International Journal of Advances in Engineering and Management (IJAEM)
Volume 2, Issue 4, pp: 235-244 www.ijaem.net ISSN: 2395-5252

Mathematical Modelling of Solar Photovoltaic Integrated with Biomass-Based Power System

Nuhu Mohammed[1]; Ademola Bello Adisa[2]; Habou Dandakouta[3]; Aje Tokan[4]
[1] *Lecturer II, Department of Mechanical/Production Engineering, Abubakar Tafawa Balewa University, Bauchi, Nigeria*
[2,3,4] *Professors, Department of Mechanical/Production Engineering, Abubakar Tafawa Balewa University, Bauchi, Nigeria*

Date of Submission: 28-07-2020 Date of Acceptance: 12-08-2020

ABSTRACT: Rural electrification is a global challenge especially in developing countries. For instance, in Nigeria, the problem of rural electrification is acute because the country has not been able to provide adequate supply to the connected consumers. More than 90 million out 180 million people in the country live without access to electricity presently and most of them reside in rural areas. However, the country is blessed with numerous resources that can provide electricity for its citizenry. As such, this research designed an off-grid hybrid power generating plant that utilises solar and biomass renewable sources for Duguriyel village, having daily average electricity requirement of 1702.84 kWh/day. Three system configurations of the hybridisation were modelled using mathematical modelling equations. Solar PV penetration of 10%, 20%, 30%, 40%, 50% were considered as configuration I. In configuration II, biomass-based power system was designed based on average power of the village and the solar PV provides the remaining; and configuration III operates in such a way that the biomass plant provides the electricity based on available feedstock in the village and the solar PV generates the supplement. It has been observed that the plant operating factor is constant irrespective of the combination, whereas, plant use factor and plant capacity factor show decrease in relation to increase in the solar PV penetration.
KEYWORDS: solar, photovoltaic, biomass, rice husk, energy, levelised cost, electricity

I. INTRODUCTION

The utilization of solar energy for human beings has been in existence for several centuries. It is the oldest energy source ever used; and the sun was adored by many ancient civilizations as a powerful god [1]. The sun is of great importance for the planet earth and the ecosystem of our society [2]. It has the greatest advantage of being clean and can be supplied without environmental pollution when compared with other forms of energy such as fossil fuels [1]. Conversion of solar energy is usually done in either active or passive mode. The active mode produces electricity as its end result; whereas, the passive mode provides means for space heating and hot water. In converting solar energy to electricity, there are two perspectives from which the conversion can be approached. The first perspective is the photovoltaic (PV) conversion that uses solar cells to generate electricity; and the second is the use of solar heat engines [3]. Many works have been done by researchers using these two approaches that include the works of [3]., [4]., [5]., [6]., and [7]. Solar energy has huge potentials of solving the world's electricity problem because all regions across the globe have this natural resource only that it is more prevalent in some regions than others. Solar PV is playing a substantial role in electricity generation in some countries as rapidly falling costs have made unsubsidised solar PV-generated electricity cost-competitive with fossil fuels in an increasing number of locations around the world' (Renewable Energy Policy Network for the 21st Century [8]. The major disadvantage of solar PV conversion is nondispatcheabilty, lower conversion efficiency, intermittency, storage requirement, require huge space and inverter must be incorporated to give alternating current (AC) etc.

On the other hand, biomass, probably the most promising source of energy for domestic activities in rural villages, is broadly categorised as woody (which includes forestry timber, agricultural residues, and co-products, etc.) and non-woody which are animal wastes, industrial and biodegradable municipal products from food processing, and high-energy crops such as rape, sugarcane, etc. [1]. Biomass in the form of agricultural residues (such as rice husk) has been providing electricity for many years with conventional steam turbine power generators. [9]. proof the suitability of this feedstock for heat and power generation. Rice husk is chosen for this research because many rice processing plants are coming on-board following the recent call by the Nigerian Government on cultivation of rice. This action makes rice husk available and will give this research an opportunity to recommend this type of power system to rice processing plants and rice farming areas. The research considered Duguriyel as the case study area. It is a small village with a population of approximately 1000 people and located at 9.9°N 9.76°E about 50 km away from Bauchi city. The village is a rice cultivation area and enjoys solar radiation suitable for solar PV applications based on Nigeria's solar map as can be found in [10].

