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A Study on Optimal Design Feasibility of Microgrid Power System for Rural Electrification: Amhara Region in Ethiopia

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Abstract - **Power system is an essential energy domain in recent years which helps to converts non-electrical energy resources, such as hydraulic, thermal, solar, wind and other natural resources to electrical energy. It conveys the generated power to the consumers via transmission and distribution networks. The conventional power system has many problems, which are significant power loss at the transmission and distribution networks, poor power quality and reliability, and ultimately it is not an environmental friendly. These problems are resolved by using a microgrid which will provide electricity to the consumer economically with improved power quality, reliability, and minimum loss by integrating and optimizing different renewable energy sources. The main objective of this research study is to enable the optimal power provision and feasibility to design a microgrid. Based on this objective of Micro grid power system, the study has extended to deliver electricity to satisfy the location of Ethiopia, Bahir Dar Town, specifically the rural electrification as a model for the interior village Abay Mado-Gedro kebele primary school, health post and local communities demand by enhancing the power quality, reliability and minimum transmission / distribution line losses. The microgrid consists of solar, wind and battery storage sources. It is designed to operate in stand-alone mode of operation. Optimum designing and sizing of different components of the microgrid is taken as major contributions of this research work to the study for the Village Gedro as a rural electrification model. Hence it is observed through the analysis and design using HOMER Optimization tool, the total power consumptions for the site of optimal power is 25 kWh / day and 6 kW peak with the consideration of various environmental parameters like solar radiation, temperature and wind speed. Based on the optimal power energy consumption resulted out that the required various power resources are 7 kW Photo-Voltaic (PV), 3 kW Wind turbine, 104 kWh storage battery and 6 kW converter with the total investment cost $ 75993.**
Keywords: **Microgrid, Hybrid, Optimum, Stand-Alone**

I. INTRODUCTION

Electricity is generated directly or indirectly from none electrical energy resources at the generation station, which are usually located away from the load center but near to the resources such as water, wind, fuel, and other natural resources, through energy conversion process [1]. Transmission and distribution networks are employed to convey the generated power to the consumers end. Grid extension is impractical because of dispersed population, or/and rugged train. Therefore, off-grid stand alone is the best option to supply the rural population economically [15] [16].

The integration of distributed micro-generation resources such as solar, wind, fuel cell, etc, storage units and controllable loads forms a microgrid. Such system can be operated in a non-autonomous way when it is interconnected to the grid, or in an autonomous way, if disconnected from the main grid. The operation of the distributed generation in the network can provide distinct benefits to the overall system performance [17].

Many researchers direct their research area towards the renewable technologies, since the merits of renewable resources. A review on configuration, control and sizing methodologies of hybrid energy systems with various implementation issues of hybrid power system is discussed [8]. A new detailed sizing method for stand-alone photovoltaic-wind hybrid system is proposed by [5]. In this paper the techno-economic analysis of the power system is analyzed using object-oriented programming and it uses fundamental photovoltaic and wind generator models, storage capacity model and loss of power supply probability algorithm.

Ethiopia is endowed with abundant renewable energy sources and has a potential to generate over 60,000 MW of electric power from hydroelectric, wind, solar and geothermal sources. The resources potentials are 45,000 MW hydro power, 5000-7000 wh/m2 solar energy, 10,000 MW wind energy and 5 GW geothermal energy [13].

Although Ethiopia has a huge renewable energy sources only less than 10 % is exploited yet. Only 12% of the total population has access to electricity, and 85% of the total population lives in rural areas from which only 2 % has access to electricity [4]. Rural areas are generally known for dispersed and isolated population, lack of access to quality education, health care and clean water supply, which leads to low standards of living due to social institutes like schools, health centers, water supply, etc. in these areas are generally have no access to electricity [14]. Areas that are connected to grid also face frequent disrupts of the power supply due to overloading of the network. Therefore, it is necessary to improve the existing power system quality and electrify the rural areas through installing a new power plant or extending the existing to the one, but this will need a huge investment cost. Hence, to solve the societal electricity problems, with respect to access and quality, establishing a local generation station from wind, solar, micro-hydro sources will be the best solution [16]. The study focuses on feasibility to design a microgrid to enable optimal power provision to satisfy their electric demand of "Gedro Kebele"-Bahir Dar, Ethiopia. To do this study the relevant data about the load demand, solar radiation, wind speeds are collected, analyzed and optimized using HOMER optimization tool.

