Optimized Hybrid Photovoltaic Diesel Storage Battery Mini-Grid System for Rural Electrification in Ethiopia

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Abstract— Hybrid power systems based on new and renewable energy sources, especially solar PV and Diesel Generator are an effective option to solve the power-supply problem for remote and detached areas from the national grids. Hybrid renewable set-up indicates that various combinations based on the renewable sources could be applied simultaneously to play energy in the form of employed in an off-gird supporting with diesel generator and battery energy storage system as backup systems. In this paper, solar PV/Diesel Generator/battery bank/converter have been simulated and optimized for the rural area of Albasa village among the woreda of Metekel Zone in Benshangul Gumuz region of Ethiopia. Based on the design of hybrid system Primary load demand of the village was 279kWh/day, peak load of 67kW, deferrable energy is about 29kWh/day, and deferrable peak load of 1.9kW with COE $0.010/kWh were involved during optimization of the power system. Well known freeware HOMER and programmable logic controller modeling tool have been used to design optimal off-grid system and energy management system respectively. Solar PV was considered as primary sources to supply electricity directly to the load and to charge battery bank when there were excess energy generation. However, either in peak load times or low generation of primary sources storage battery bank discharged and Diesel Generator could also be used as a source. The load has been suggested for residential loads and deferrable load. During design of this power system set-up, the simulation and optimization was done based on the load demand, climatic data, economics of integrated system components and other parameters in which the total NPC and levelized COE have to be minimized to select economically feasible and technically capable hybrid power system. Furthermore; a programmable logic controller modeling is also modeled to compare the possible potentials available and take a decision. The decision of programmable logic controller modeling is based on the instructional rules written on it.

Keywords— HOMER, programmable logic controller, hybrid system, solar PV, Diesel Generator, Battery bank, primary load, deferrable load, rural electrification.

I. Introduction

Energy is the fuel for growth of a country or generally growth of the world. An increased access to electricity enhances opportunities for industrial development and improves health and education. But currently still about 37% of the world's population have no access to electricity. Most of rural people depend almost exclusively on biomass for their daily energy need. According to the report of United Nations Food and Agriculture Organization, the numbers of people suffering from shortage of wood fuel were expected to highly increase in the coming years [1], [2].The Ethiopian Government tried to connect this rural location by using national grid extension for the last two decades. However, still the current electricity access is below 50% and the real connection is less than 14% [2], [3]. Today it is widely accepted that Renewable energy system (RES) have a large potential to contribute to the strengthening and development of national sustainable energy infrastructures in many countries in the world by securing better energy independence through the mobilization of domestic renewable energy resources especially in rural areas [4], [5].

A stand-alone power system (SAPS), also known as remote area power supply (RAPS), is an off-grid electricity system for locations that are not fitted with an electricity distribution system. Typical SAPS include one or more methods of electricity generation, energy storage, and regulation [6], [7], [8]. Hybrid renewable energy systems (HRES) are becoming popular as stand-alone power systems for providing electricity in remote areas due to advances in renewable energy technologies and subsequent rise in prices of petroleum products. A hybrid energy system, or hybrid power, usually consists of two or more renewable energy sources as well as a backup is used together to provide increased system efficiency as well as greater balance in energy supply [9], [10], [11]. The following Figure 1 shows that the history of Ethiopian electric power generation starting from the beginning until the current situation.