II. SOLAR-BIOMASS INTEGRATION

Integration in the context of this research refers to incorporation or combination of two or more sources energy to achieve a desired output. Solar energy is an intermittent renewable energy source in nature [11]. The thermal efficiency of heat engines that utilizes solar thermal energy is generally low because of the limitation of the high temperature that can be attained with solar-thermal collectors [3]., but can be complemented by integrating biomass boiler. Hybridization of solar with biomass combustion complements each other, both seasonally and diurnally, to overcome their individual drawbacks and results in continuous and uniform supply'' cited [11]. The hybridization using solar may be employed by using solar concentrators or solar PV. However, solar energy conversion using solar PV is the simplest, requires less maintenance and has lower initial capital cost as compared to solar concentrators. So, the sun's rays can be harnessed easily by solar PV and biomass feedstock can be burnt as a supplementary fuel to achieve constant base load operation. Several works carried out on solar-biomass systems based on solar PV and concentrated solar power (CSP) technology. However, research shows that CSP technologies are most favourable in 'North Africa, Southern Africa, the Middle East, southern Europe, north western India, the south western United States, Mexico, Peru, Chile, the western part of China and Australia'[12]. It can be deduced that countries located in West Africa and other regions not mentioned above, are more suitable for solar PV. Consequently, this research considered solar PV for the hybridization.

III. METHOD

3.1 Input parameters

The input parameters for the integration are the load demand, solar resources, and the biomass fuel.

3.1.1 Load demand

The load of the village is categorised in to residential, school, place of worship, healthcare centre and business enterprises loads. Thus, the modelling equations for the load demand are expressed in equation (1 & 2) [13]. and the load demand profile obtained is as depicted in Figure 1.

$$\mathbf{P_{Load}(t) = P_{RL}(t) + P_{SL}(t) + P_{PWL}(t) + P_{HCL}(t) + P_{BEL}(t)} \quad (1)$$

$$P_{RL}(t) = P_{SL}(t) = P_{PWL}(t) = P_{HCL}(t) = P_{BEL}(t) = \sum_{i=1}^{N}[P_i \times t_i \times n] \quad (2)$$

Where:

$P_{Load}(t)$ = the total hourly load at time t ;
$P_{RL}(t)$ = hourly residential load at time t
$P_{SL}(t)$ = hourly school load at time t ;
$P_{PWL}(t)$ = hourly place of worship load at time t
$P_{PWL}(t)$ = hourly healthcare load at time t
$P_{BEL}(t)$ = hourly businesses load at time t
P_i = power consumed by appliance i;
t_i = time of appliance usage
n = number of devices
i = type of device, and
N = number of electric appliance used

International Journal of Advances in Engineering and Management (IJAEM)
Volume 2, Issue 4, pp: 235-244 www.ijaem.net ISSN: 2395-5252

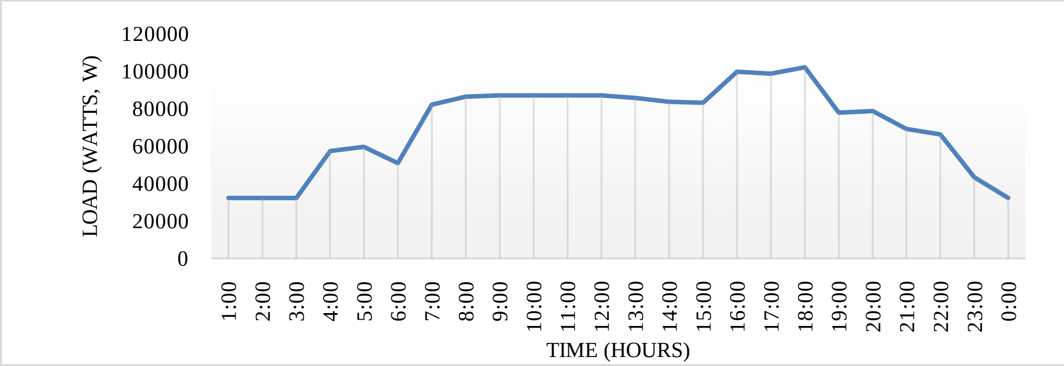

Figure 1: Total electricity load demand profile

The daily total electricity load demand of the village was estimated to be 1702.84 kWh/day.

3.1.2 Solar radiation

The solar radiation of the location was estimated to be as depicted in Figure 2.

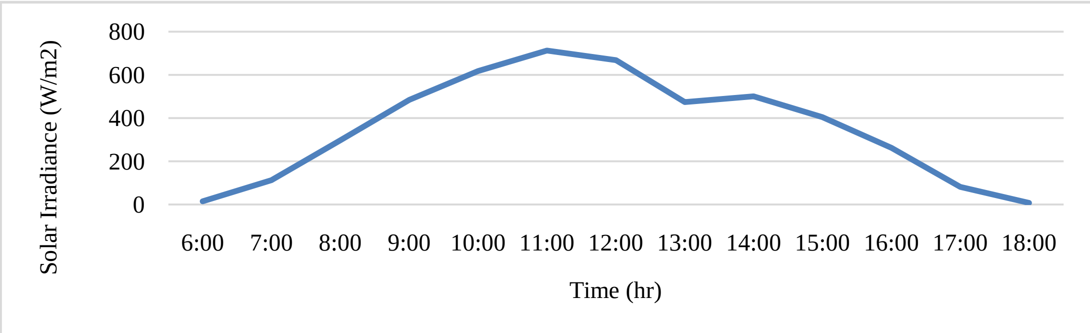

Figure 2: Average solar radiation of Duguriyel Bauchi

3.1.3 Biomass power plant

The estimate shows that about 196 tonnes of rice husk may be realised from the farmers, however, design of a standalone rice husk power system indicates that up to 1954 tonnes of rice husk is required yearly to meet the load demand of the village. Rice husk just like other biomass and conventional fuels can be bought in the market, as such, the deficit can be obtained from buying or the plant be integrated with solar PV as proposed in this research.