II. MICROGRID CONFIGURATION AND MODELING

A. Microgrid Configuration

The microgrid is intended to operate in isolated mode and for its normal operation it uses photo- voltaic and wind energy sources for its power generation. Solar radiation and wind speed is intermittent and it is season dependent, therefore a storage device is mandatory to supply electric power to the load for the slack periods. The general microgrid configuration for this study as shown in Figure 1 below.

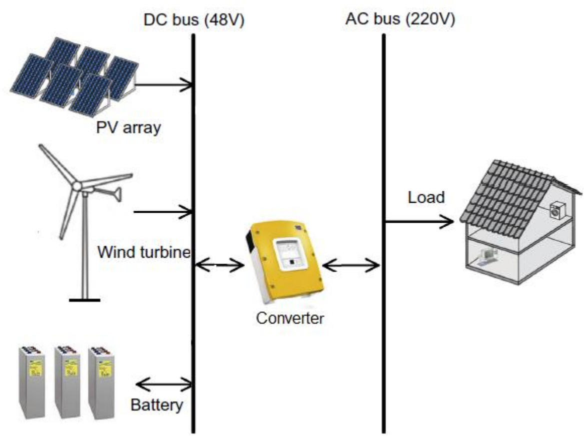


Fig. 1 Proposed microgrid configuration

B. Components and Mathematical Modeling Photovoltaic System

Photo voltaic is a technology involving the direct conversion of sunlight, which is one of the most important renewable, clean and ecofriendly energy sources, into electricity using solar cell [15]. A solar cell is essentially a specialized semiconductor diode with a large barrier layer when exposed to light allows for direct conversion of the light quanta or photon into DC electricity. The basic building block of the PV power system is called a solar cell, which produces about 1 W of power. To obtained high power, numerous cells are connected in series and parallel circuits, which gives a panel or module [1].

The complex performance of the PV cell can be represented by its model which can be expresses by the equivalent electrical circuit as depicted in Figure 2 [2]. The open circuit voltage and short circuit current are the key parameters of the model. The short circuit current depends on the illumination, while the open circuit voltage is affected by the material and temperature.

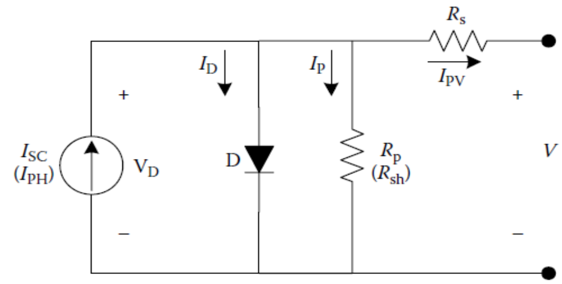


Fig. 2 Solar cell model

The equations describing the model are [2]:

$$I_D = I_o\left(\exp^{\frac{V_{pv}}{\alpha V_T}} - 1\right) \quad (1)$$

Since the shunt resistance is much higher than the series resistance, then

$$I_{pv} = I_{SC} - I_D \quad (2)$$

$$V_{pv} = \alpha V_T \ln\left(\frac{I_{SC} - I_{PV}}{I_o}\right) \quad (3)$$

The I-V characteristic of the solar cell can be defined also:

$$I_{PV} = I_{PH} - I_D$$

$$= I_{PH} - I_O\left[\exp\left(\frac{q(V + R_s I_{PV})}{\alpha kT}\right) - 1\right] - \frac{V_{PV} + R_s I_{PV}}{R_P} \quad (4)$$

Where I_{PH} is photon current (A), I_D is the diode current (A), R_s is the series resistance, R_P is the parallel resistance and V_{PV} is the PV cell output voltage.

C. Wind Energy System

Kinetic energy of the wind is converted to electrical energy using wind turbine, which is comprised of one or more units, such as tower, wind turbine, gear, electrical generator, speed control mechanisms, etc. The wind turbine captures the wind's kinetic energy in a rotor consisting of two or more blades mechanically coupled to an electrical generator and further converted to electrical energy using the generator. The wind turbine is commonly designed with two distinctly different configurations, the horizontal axis configuration and the vertical axis configuration. Most modern wind turbines use a horizontal axis design [1][2].