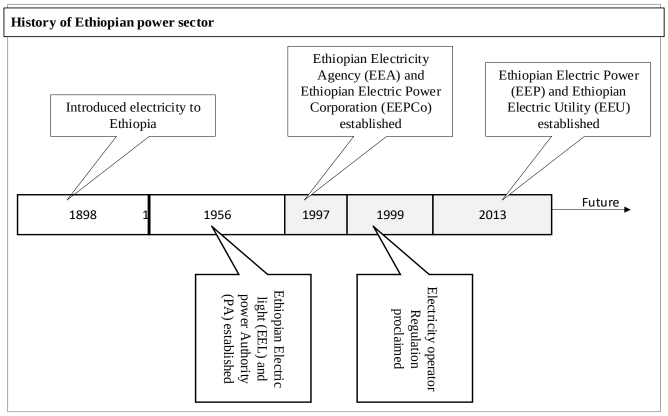


Fig.1 History of Ethiopian Electric Power Sector

Despite of the abundant renewable energy resources, many communities still live without access to electricity either from the utility grid or off-grid renewable energy generated electricity. Energy consumption involves all energy harnessed from every energy source applied towards activity across all industrial and technological sectors in every country. According to current figures about 30% of the Ethiopian citizens are estimated to have electricity access and the per capital energy consumption is still less than 100 KWh per household, which is the lowest in the world and almost using biomass [12], [13], [14]. This had a direct impact on deforestation. However, energy supply thereby is covered by bio-energy which accounts about 90% of final energy consumption, while a transport sector is predominantly run by imported petroleum; which accounts about 4.5% and the modern energy contributes only about 6% of the overall energy consumption. Nowadays Ethiopia total installed capacity of electric generation is about 4.5 GW (2019) mainly generated by hydro (90%) and followed by wind energy (7.6%). Only few researchers were conducted in Ethiopia to solve problem in rural energy access and empower the development of alternative energy technology. The lack of electricity access causes for social and economic problems such as poverty, poor health services, low quality of education, gender inequity and so on.

The proposed method presents the review of Ethiopia renewable energy potential with current state in a more comprehensive way and provides valuable information for researchers, industrial companies and decision makers to promote investment in renewable energy technology development. During design of hybrid system, it is needed to design efficient control system. If the control system failed to switch to an appropriate power source at desired time, the efficiency of the system will decrease. Hence attentions should be given to the control system during designing of hybrid power system. Design and Optimization of a Hybrid PV/ESS/Diesel Based Mini-Grid Power System Generation of Rural Electrification. As a Case Study of Albasa Villages/Metekel Zone in Benishangul Gumuz Region, Ethiopia, to select the best optimized hybrid model for providing electricity to the community by considering its overall installation cost, contribution of renewable energy sources and energy cost per kWh.To analyze the power and energy demand of the society of the selected areas by considering the basic needs of the people. To select appropriate solar modules, Diesel Generators and batteries depending on the energy demand for the selected sites. To determine the demand of the community at the life span of the project through load forecasting. To control the system using programmable logic controller, draw conclusions and give recommendations for future works.

II. Materials and Methods

A. Modeling of Hybrid Energy System Components-Mathematical Modeling of PV System

The operation and the performance of PV generator is interested to its maximum power, the models describing the PV module's maximum power output behaviors are more practical for PV system assessment. Using the solar radiation available on the tilted surface, the ambient temperature and the manufacturers data for the PV modules as model inputs, the power output of the PV generator, P_{PV}, can be calculated according to equation (1.1)

$$= \eta_g N A_m G_t \qquad (1.1)$$

Where, - is the instantaneous PV generator efficiency, - is the area of a single module (m^2), - is the global irradiance incident on the titled plane (KW/m^2) and N - is the number of modules. All the energy losses in a PV generator, including connection losses, wiring losses and other losses, are assumed to be zero. The instantaneous PV generator efficiency is represented by the following equation:

$$= \eta_r \eta_{pt} [1 - \beta_t (T_c - T_r)] \qquad (1.2)$$

Where, η_r is the PV generator reference efficiency, η_{pt} is the efficiency of power tracking equipment which is equal to 1, T_c is the temperature of PV cell (°C), T_r is the PV cell reference temperature and β_t is the temperature coefficient of efficiency, ranging from 0.004 to 0.006 per °C for silicon cells.Based on the energy balance the PV cell temperature can be expressed as follows:

$$T_c = T_a + G_t \left(\frac{\tau\alpha}{U_L}\right) \qquad (1.3)$$

Where, T_a is the ambient temperature (°C), U_L is the overall heat loss coefficient (W/m^2/ °C), τ and α represent the transmittance and absorptance coefficients of PV cells respectively.The overall heat loss coefficient $\tau\alpha/U_L$ can be estimated from the nominal operating cell temperature (NOCT) as follows:

$$\left(\frac{\tau\alpha}{U_L}\right) = \frac{NOCT-20}{800} \qquad (1.4)$$

Consequently, the instantaneous PV generator efficiency can be expressed as follows:

$$\eta_g = \eta_r \eta_{pt} \left\{1 - \beta_t (T_a - T_r) - \beta_t G_t \left(\frac{NOCT-20}{800}\right)(1 - \eta_r \eta_{pt})\right\} \qquad (1.5)$$