3.2 Hybrid System Configuration

Figure 3 depicts the block diagram the stand-alone hybrid energy system considered.

International Journal of Advances in Engineering and Management (IJAEM)
Volume 2, Issue 4, pp: 235-244 www.ijaem.net ISSN: 2395-5252

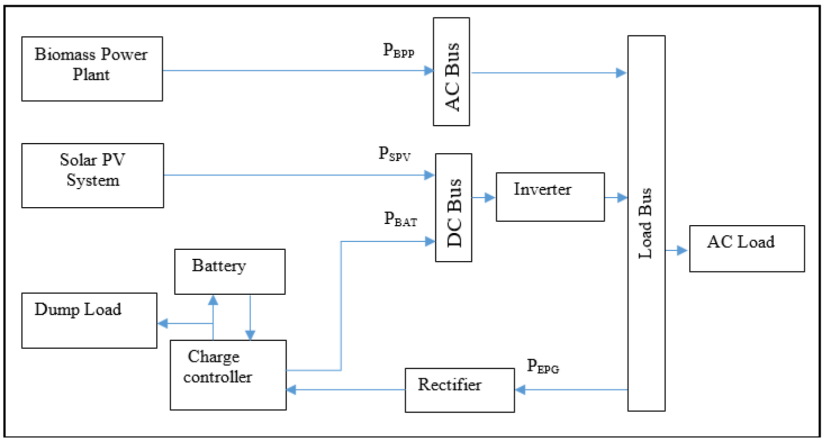

Figure 3: Hybrid Energy System Configuration

The system consists of biomass power system solar photovoltaic (SPV), battery bank storage and dump load. 'Provisions for the availability of both AC and DC buses are made using electronic converters' [13], and the electrical energy that serve the load can be produced either directly from solar PV system and biomass power plant, or indirectly from the battery bank storage as expressed in Equations (3) through (7) {[13]; [14]}.

$$P_{SPV}(t) = P_{SPV,load}(t) + P_{SPV,BAT}(t) + P_{SPV,Dump} \quad (3)$$

$$P_{BPP}(t) = P_{BPP,load}(t) + P_{BPP,BAT}(t) + P_{BPP,Dump}(t) \quad (4)$$

$$P_{TOTAL}(t) = P_{SPV}(t) + P_{BPP}(t) \quad (5)$$

Where:

$P_{SPV}(t) =$ Power generated by solar PV; $P_{SPV,\ load}(t) =$ Power used to serve AC load by solar PV; $P_{SPV,\ BAT}(t) =$ Power used to charge battery from solar PV; $P_{SPV,\ Dump}(t) =$ Power generated by solar PV but not utilised; $P_{BPP}(t) =$ Power generated by biomass power plant; $P_{BPP,\ load}(t) =$ Power used to serve AC load by biomass power plant; $P_{BPP,\ BAT}(t) =$ Power used to serve to charge battery from biomass power plant; $P_{BPP,\ Dump}(t) =$ Power generated by biomass power plant but not utilised; $P_{TOTAL}(t) =$ Total power generated by the hybrid system

The energy available to charge the battery bank (BAT) in any hour t, is represented in Equation (6), and the energy available from the battery to serve the load is as shown in Equation (7).

$$P_{BAT,\ IN}(t) = \eta_{CHG} \times \eta_{CC} \times [P_{SPV}(t) + P_{BPP}(t)] \quad (6)$$

$$P_{BAT,\ Load}(t) = \eta_{DCHG} \times P_{BAT,\ IN}(t) \quad (7)$$

The total energy available to serve the load is as written in Equation (8)

$$P_{LOAD}(t) = P_{BPP,load}(t) + \eta_{CHG} \times [P_{SPV,load}(t) + P_{BAT,Load}(t)] \quad (8)$$

3.2.1 Mathematical model of biomass power plant

The annual delivered energy output (P_{BPP}) of the biomass power system is dependent on its capacity utilization factor and rated power output of electricity generator [13]. The hourly energy output was calculated using equation (9)

$$P_{BPP}(t) = P_{BPP,\ RATED\ POWER}(t) \times \eta_{BPP} \quad (9)$$

3.2.2 Mathematical Model of Solar PV System

The solar PV system power output has approximately a linear relationship to the insolation (irradiance) [13]. Using the solar radiation available on the tilted surface the hourly energy output of the solar PV system was modelled according to equation (10)

$$P_{SPV}(t) = A \times \eta_{SPV} \times H_{\alpha}(t) \times PR \quad (10)$$

Where: E = Energy (kWh);
A = Total solar panel Area (m^2);
η_{SPV} = solar panel yield or efficiency (%) ;
H_{α} = average solar radiation on tilted panels;
PR = Performance ratio, coefficient for losses (range between 0.5 and 0.9, default value = 0.75).