The mechanical power extracted by the rotor, which drives the electrical generator is [1]:

$$P_o = \frac{1}{2}\left[\rho A \frac{(V + V_o)}{2}\right](V^2 - V_o^2) \quad (5)$$

$$P_o = \frac{1}{2}\rho A V^3 \frac{\left(1 + \frac{V_o}{V}\right)\left(1 - \left(\frac{V_o}{V}\right)^2\right)}{2} \quad (6)$$

$$P_o = \frac{1}{2}\rho A V^3 C_p \qquad (7)$$

Where: P_o is mechanical power extracted by the rotor, V is upstream wind velocity at the entrance of the rotor blades, V_o is downstream wind velocity at the exit of the rotor blades, ρ air density, A is area swept by the rotor blades, V is the velocity of the air and C_P is the power coefficient of the rotor which is given by;

$$C_p = \frac{\left(1+\frac{V_o}{V}\right)\left(1-\left(\frac{V_o}{V}\right)^2\right)}{2} \qquad (8)$$

C_p depends on the ratio of the downstream to the upstream wind speeds (Vo /V).

The maximum power (P_{max}) is extracted from the wind at the speed ratio equals to 0.59 [1]:

$$P_{max} = \frac{1}{2}\rho A V^3 x 0.59 \qquad (9)$$

III. RESOURCE ASSESSMENT

A. Study Site Description

This study is conducted in "Gedro Kebele" which is approximately 10 kilometers far from Bahir Dar town. The kebele comprises of an elementary school named as "Gedro primary school" and a health post. The primary school an enrollment capacity of more than 500 students. The health post gives health care for the community and highly engage in safe maternal deliveries and this has a great contribution in reducing death during child delivery. At the vicinity of the health post there are a number of households, therefore, this research focus on electric energy demand assessment and feasibility of the microgrid design which has the capability to deliver the required electrical energy to enhance safe health care, quality education and better living standards of the community.

B. Data Collection

1. Input Load Data

Load energy consumption dictates the size and cost of the microgrid system required and is a vital design parameter. The total daily power demand for winter (September-June) and summary (July and August) seasons that are generated by the HOMER software are shown in Figure 3 and 4 respectively

2. Wind Resource

The average wind speed for the study area is fed to the HOMER software. The monthly average Wind speed which is generated by the HOMER software is shown in Figure 5 below.

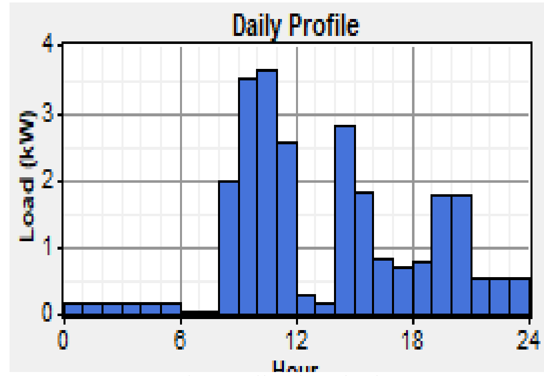


Fig. 3 Daily winter load

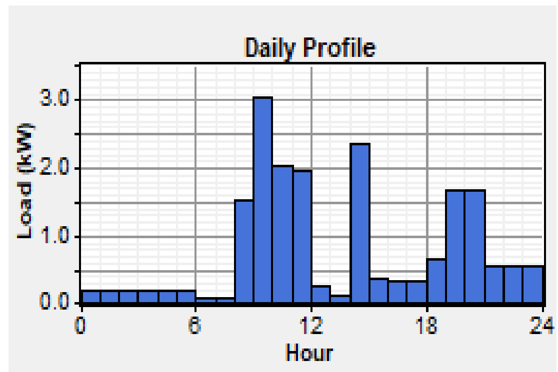


Fig. 4 Daily Summer Load

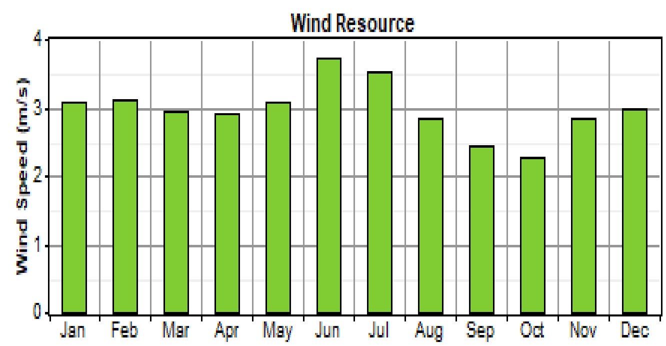


Fig. 5 Average wind speed per month in a year

3. Solar Radiation Resource

The monthly average horizontal solar radiation (in kWh/m2/day) for the study area that are fed to and generated by the HOMER for the sizing of the microgrid components are shown in Figure 6 below.