Where, η_{pt}, β_t, NOCT, A_m were parameters that depend on the type of module and given by the manufacturer of the modules. Using the solar radiation available the hourly energy output of the PV generator (E_{PVG}) can be calculated according to the following equation (1.6)

$$E_{PVG} = G(t) * A * P_{PV} * \eta_{PVG} \qquad (1.6)$$

Where, G (t) is the hourly irradiance in kWh/m^2, A is the surface area in m^2, P_{PV} is the PV penetration level factor and η_{PVG} is the efficiency of PV generator.

B. *Population Growth and Load Forecasting*

The population of Ethiopia accounts all residents regardless of legal status/citizenship except for refugees not permanently in the country of asylum, which are generally considered part of the population of the country of origin. The average annual population growth rate of Ethiopia was 2.65% from 2005 to 2019 G.C. (source: www.google.com)

The formula used for population forecasting is:

$$P_n = P_0 \left(1 + \frac{r}{100}\right)^n \qquad (1.7)$$

Where: P_n – is population at the n^{th} year, P_0 – is the current population and r – is annual population growth rate in %.

C. *Load Forecasting*

The load forecasting was done for the two load estimations separately. It was obvious that previously recorded data was required as an input to conduct load forecasting using different techniques. But since the selected area was not electrified so far, the previous data were extracted by using the load forecasting method which was in use by UEAP. This was a governmentally owned company endowed in supplying electric access to rural areas by extending the national grid. The annual load growth rate was about 5% which was calculated by considering the data taken from previously electrified areas. Hence, a primary load forecasting for the first ten years were done using equa. (1.8) given below. The current electric load was taken to be 279kWh/day which was calculated by considering the total primary load of the community.

$$E_n = E_0\left(1 + \frac{r}{100}\right)^n \qquad (1.8)$$

Where: E_n - is electric load at the n^{th} year, E_0 - is the current electric load and r - is the annual electric load growth (i.e. 5%)

The result of this analysis was shown in Table 1.1 below. These values are then used as input to forecast for the coming 10 years (2030) using the exponential method of forecasting.

Table I: Results of primary load forecasting

Year	2020(0)	2021(1)	2022(2)	2023(3)	2024(4)
Load	279 kw	290 kw	301.65 kw	314.98 kw	329.03 kw

Thus, the principle of regression theory was used to forecast the load for the coming ten years by using the results in Table I as a previous data. Its principle was that any function y = f(x) can be fitted to a set of points (x_1, y_1), (x_2, y_2) so as to minimize the sum of errors squared at each point, i.e.

$$\sum_{i=1}^{n}\{y_i - f(x_i)\}^2 = \text{minimum} \ (1.9)$$

Among the different typical regression curves used in power system forecasting the simple least square line was used for forecasting the load in this paper. The line $y = a_0 + a_1x$ was fitted to the sets of points (x_1, y_1), (x_2, y_2) … (x_n, y_n).Where, y - is dependent variable, a_1- is slope, x - is independent variable, a_0- is y-intercept and n are number of years.

$$\varepsilon^2 = \sum_{i=1}^{n}[y_i - (a_0 + a_1x_i)]^2 = \text{minimum} \ (1.10)$$