3.3 Dispatch strategy

Operation strategy was considered in this study i.e. the battery charging strategy and battery discharging strategy (in which the absorbed surplus power may be used to meet the net-load in a time step). The hourly net-load is the output from power plant subtracted from the hourly total load demand as expressed in Equation 11:

$$P_{net-load}(t) = P_{Load}(t) - P_{Total}(t) \quad (11)$$

3.3.1 Battery storage constraints

Battery must be operated between 20% and 100% of the capacity. Battery must be discharged at least 95% of maximum level before 6:00 am, so that battery recharging can be started in the early hours of the day.

3.3.2 Solar PV penetration strategy

Three different penetration strategy of the solar PV system were designed to provide the peak load demand of the village and cost of the electricity was calculated for each of the penetration.

3.3.2.1 Penetration Strategy I

In this strategy, different percentage of solar power contribution was considered to complement the biomass power system as can be seen in Table 1.

Table 1: Percentage of Solar Contribution

Power plant		**% of contribution**					
Solar PV	0	100	10	20	30	40	50
Biomass	100	0	90	70	70	60	50

3.3.2.2 Penetration Strategy II

In this case, biomass power system was designed based average power of the village and the solar PV provides the remaining.

3.3.2.3 Penetration Strategy III

Here, the biomass plant provides the electricity based on available feedstock in the village and the solar PV generates the supplement.

IV. RESULT AND DISCUSSION

4.1 Dispatch strategy analysis

The dispatch control deals with the flow of energy in the system from the various sources to load as depicted in Figure 4.

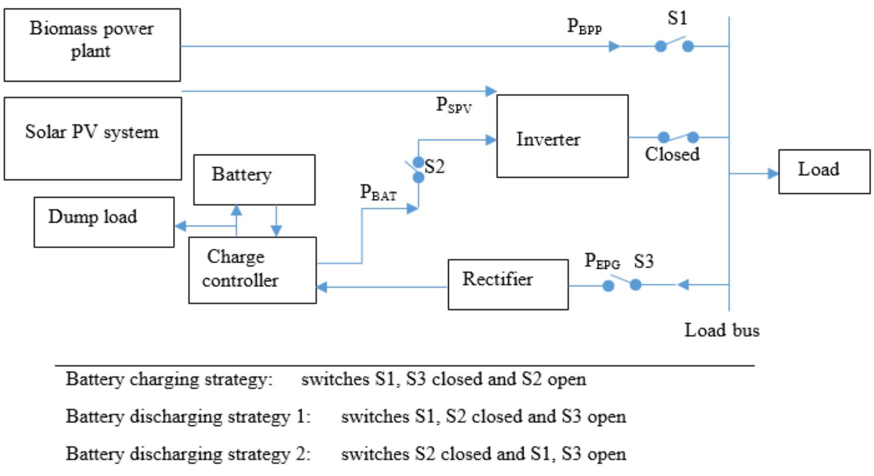

Figure 4: Dispatch strategy energy flow

The use of battery storage in hybrid renewable power systems is not simply about the provision of electricity outside of daylight hours, but plays an important role in ensuring that the mini-grid system can operate stably. It can immediately act to inject power if clouds pass over solar PV array or the total generation cannot meet the demand. This is important because small-scale solar PV systems are more vulnerable to passing clouds [15].

4.1.1 Dispatch Strategies

Three conditions of dispatch operation were considered to supply the net-load.

4.1.1.1 Battery charging strategy ($P_{total-gen} \geq P_{load}$)

When the energy generated from the hybrid power system (solar PV and biomass plant) exceeds the load demand of the village, the excess energy charges the battery bank (provided they are not already fully charged). This means that switches S1 and S3 will be closed whereas S2 will be opened.

4.1.1.2 Battery discharging strategy I ($P_{total} \leq P_{load}$)

When the total energy generated from the hybrid power system is lower than the load demand at any particular time, then the battery bank will be discharged by the amount needed (P_{needed}) to cover the net-load. Battery discharging strategy 1 will be activated, making switches S1 and S2 to be closed while S3 get opened. The battery discharging continues until the hybrid power plant generates sufficient power to meet the load demand.

4.1.1.3 Battery discharging strategy II ($P_{batt} \geq P_{load}$ and $P_{total} = 0$)

The battery bank power is sufficient to meet the load demand requirement of the village between 23:00 pm to 5:00 am and the biomass plant is off during that time. Battery discharging strategy 2 will get activated and switches S2 will be closed and S1, S3 will get opened. Here, the battery discharging continues until minimum battery state of discharge (20%) is reached.

