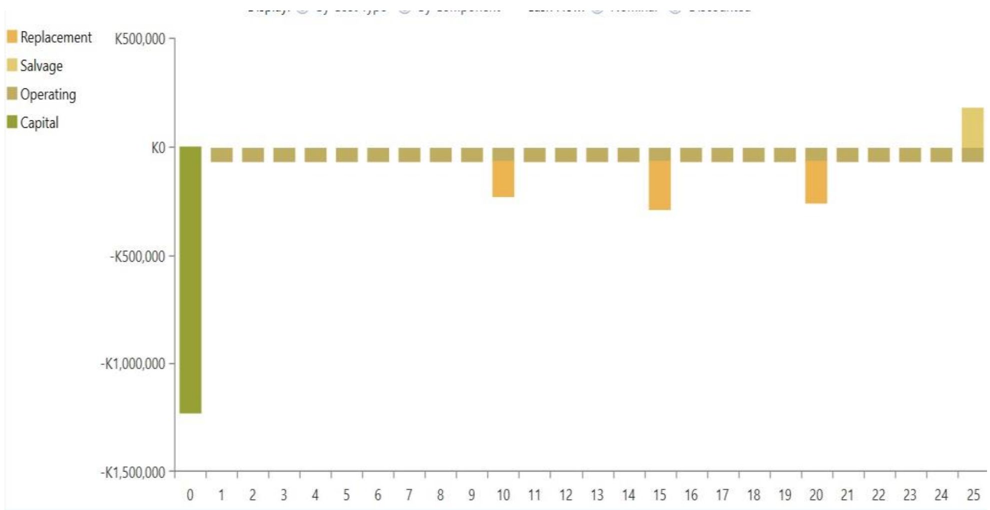


Figure 4.2 Cash flow summary for Mpulungu

4.2 PVsyst Results for Mpulungu

Using PVsyst considering backup power for 1days the system architecture parameters were as shown in table 9. In this model PV system and backup batteries were used to come up with simulations for a 6kw loading system with the battery autonomy of 1 days (24hrs) at the depth of discharge (DOD) of 85%.

Table 10. PVsyst system Architecture

System Architecture			
No			**Unit**
1	**Site Load**	**6**	**KW**
2	**PV array Rating**	**36.9**	**KW**
3	**PV modules**	**455**	**w**
4	**PV model**	**CS-3W-455-MS**	
5	**Modules in series**	**3**	**Pc**
6	**Modules in parallel**	**27**	**strings**

7	**Tilt Angle North**	**16**	**degrees**
8	**Azimuth**	**0**	**degrees**
9	**Backup Battery**	**3542**	**AH**
10	**Battery Type**	**Lithium (48VDC)**	
11	**Single Battery Rating**	**50**	**AH**
12	**Converter**	**15**	**KW**

The stand-alone PV and backup Lithium batteries was simulated for the backup time of 1 days at the load of 6KW. Financial analysis was generated using PVsyst and the results were as shown in table 10. From table 10 the return of investment was as shown in table 9.

Table 11 Return on investment

Return on Investment		
1	Payback period	0.8years
2	Net present value (NPV)	2,549,981.08USD
3	Return on Investment (ROI)	2447.4%

Table 12 Mpulungu Solar and Lithium backup batteries financial analysis

PVSYST 7.0.11		25/04/24	Page 9/9

Stand alone system: Financial analysis

Project :	**New Project_PV_Battery Energy system 25**
Simulation variant :	**New simulation variant**

Main system parameters	System type	**Stand alone system with batteries**		
PV Field Orientation	tilt	16°	azimuth	0°
PV modules	Model	CS-3W-455-MS	Pnom	455 Wp
PV Array	Nb. of modules	81	Pnom total	**36.9 kWp**
Battery	Model	US2000B_50Ah	Technology	Lithium-ion, LFP
Battery pack	Nb. of units	70	Voltage / Capacity	**48 V / 3542 Ah**
User's needs	Daily household consumers	Constant over the year	Global	52.6 MWh/year

Detailed economic results (USD)

	Gross income	Run. costs	Deprec. allow.	Taxable income	Taxes	After-tax profit	Cumul. profit	% amorti.
2025	136'379	2'220	4'495	129'664	0	134'159	29'969	128.8%
2026	136'379	2'331	4'495	129'553	0	134'048	164'017	257.4%
2027	136'379	2'448	4'495	129'437	0	133'931	297'948	386.0%
2028	136'379	2'570	4'495	129'314	0	133'809	431'757	514.4%
2029	136'379	2'698	4'495	129'186	0	133'680	565'437	642.7%
2030	136'379	2'833	4'495	129'051	0	133'546	698'983	770.9%
2031	136'379	2'975	4'495	128'909	0	133'404	832'387	898.9%
2032	136'379	3'124	4'495	128'761	0	133'255	965'642	1026.8%
2033	136'379	3'280	4'495	128'604	0	133'099	1'098'741	1154.6%
2034	136'379	3'444	4'495	128'440	0	132'935	1'231'676	1282.1%
2035	136'379	3'616	4'495	128'268	0	132'763	1'364'439	1409.6%
2036	136'379	3'797	4'495	128'087	0	132'582	1'497'020	1536.8%
2037	136'379	3'987	4'495	127'898	0	132'392	1'629'413	1663.9%
2038	136'379	4'186	4'495	127'698	0	132'193	1'761'605	1790.8%
2039	136'379	4'395	4'495	127'489	0	131'983	1'893'589	1917.4%
2040	136'379	4'615	4'495	127'269	0	131'764	2'025'352	2043.9%
2041	136'379	4'846	4'495	127'038	0	131'533	2'156'885	2170.1%
2042	136'379	5'088	4'495	126'796	0	131'291	2'288'176	2296.2%
2043	136'379	5'343	4'495	126'542	0	131'036	2'419'212	2421.9%
2044	136'379	5'610	4'495	126'275	0	130'769	2'549'981	2547.4%
Total	**2'727'577**	**73'406**	**89'890**	**2'564'281**	**0**	**2'654'171**	**2'549'981**	**2547.4%**

5. Conclusion

The analysis in this paper shows that the hybrid PV and wind with backup batteries system is a pragmatic and lucrative solution which can be deployed on a 6-kw telecommunication site in Mpulungu. The optimal hybrid system consists of 174kw PV arrays with an output of 24kw, 10kw wind turbine, 3900AH Lithium batteries, system converter rated at 25kw and addition solar converter rated at 24kw. Solar PVs are the largest contributor of electrical energy per year and produces 89182Kwh/year. Wind energy contributes 24133Kwh/year. For this optimal system, the NPC is lower (K1784133), a best scenario as compared with PV/battery and wind/battery scenarios. The cost of energy for the proposed system is k4.35 per kwh and percentage return on investment of 302.8%. Using solar PVs and batteries as backup, the amount PVs and batteries as well as PVs are increased to archive backup time of 24hrs. The optimal renewables required for powering a maximum load of 6kw as well as charging back up lithium batteries is 36kw of renewable power output. This is almost the case when PVsyst was used for the similar setup at the same location in Mpulungu. At the DOD of 85% the maximum battery backup time is 24hrs. For proper power plant sizing vital software required is HOMER and PVsyst.

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