Partial differentiation with respect to the regressions coefficients (a_0 and a_1) is made and the equations set to zero to obtain the minimum error criterion. This gives us a set of simultaneous equations in a_0 and a_1:

$$\text{For} a_0: 2\sum[y_i - (a_0 + a_1x_i)] = 0, \text{We get,}$$

$$\sum a_0 + a_1\sum x_i = \sum y_i$$

$$Na_0 + a_1\sum x_i = \sum y_i$$

$$\text{For} a_1: 2\sum[y_i - (a_0 + a_1x_i)]x_i = 0$$

$$a_0\sum x_i + a_1\sum x_i^2 = \sum x_iy_i$$

Which yield

$$a_0 = \frac{(\sum y)(\sum x^2) - [\sum(x)]\sum xy}{N\sum x^2 - (\sum x)^2} \qquad (1.11(a))$$

$$a_1 = \frac{N\sum xy - (\sum x).(\sum y)}{N\sum x^2 - (\sum x)^2} \qquad (1.11(b))$$

Table II(a): Results of the analysis

Year	Peak demand (kw)	x_i	$pDi = \frac{\text{Peak demand}}{10}$
2020	279	-2	27.9
2021	290	-1	29.0
2022	301.65	0	30.165
2023	314.98	1	31.498
2024	329.03	2	32.903
		$\sum x_i = 0$	

Table II (b)

Y_i = InpDi	$x_i y_i$	x_i^2
3.25809	-6.51618	4
3.30689	-3.30689	1
3.35568	0	0
3.40446	3.40446	1
3.45325	6.9065	4
$\sum y_i = 16.7784$	$\sum x_i y_i = 0.4879$	$\sum x_i^2 = 10$

Table II(c)

a_0	a_1	x_i
3.35568	0.04879	5

Finally, the values in Table II are used to determine the load of the selected area in 2030 G.C. The forecasting is then done using equation 3.57 (a) and (b) shown below by considering 2030 as a reference year. Therefore, the load is obtained to be 365.85kWh/day.

$$Y = a_0 + a_1.x_i \qquad (1.12(a))$$

$$E_n = 10e^Y \qquad (1.12(b))$$

D. PLC in hybrid system

Table III below depicts energy management system using plc. When a system has more than two sources it is necessary to have an energy management system which is expected to optimize the power sharing among resources, the cost production and emission. In this paper, the main purpose of EMS is - Load control (switching) - on/off loads to achieve economic and effective energy use. Source control (switching) which type source at what time (solar, diesel generator and battery) supplies to get continuous and reliable operation at economic level. The PLC SIMATIC manager control makes decision on the output based on the operating state of the input.

III. Result and Discussion

A. Optimization Analysis of the Selected Scenario

The modeling simulates one year of operation and thousands of different system configurations. The system with the overall least cost of energy is the one highest on the list. The remaining columns show the optimized capacity of each component, the initial capital cost, the total NPC, the COE (in $ per kWh) and renewable energy fraction. Based on the HOMER modeling, the optimal system for Albasa village in categorized optimization results a first row, shows a hybrid solar PV/diesel generator/storage battery, with mean output power of 25kW solar PV, 14kW Diesel Generator, 80 S4KS25P batteries (each of 1900Ah capacity) and 85kW bi-directional convertor (85kW rectifier, 85kW invertors) are required power supplied for the selected village. This “optimal” system uses 98.5% renewable energy and the COE is $0.080/kWh.All of the power schemes remain producing electricity throughout the year.

Table III: States of Power Supply Units With Respect To Load Demand and Operating Time

Operating Time(hr.)	Load (kw)	Solar energy	Diesel generator	Battery (Lithium-Ion)
00:00-6:00	3.565	Off	Off	On
6:00-7:00	10.825	Off	On	On
7:00-8:00	14.77	On	Off	Off
8:00-10:00	19.18	On	Off	Off
10:00-11:00	14.66	On	Off	Off
11:00-12:00	1.16	On	Off	Off
12:00-14:00	11.3	On	Off	Off
14:00-15:00	13.895	On	Off	Off
15:00-16:00	21.035	On	Off	Off
16:00-18:00	12.43	On	Off	On
18:00-19:00	33.385	On	On	On
19:00-22:00	38.075	Off	On	On
22:00-23:00	10.095	Off	On	On
23:00-00:00	3.75	Off	Off	On