4.2 Hybrid Power Generation

4.2.1 Penetration Strategy I result

Five solar PV contributions were designed as apart from 100% biomass power generation and 100% solar PV power production. An off-grid design was considered since the grid infrastructure was very poor and unreliable. The hybrid power plant was designed to operate between 6:00 am to 22:00 pm, to avoid huge amount of dump power that will be generated from 24 hours plant operation. Also operating the biomass-base plant at lower efficiency risk the plant from underperforming and will require high level of control, which make systems complex. For that reason, excess generation will be stored in battery to be used during the downtime of the power plant (23:00 pm to 5:00 am). From Figure 5 through 11, the green bars indicate the generation by the biomass-base plant, the red bars depict the power generated by the solar PV, whereas the orange bars on the positive axis indicates battery charging and those on the negative axis indicates the discharge.

4.2.1.1 100% biomass-base power plant (S0,B100)

Figure 4 depicts the dispatch of the energy generated by 150 kW capacity steam turbine generator plant designed to meet the load demand of the village by generating 1890 kWh daily at 80% efficiency using 3.57 tons/day of rice husk. An estimated power bank capacity of 340 kWh/day (14706 Ah) is required and 70 kWh representing 4% of total daily generation may be sent as dump load.

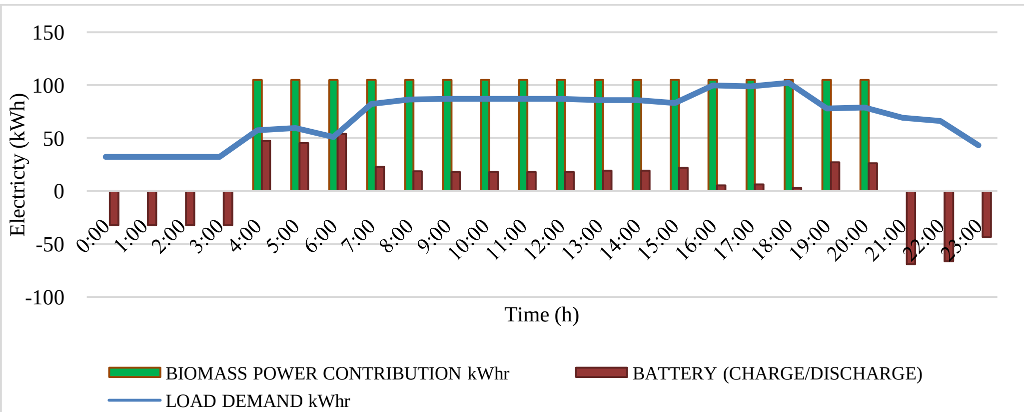

Figure 4: 100% biomass

4.2.1.2 100% solar PV power system (S100,B0)

As for the standalone (100%) solar PV power system, a facility capacity of 444 kW was designed to generate 1755 kWh of electricity per day to meet the demand of the village. Solar power is non-dispatchable and intermittent in nature; as a result, storage system was incorporated. The excess generation has to be stored in batteries and discharged when the solar PV is not generating i.e. during the night time or when there is cloud. A battery capacity of 26552 Ah/day was required to store the excess generation of 650 kWh/day with 30.2 kWh to be sent as dump load.

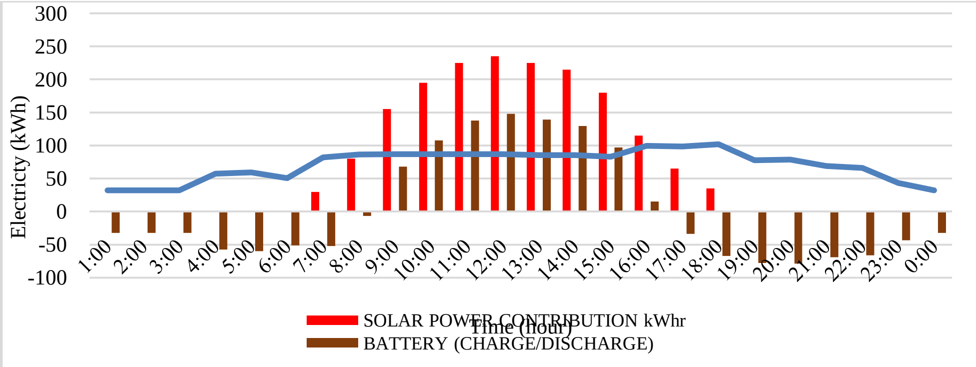

Figure 5: 100% solar PV

4.2.1.3 10% solar PV penetation (S10,B90)

In this case, the solar power contributes 10% of the total load demand, having a facility capacity of 44 kW and generating a total of 175.5 kWh at 15% conversion efficiency. The biomass power plant operates between 06:00 am to 22:00 pm generating a total power of 1680 kWh and off for the remaining hours as can be seen in Figure 6.

