Simulation and Optimization of Hybrid Solar PV-Biomass Power Plant for Rural Rajasthan

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Abstract: **Energy scarcity is among the biggest challenge that India is facing now-a-days. So, we are heading towards non-conventional sources of energy which are economical as well as available in ample quantity from nature. Reluctant effects of energy scarcity are clearly visible in today's era, hence there is a desperate need of sustainable energy to reduce our dependency on fossil fuels. We receive Solar energy for 5-6 hours per day and prices of Biomass vary widely. Jointure of Solar energy with Biomass energy complements each other and provides balance to the system by overcoming individual demerits of both. Thus Hybrid Solar PV-Biomass Power Plant supllies continuous and uniform electricity. Rajasthan receives solar radiation of 6-7 kWh/m^2 according to data taken from NREL(National Renewable Energy Laboratory) and is blessed with bulk surplus quantity of biomass all around. Major biomass in Rajasthan that are used for generating electricity are Julie Flora, Guar Stalks, Cotton Stalks and Mustard Husk. The main objective is to find best configuration of Hybrid Solar PV-Biomass Plant in terms of optimum sizing Total Net Present Cost (NPC) and Cost of Energy (COE).**

Keywords: Hybrid, HOMER, NREL, NPC, COE

1. INTRODUCTION

Renewable power generation technologies holds vital importance in preserving natural resources and reducing carbon emissions. Rural electrification by off-grid hybrid energy system may be better than extending the grid because power can be sourced from local renewable resources and due to short distance between generator and consumer there are very little electrical system losses. There is a growing interest in harnessing renewable energy sources since they are available in abundance, pollution free and inexhaustible. However renewable energy has some drawbacks such as poor reliability. We cannot depend totally on renewable energy because solar energy is available for limited number of hours, affected by clouds and biomass such as crops and their residue depends on whether condition and their prices vary on wide scale. These combined drawbacks of solar and biomass energy can be removed by making the system hybrid [1]. Hybridization of solar with biomass will complement each other both seasonally and diurnally and will overcome the drawbacks that they both individually possess [2].

2. LITERATURE REVIEW

In past years in HES(Hybrid Energy Systems), various investigations are carried out in the literature which studies the different aspects of optimization of renewable energy systems especially solar, wind and biomass energy. Sachchidanand Pandey et al. presented a paper on techno economic analysis of HES consisting of PV- Biomass energy for a village in Gorakhpur District and concluded that hybrid system is a viable green technology source for rural electrification[1]. W.S. Ho et al. formulated MILP (Mixed Integer Linear Programing) model for optimization of hybrid Solar- Biomass plant in Iskandar Malaysia (IM) and concluded that it is indeed feasible for IM to rely on HES to satisfy average daily load of 16,900kWH/day[3]. Ali Heydari et al. proposed a paper on optimization of biomass based PV Plant for off grid application using Harmony Search Algorithm and proved that hybrid plant is better than PV only plant for problems of agricultural well electricity demand in Iran[4]. Mahadevan Mahalaxmi presented a paper on Economic and environmental analysis of biomass-solar hybrid system using HOMER Pro Software and concludes that from economic point of view grid only system costs less than HES in present scenario in India[5]. U.K. Rathod et al. presented a paper on Modelling of Hybrid Power System for economic analysis and environmental impact to reduce grid extension and concluded that COE of Hybrid Energy system is lesser than single unit of 250 MW of STP Plant[6] M. Chandel et al. presented a paper on Techno-economic analysis of solar PV plant for garment zone in Sitapura Industirial area in Jaipur. Energy required was 27,481 kWh/day which was completely fed by the rooftop Solar-PV power plant. LCOE comes out to be Rs. 14.94/kWh, making the plant feasible and reliable[7]. Norat Mal Swarnkar et al. presented a paper on Analysis of Hybrid Energy system for supplying residential load by HOMER and RETscreen software in Rajasthan and concluded that the PV-Wind system is feasible with COE of Rs. 16.12/kWh and payback period of 7 years[8]. Anis Afzal et al. presented a paper on Hybrid Renewable energy system for energy security using optimization technique and concluded that sometimes optimal configuration simulated by the software are not practically possible to install, hence compromise has to be made in favour of second or third most economical configuration[9]. Akash Kumar Shukla et al. presented a paper on simulation and performance analysis of 110kW grid connected Solar PV plant for residential hostel building at MANIT, Bhopal and compared four types of PV Technologies and paper concludes that PR of these PV systems varies from 70% to 88% and (a-si) and (CdTe) PV systems have their PRs higher than 75%[10]. Kunal K Jagtap et al. presented paper on Techno Economic modelling with Wind-Solar PV and

Wind-Solar PV-Biomass Hybrid energy system using HOMER Pro software and MATLAB. Paper concluded that the reliability of Wind-Solar PV-Biomass combination is 75.01% with COE of Rs. 4.70/kWh while reliability of Wind-Solar PV combination is 28.37% with COE of Rs. 4.98/kWh[11].