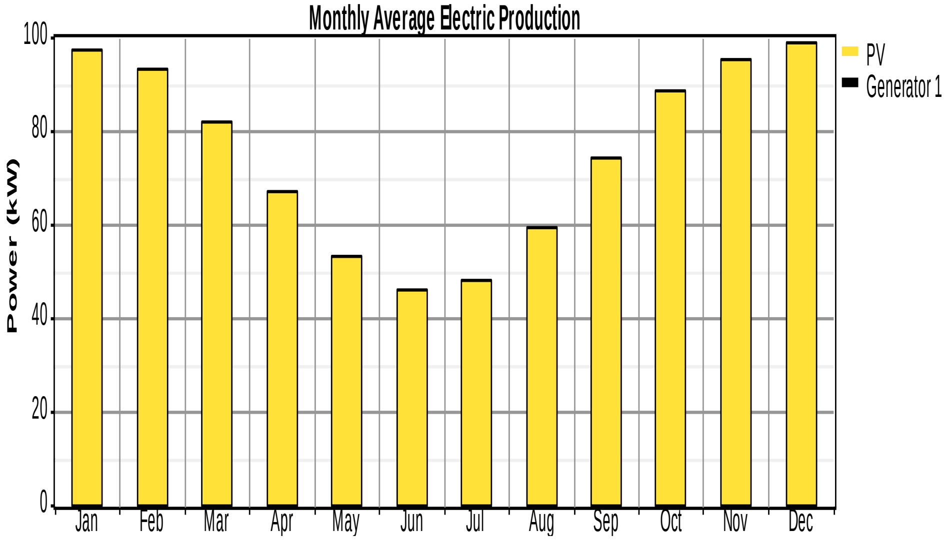


Fig. 2: Share of Electricity Generation

The electricity generation by individual power units of the hybrid system and consumptions by AC primary and deferrable load are given in Fig.2

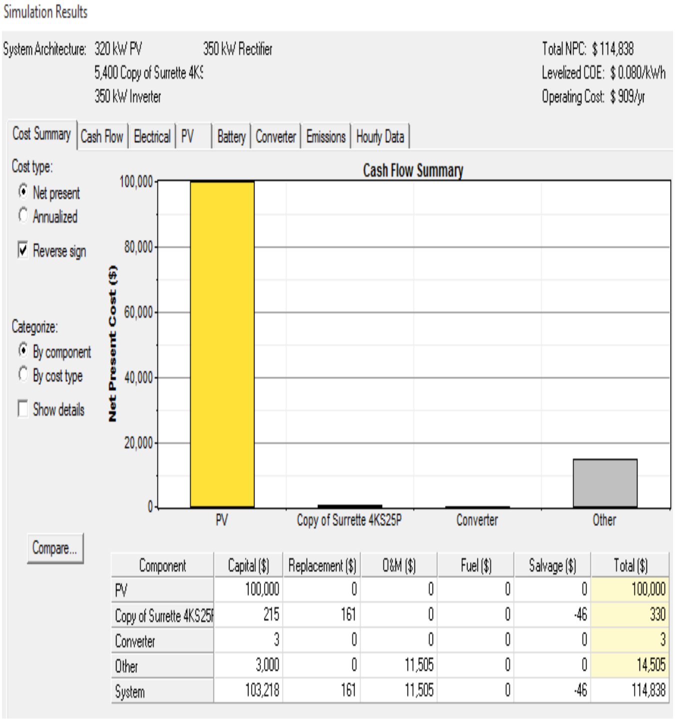
PV array power production accounts for 98.5% (659,278kWh/year) whereas Diesel Generator generation covered 1.5%(1,053kWh/year) of total electricity produced by the hybrid scheme. The total power generation of this power system setup was 660,331kWh/year (100%), whereas the total electric power consumption of the AC load was about 101,835kWh/year i.e91% of the electricity consumed by AC load and the consumption of deferrable load10,602kWh/year i.e. 9% were consumed by deferrable load. In addition to this an excess electricity of 79.5%, a capacity shortage of (0.0%) and unmet electric load of (0.0%) were experienced during the year. Actually, this power system architecture indicates that excess electricity would enable to supply the demand growth of the community in the future. In addition to this, excess electricity could provide to neighboring villages or introduce small businesses to increase the load factor of the power system; consequently, the cost of electricity will also decrease.