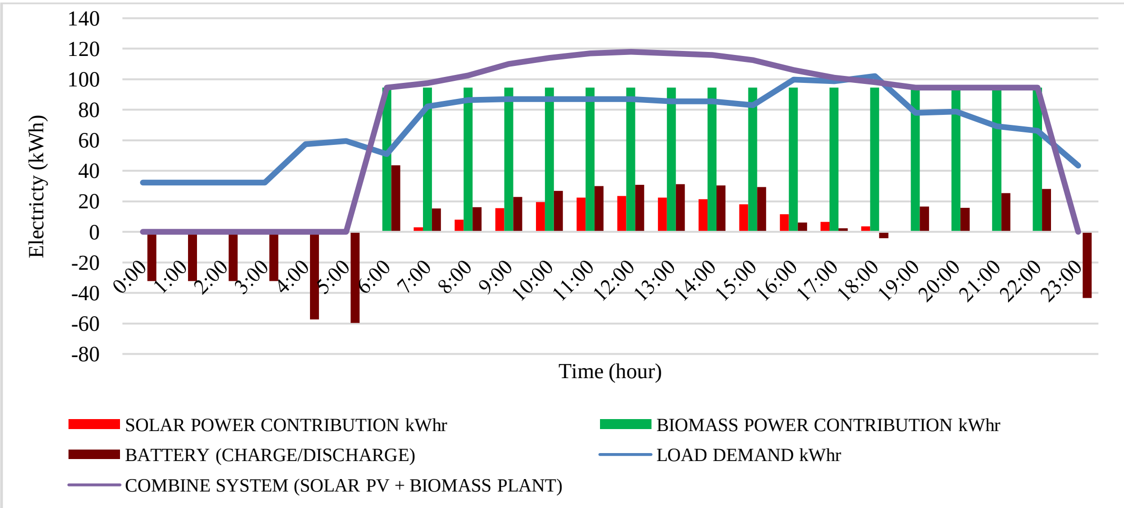

Figure 6: 10% solar PV

The battery bank capacity has to store 290 kWh per day and 77 kWh is considered as dump power. This stored power was used to meet up the generation shortfall and deliver the required power between 23:00am to 5:00 am. A biomass reduction of 0.357 tons/day was experienced when compared to 100% biomass-based power plant.

4.2.1.4 Other penetration strategies

The graphical representation of the dispatch for the other penetration strategies follow similar pattern to that of S10,B90, as such, Table 2 highlight their findings.

Table 2: Result of other penetration strategies

Penetration strategy	Solar PV capacity (kW)	Solar PV Electricity generation (kWh)	Biomass-based plant electricity generation (kWh)	Battery storage requirement (kWh)	Dump load (kWh)	Biomass reduction (tons/day)
20% solar PV penetation (S20,B80)	90	351	1470	296	74	0.714
30% solar PV penetation (S30,B70)	133	526	1260	323	71	1.071
40% solar PV penetation (S40,B60)	180	702	1071	371	68	1.428
50% solar PV penetation (S50,B50)	222	877	892.5	432.4	65	1.854

4.2.2 Configuration II

In this case, biomass power system was designed to operate based on average power (65 kW) to provide part of electricity demand of the village and the solar PV makes available the remaining. Figure 7 depicts the power contributions by the elements of the hybrid system. Solar PV installed capacity of 290 kW is required together with 80 kW steam turbine generators to serve the necessary power demand of the village.