3. STUDY LOCATION

Jaiprakashpura is a small village in Chaksu district, merely 52 km from the state capital of Rajasthan.

Table 1 Study Location Description

Location	Jaiprakashpura, Rajasthan, 303901, India
Latitude	26 degrees 33.15 minutes North
Longitude	76 degrees 1.48 minutes East
Time Zone	Asia/Kolkata

3.1 LOAD PROFILE

Jaiprakashpura village consists of 38 households out of which 26 are electrified[20]. Each house comprises of 4 led bulbs(7W each), 2 fans(60W each), TV (60W), regular appliances. 5 street lights of 15W each and load of village school is also considered. So average load considered in this paper is 190 kWh/day with peak load of 11.5kW and 6 kWh/day with peak load of 0.75 kW for school and street lights.

Figure 1 represents the daily load demand of the village houses, Figure 2 represents daily load demand of the school (9-15 hours) and Figure 3 represents the daily load demand of the street light (0-5 and 19-23 hours).

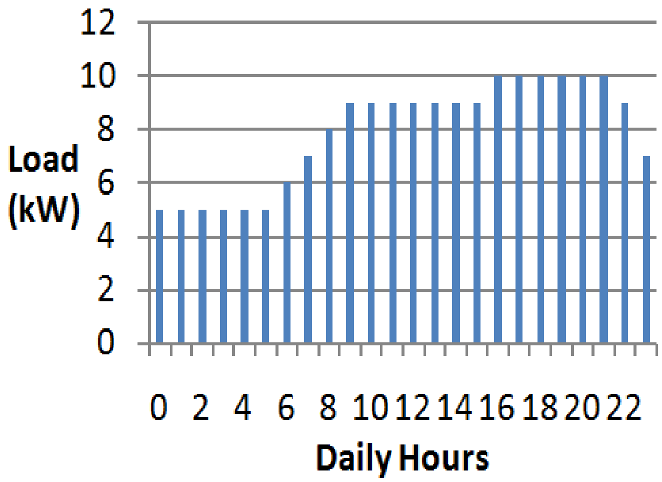

Figure 1 Daily load demand of village houses

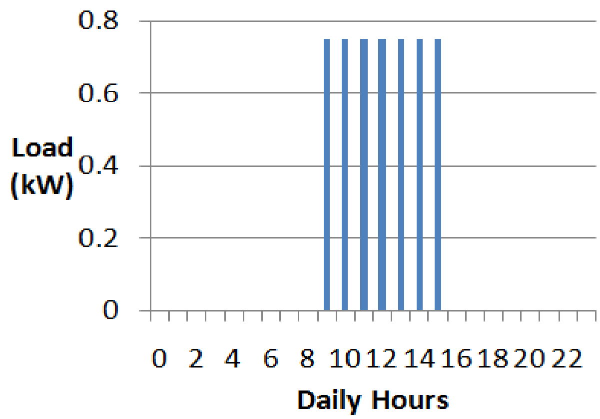

Figure 2 Daily load demand of village school

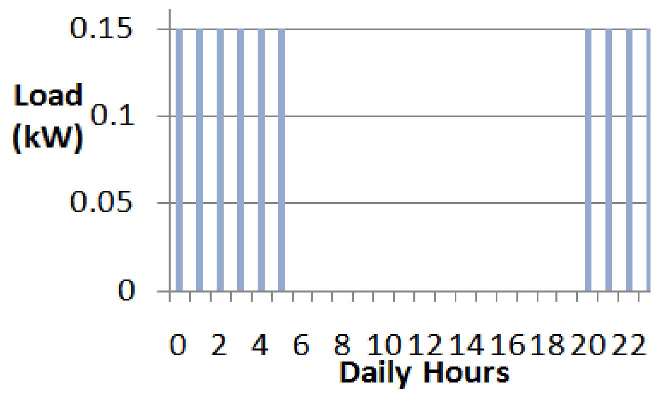

Figure 3 Daily load demand of street lights

3.2 POTENTIAL OF SOLAR ENERGY

Rajasthan is blessed with abundant solar energy and if harnessed efficiently, the state is capable of producing electricity on a large scale[2]. Figure 4 represents daily radiation data and clearness index of the proposed area.