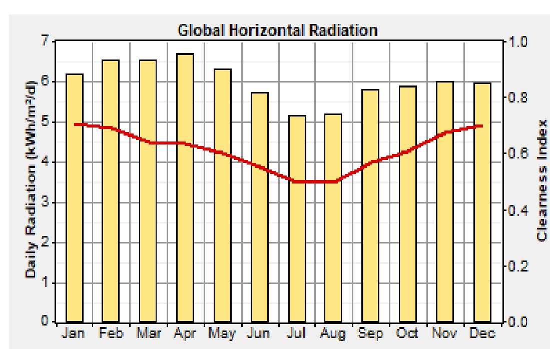


Fig. 6 Monthly Average Horizontal Solar Radiation

II. RESULT AND DISCUSSION

A. Optimized Size of Microgrid Components

The microgrid power system shown in Figure 7 is optimized and simulated using HOMER optimization tool. Figure 8 shows some of the optimization results of the proposed microgrid configuration shown in the HOMER model that will supply the total load.

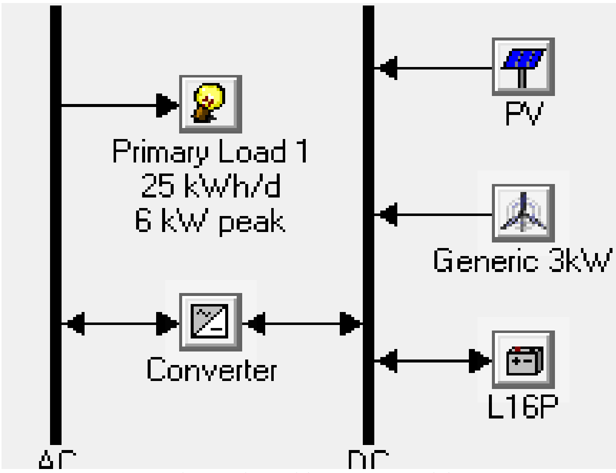


Fig. 7 Microgrid HOMER model

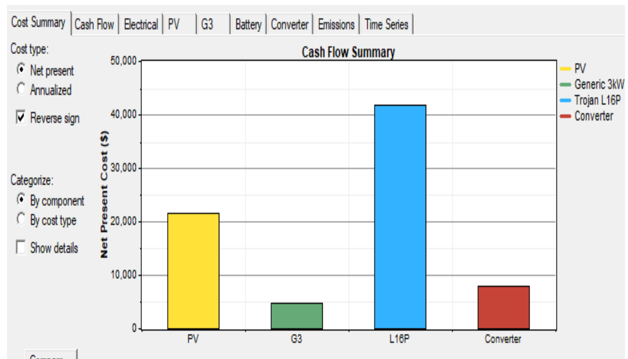
Despite the numerous alternatives, the choice of optimal type is restricted by the varying nature of initial capital, net present cost and excess electricity. The first optimal alternative is a combination of solar panel, battery and converter. Due to the intermittent nature of renewable energy sources, hybrid systems are more reliable in producing electricity and delivering quality power to the remote communities than photovoltaic or wind turbine system alone, often hybrid system represents the best solution to electrify the remote areas [15]. As a result, the blue marked alternative which comprises of solar panel, wind turbine, battery storage and converter is the selected optimum microgrid power system configuration and size of components of this study.

PV (kW)	G3	L16P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Batt. Lf. (yr)
8		48	6	$ 37,400	2,885	$ 74,275	0.647	1.00	10.0
8		48	7	$ 37,900	2,948	$ 75,584	0.659	1.00	10.0
7	1	48	6	$ 39,200	2,878	$ 75,993	0.662	1.00	10.0
8		48	8	$ 38,400	3,011	$ 76,893	0.670	1.00	10.0
7	1	48	7	$ 39,700	2,941	$ 77,302	0.673	1.00	10.0
9		48	6	$ 39,600	2,954	$ 77,361	0.674	1.00	10.0
8		48	9	$ 38,900	3,074	$ 78,202	0.681	1.00	10.0
7	1	48	8	$ 40,200	3,005	$ 78,611	0.685	1.00	10.0
9		48	7	$ 40,100	3,017	$ 78,670	0.685	1.00	10.0
8	1	48	6	$ 41,400	2,947	$ 79,079	0.689	1.00	10.0
8		48	10	$ 39,400	3,138	$ 79,511	0.693	1.00	10.0
7	1	48	9	$ 40,700	3,068	$ 79,920	0.696	1.00	10.0
9		48	8	$ 40,600	3,080	$ 79,979	0.697	1.00	10.0
8	1	48	7	$ 41,900	3,011	$ 80,388	0.700	1.00	10.0
10		48	6	$ 41,800	3,023	$ 80,447	0.701	1.00	10.0
7	2	48	6	$ 43,200	2,941	$ 80,797	0.704	1.00	10.0
7	1	48	10	$ 41,200	3,131	$ 81,229	0.708	1.00	10.0
9		48	9	$ 41,100	3,144	$ 81,288	0.708	1.00	10.0
8	1	48	8	$ 42,400	3,074	$ 81,697	0.712	1.00	10.0
10		48	7	$ 42,300	3,086	$ 81,756	0.712	1.00	10.0
7	2	48	7	$ 43,700	3,004	$ 82,106	0.715	1.00	10.0
9	1	48	6	$ 43,600	3,017	$ 82,165	0.716	1.00	10.0
6	3	48	6	$ 45,000	2,935	$ 82,515	0.719	1.00	10.0
9		48	10	$ 41,600	3,207	$ 82,597	0.720	1.00	10.0
8	1	48	9	$ 42,900	3,137	$ 83,006	0.723	1.00	10.0
10		48	8	$ 42,800	3,150	$ 83,065	0.724	1.00	10.0
7	2	48	8	$ 44,200	3,068	$ 83,415	0.727	1.00	10.0
9	1	48	7	$ 44,100	3,080	$ 83,474	0.727	1.00	10.0