A. Cost Summary in terms of NPC by Component Type

The following Fig.3 shows that the cost summary in terms of NPC by component type which were the system set-up. It shows graphical representation of each component and also other required materials NPC ($). In addition to these, it shows table representation of the capital cost ($), replacement cost ($), O & M cost ($), salvage cost ($) and total cost ($)of each component as given below.

B. Cost Summary of the System by Cost Type

The Fig.4 below displays cost break down summary of the components with 100% renewable fraction hybrid power scheme. It is clearly seen from the graph the total capital cost, NPC and COE of the optimal configuration of the hybrid system is calculated by the HOMER software to be $114,838, $103,221 and $0.080/kwh respectively.



System Architecture: 320 kW PV
5,400 Copy of Surrette 4KS
350 kW Inverter
350 kW Rectifier

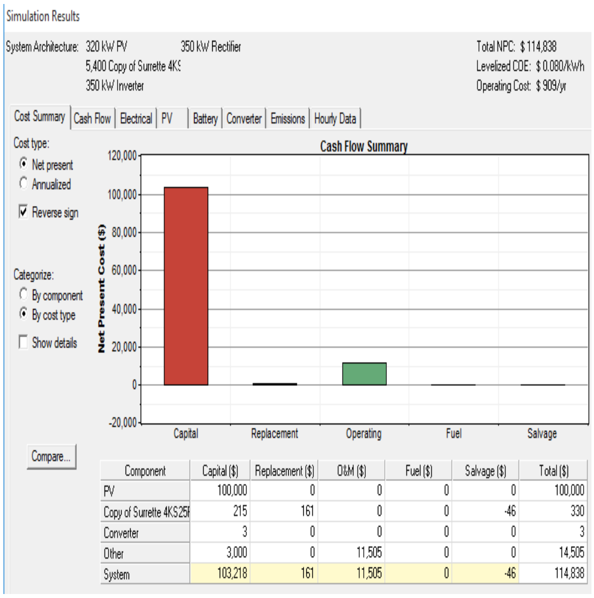
Total NPC: $ 114,838
Levelized COE: $ 0.080/kWh
Operating Cost: $ 909/yr

Cost type:
● Net present
○ Annualized
☑ Reverse sign

Categorize:
● By component
○ By cost type
☐ Show details

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	100,000	0	0	0	0	100,000
Copy of Surrette 4KS25F	215	161	0	0	-46	330
Converter	3	0	0	0	0	3
Other	3,000	0	11,505	0	0	14,505
System	103,218	161	11,505	0	-46	114,838

Fig.3: Cost summary in Terms of NPC by Component Type



Simulation Results

System Architecture: 320 kW PV
5,400 Copy of Surrette 4KS
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Total NPC: $ 114,838
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Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
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Copy of Surrette 4KS25F	215	161	0	0	-46	330
Converter	3	0	0	0	0	3
Other	3,000	0	11,505	0	0	14,505
System	103,218	161	11,505	0	-46	114,838

Fig. 4: Cost summary of the system by cost type

C. Sensitivity Results Consideration

Sensitivity is a measure of how the optimal mix of components changes for any parametric variations in the lifelong of the system. The HOMER software simulates all the systems in their respective search space for each of the sensitivity values. An hourly time series simulation is performed for one complete year.

In Fig.5 the line graph below shows PV array capacity variations (KW) and AC primary load (KW) is displayed within given month of April. Considering only two of the sensitivity cases (solar PV power (KW) and AC primary load (KW)) by keeping the other variables as fixed minimum renewable fraction were one.