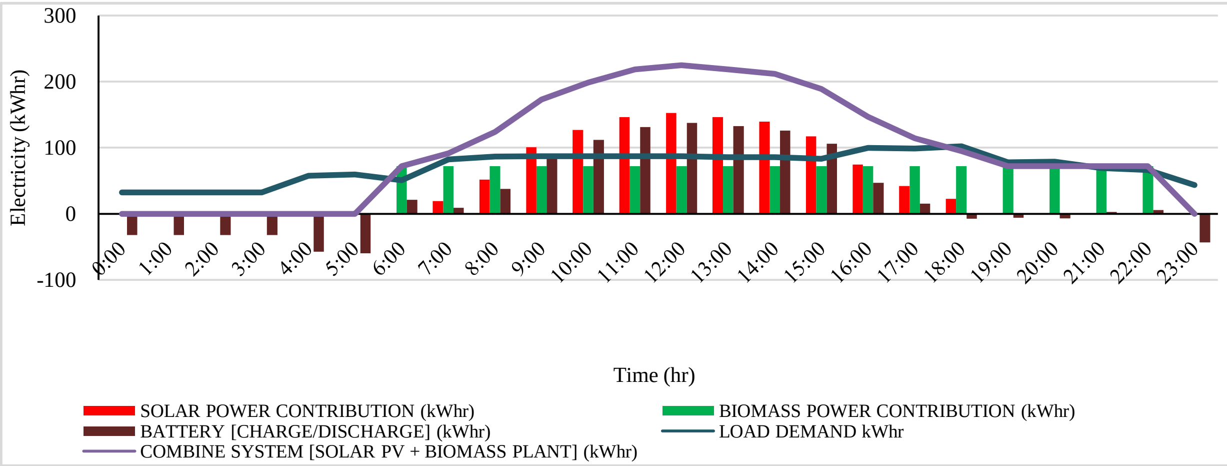

Figure 7: Biomass plant based on average power

The excess power generated by the two is stored in the battery and to be discharged when the two systems are not generating between 23:00 pm and 5:00 am or is not enough to cater for the load demand as in the case of 7:00 am. From the result, it has been found that a battery capacity of 30000 Ah is required to store the surplus generation that can meet the load demand.

4.2.3 Configuration III

Here, the biomass plant provides electricity based on the available feedstock in the village and the solar PV generates the supplement. Figure 9 depicts the contribution by each power system. It has been found that 333 kW solar PV capacity was required to produce 1316.25 kWh of electricity representing the 77% of the village load demand.

International Journal of Advances in Engineering and Management (IJAEM)
Volume 2, Issue 4, pp: 235-244 www.ijaem.net ISSN: 2395-5252

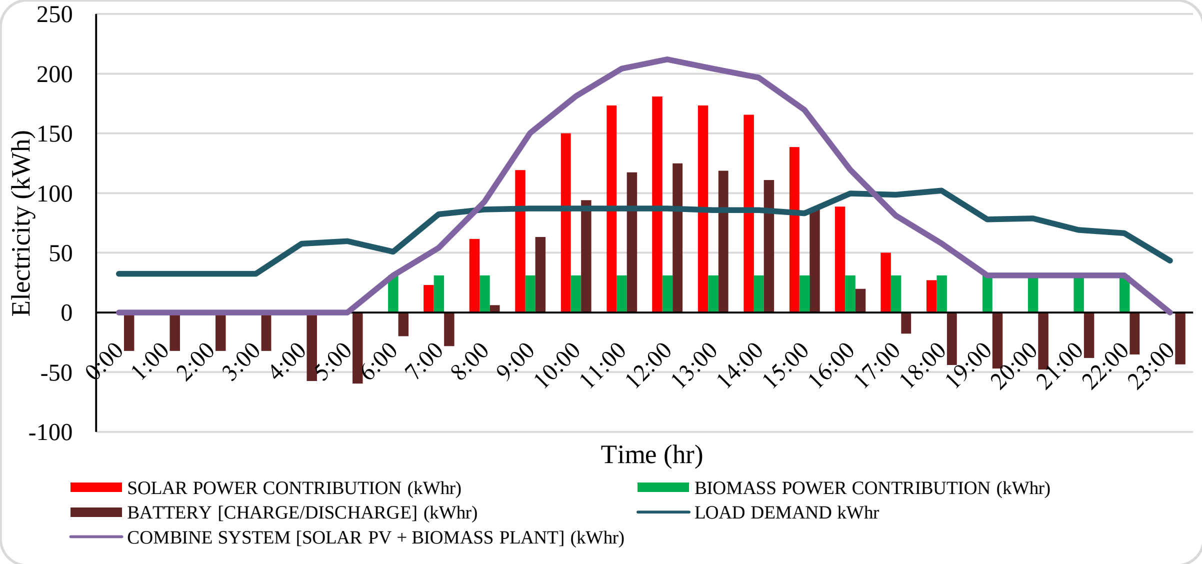

Figure 8: Power generation based on available feedstock

The biomass power plant operates between 6:00 am and 22:00 pm to generate 573.75 kWh, representing the remaining 23%. A battery storage capacity of 25000 Ah is required to store 600 kWh that will be used during load demand deficit. The capacity of the steam turbine generator required is 70 kW.

4.2.4 Hybrid Plant Performance

The performance of the hybrid power system for configuration I was analysed by considering plant use factor, operating factor and the plant capacity factor as presented in Figure 10. It can be seen that the plant operating factor is constant irrespective of the combination; this is because the number of hours of the hybrid plant operation is constant irrespective of the combination. When the plant use factor was plotted, it shows a decrease in relation to increase in the solar PV penetration. This is as a result of decrease in the generation by the biomass plant and the contribution of the solar PV is not equal to the decrease. Equally, for the plant capacity factor, the trend is similar due to same reason as that of use factor.