Fig. 8 Microgrid HOMER Optimization Result

B. Cost Summary

The optimized microgrid configuration consists of PV array, wind turbine, Converter and Storage battery. Among them the storage battery and the PV array takes the largest cost, which is $41734 for battery and $21601 is for PV array. Figure 9 shows below is the detailed cost share of the microgrid components.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	15,400	3,929	4,474	0	-2,202	21,601
Generic 3kW	4,000	1,247	256	0	-699	4,804
Trojan L16P	16,800	14,619	12,272	0	-1,957	41,734
Converter	3,000	1,252	3,835	0	-233	7,854
System	39,200	21,047	20,837	0	-5,091	75,993

Fig. 9 Microgrid Components Optimized Cost share

C. Electrical Power Production

The total electrical power produced from the system is expected to supply all the loads at any time. In addition, the amount of excess power must be minimum or has to be stored in order to use for the slack time. The total system power production is given in Figure 10 below. From the figure most of the power is produced by the PV, which is 94%, and the remaining 6% of the production is by wind turbine. There is no capacity shortage in the system, but around 17.4% has excess electricity and this will be stored in the battery in order to supply the load during low power production time.

System Architecture: 7 kW PV, 1 Generic 3kW, 48 Trojan L16P; 6 kW Inverter, 6 kW Rectifier
Total NPC: $ 75,993
Levelized COE: $ 0.662/kWh
Operating Cost: $ 2,878/yr

Cost Summary | Cash Flow | Electrical | PV | G3 | Battery | Converter | Emissions | Time Series

Production	kWh/yr	%
PV array	11,999	94
Wind turbine	796	6
Total	12,795	100

Consumption	kWh/yr	%
AC primary load	8,979	100
Total	8,979	100

Quantity	kWh/yr	%
Excess electricity	2,224	17.4
Unmet electric load	0.0313	0.0
Capacity shortage	2.66	0.0

Quantity	Value
Renewable fraction	1.00
Max. renew. penetration	10,735 %

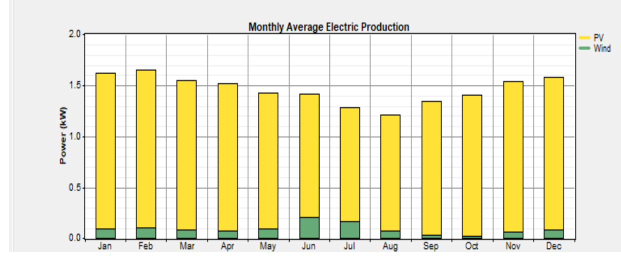


Fig. 10 System Electrical Power Production

III. CONCLUSION

Electrifying rural communities through expansion of the conventional power system is very costly due to high transmission and distribution networks cost, in addition the system reliability also highly reduces. The best way is to establish a local microgrid that will supply the load with minimum long run cost with high reliability.

For the study area using HOMER optimization tool, the microgrid components are optimally determined. The site power demand, solar, wind and temperature resources are determined to optimize the components. To electrify the primary school, health post and the community, 25 KW/h/day with 6 kW peak power is required with total investment cost $ 75993. The storage battery and the PV array takes $41734 and $21601 respectively.

Most of the power which accounts 94% is delivered to the load by the PV array and the remaining 6% is by wind turbine. 17.4% excess production is stored in the battery to supply the customer energy demand during night time or when there is no sufficient power production from the sources.

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