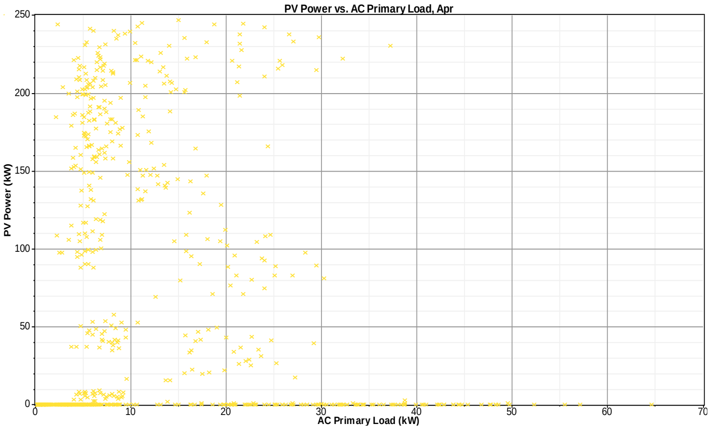

Fig. 5: PV Array Capacities vs. AC Primary Load

D. Programmable Logic Control System Results

Based on the above Table III Source control (switching) which type source at what time (solar, diesel generator and battery) supplies to get continuous and reliable operation at economic level given depicts energy management system using PLC as a reference of generation and demand was discussed as follows the result given below. A system has more than two sources it is necessary to have an energy management system which is expected to optimize the power sharing among resources, the cost production and emission. The PLC SIMATIC manager control makes decision on the output based on the operating state of the input variables. The results of PLC SIMATIC were as network 1 for household loads, commercial loads, community loads and deferrable loads given in parallel as follows and shown in Fig.6.

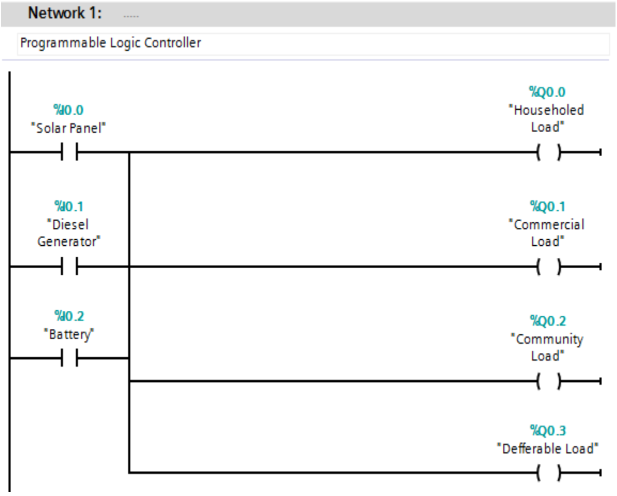

Fig.6: Hybrid system energy management model using PLC SIMATIC Manager

IV. Conclusions

The crucial objective of this paper was to find a best techno-economic of an off-grid power system to supply a rural area in Albasa Village with energy management system. In the design of solar PV/Diesel Generator and battery bank for Albasa village, the paper arrived at 5.013 kWh/m^2/day average daily solar radiation and Diesel Generator/Storage battery backup for a household with a total number of 1110households and the total average energy demand was about 279kWh/day with maximum load of 67kW.Off-grid renewable energy-based power systems cannot provide a continuous supply of electricity without a storage medium. Consequently, storage battery banks were added to the hybrid system. After selecting the appropriate components and studied their characteristics, the hybrid system has been modeled in HOMER, PLC software and simulations have been made to determine the best system which can supply the village load with the required level of availability. The usefulness cost of all hybrid structure that can fulfill the continuous load demand has been calculated to determine the system which provides the lowest cost.

A solar PV/Diesel Generator/battery bank and converter hybrid system has been found as the optimum system with mean power output of 25kw, 14kw, 80 S4KS25P batteries and 85kw converter respectively. The implementation of hybrid solar PV/Diesel Generator/storage battery bank systems in residential, non-governmental and governmental institutions and also commercial areas across Ethiopia would reduce unexpected power interruption, high power loss and blackouts on the national power grid. As far as the environmental aspects are concerned, these kind of renewable hybrid systems have to be wide spread in order to cover the energy demands of rural areas and used to apply green energy policy, by reducing the greenhouse gases emission and environmental pollutions were an important point taken to account.

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