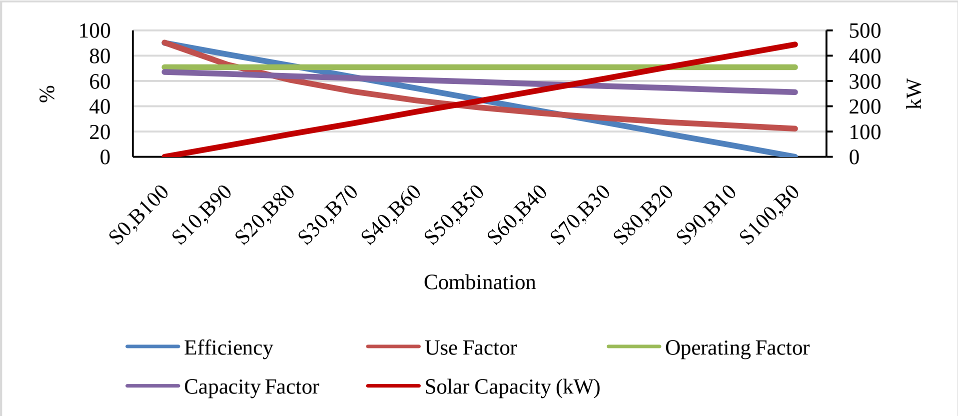

Figure 9: plant performance

In relating the effect of solar PV penetration to the efficiency of the biomass plant for configuration I, it was observed that the efficiency of biomass plant decreases owing to the fact that the generation or utilisation of the plant reduces.

V. CONCLUSION

A solar PV power system integrated with biomass (rice husk)-based power plant to meet the electricity load demand of Duguriyel village was modelled in this research. A dispatch strategy that enabled smooth integration of the power system was designed. It includes battery charging strategy, battery discharging strategy I; and battery discharging strategy II. It has been observed that the plant operating factor is constant irrespective of the combination, whereas, plant use factor and plant capacity factor show decrease in relation to increase in the solar PV penetration.

ACKNOWLEDGMENT

My profound appreciation goes to Petroleum Technology Development Fund (PTDF) and Abubakar Tafawa Balewa University Bauchi for their endless support to the conduct of the research.

REFERENCES

[1]. Soteris, K. A. (2014). Solar Energy Engineering Processes and Systems. Oxford: Academic Press.

[2]. Felix, F. A., & Godoy, S. M. (2006). Integration of alternative sources of energy. New Jersey, Canada: John Wiley & Sons, Inc.

[3]. Bugaje, I. M. (1999). Remote area power supply in Nigeria: the prospects of solar energy. Renewable Energy, 491-500.

[4]. Moghavvemia, M., Ismaila, M. S., Muralia, B., Yangd, S. S., Attarana, A., & Moghavvemie, S. (2013). Development and optimization of a PV/diesel hybrid supply system for remote controlled commercial large scale FM transmitters. Energy Conversion and Management, 542–551.

[5]. Adeoti, O., Oyewole, B. A., & Adegboyega, T. D. (2001). Solar photovoltaic-based home electrification system for rural development in Nigeria: domestic load assessment. Renewable Energy, (24) 155–161.

[6]. Moh'd, S., Ashhab, S., Hazem, K., & Abdallah, A. (2013). PV solar system feasibility study. Energy Conversion and Management, (65) 777–782.

[7]. Oparaku, O. U. (2002). Photovoltaic systems for distributed power supply in Nigeria. Renewable Energy, (25) 31-40.

[8]. REN21. (2015). Renewables 2015 Global Status Report. Paris: RENS21.

[9]. Richard, V. D., Andre, F., & Ad Van, W. (1996). Biomass combustion for power generation. Biomass and Bioenergy, II(4), 27 I-281.

[10]. Jonathan, O. O., Andrew, A., & Jeremy, N. (2014). Design Template for a Small Scale Solar Power Plant in Nigeria. International Journal of Scientific and Research Publications , 4. (11) 1-4.

[11]. Srinivas, T., & Reddy, B. V. (2014). Hybrid solar–biomass power plant without energy storage. Case Studies in Thermal Engineering(2), 75–81.

[12]. Silvia, M. R. (2016, 12 04). CSP: Solar Resource Assessment. Washington DC, United States of America: World Bank/Energy Sector Management Assistance Program [ESMAP].

[13]. Ajai, G., Saini, R. P., & Sharma, M. P. (2011). Modelling of hybrid energy systemdPart I: Problem formulation and model development. Renewable Energy , (36) 459-465.

[14]. Juhari, A. R., Kamaruzzaman, S., Zulkifli, M. N., Azami, Z., & Yusoff, A. (December 29-31, 2007). Optimal Operational Strategy for Hybrid Renewable Energy System Using Genetic Algorithms. 12th WSEAS Int. Conf. On Applied Mathematics, (Pp. 235-240). Cairo, Egypt, : Applied Mathematics.

[15]. IRENA. (2016). Solar PV in Africa: Costs and Markets. Bonn: International Reneawable Energy Agency.

International Journal of Advances in Engineering and Management
ISSN: 2395-5252

IJAEM

Volume: 02 Issue: 01 DOI: 10.35629/5252

www.ijaem.net
Email id: ijaem.paper@gmail.com