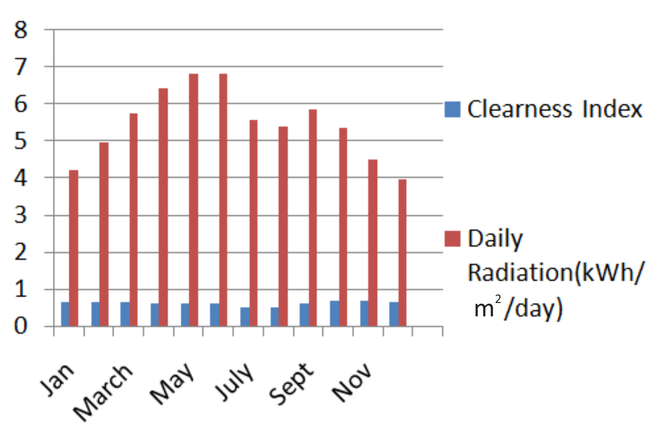

Figure 4 Solar Radiation and Clearness Index Data of Jaiprakashpura[14]

3.3. POTENTIAL OF BIOMASS ENERGY

Biomass is the oldest source of energy known to humans. The term biomass encompasses a large variety of materials, including wood from various resources, agricultural residues, and animal and human waste[3]. In comparison with many renewable energy options, biomass has the merit of dispatch ability. This means that biomass energy is controllable and available when it is required. However, the disadvantage of such system is that the fuel needs to be procured, delivered, stored and paid for. One of the technologies for the extraction of energy from biomass resource is anaerobic digestion. Anaerobic digestion is a series of biological processes in which microorganisms break down biodegradable materials such as livestock manure, municipal wastewater solids, food waste, fats, oils and various other organic wastes in the absence of oxygen. One of the end products is biogas which is used to generate electricity and heat. Biogas produced in anaerobic digesters consists of methane (45–75%), carbon dioxide (25–55%) and trace levels of other gases. For conversion of bio-methane into heat and electricity, a biogas engine–generator is used[4].

Table 2 Potential of biomass in Rajasthan

Major biomass consumed by power plant	Mustard stalks and husk Guar stalks Prosopis Juliflora wood Cotton stalks
Estimated average price of all biomass in 2017 (excluding storage and feeding cost) Rs./ton	Rs. 2797
Average escalation of all major biomass cost	10.50%
Average storage and feeding cost (Rs./ton)	Rs. 220
Biomass storage and handling cost	2%

It is found that, the biomass generated from agricultural activity is 5,26,89,79 tons/year, about 4,78,13,642 tons/year (90.75 %) consumed by local people for fodder, manure, fuel for thermal energy consuming industries, biomass power plants, brick kiln, etc. and about only 48,76,155 Tons/year(9.25%) is available as surplus[15].

4. HOMER PRO SOFTWARE

For the past few years much research has been conducted regarding standalone and grid-connected Renewable Energy (RE) sources all over the world. The HOMER tool has been used to analyze a hybrid electric supply system (hydro/PV/wind/biomass) and to find the optimum sizing of components for a diesel-based RE system [5]. The name HOMER is an abbreviation of Hybrid Optimization Model for Electrical Renewable and it is developed by U.S. National Renewable Energy Laboratory (NREL). HOMER Pro allows simulation of various combinations of Solar PV modules, Wind turbines, and Biomass based generators[12].Working effectively with HOMER requires understanding of its three core capabilities[19] –

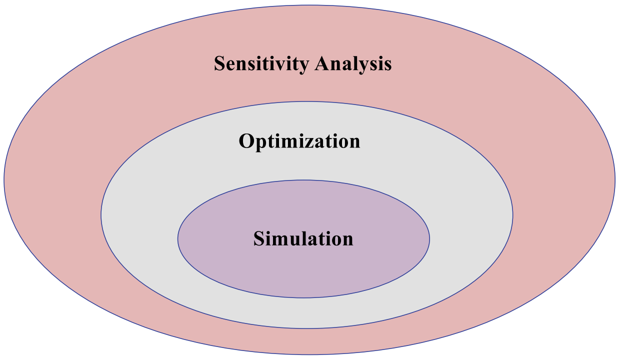

Figure 5 Three capabilities of HOMER

Simulation: At its core, HOMER is a simulation model. HOMER simulates a viable system for all possible combinations of the equipment that is to be considered. Depending on the problem, HOMER may simulate hundreds or even thousands of systems.

Optimization: The optimization step follows all simulations. HOMER sorts all the simulated systems and filter them according to criteria define defined by us, so that we can see the best possible fits.

Sensitivity analysis: This is an optional step that HOMER allows to model the impact of variables that are beyond our control, such as wind speed, fuel costs, etc., and see how the optimal system changes with these variations.

4.1. ECONOMIC MODELING

To represent the life cycle cost of the system, HOMER uses total Net Present Cost (NPC). The total NPC consists of all the costs and revenue that occurs within the project lifetime. The NPC includes the cost of initial construction, component replacement and fuel. For calculation of NPC, HOMER uses the following equation :

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \quad \text{(i)}$$

$C_{ann,tot}$ is the total annualized cost,
i is the annual interest rate (the discount rate),
CRF is the Capital Recovery Factor.
CRF is given by the following equation :

$$\mathrm{CRF}(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad \text{(ii)}$$

Where, i is the annual interest rate,
N is the number of years.
For calculation of COE, HOMER uses the following equation :

$$\text{COE} = \frac{C_{ann,tot}}{E_{prim}+E_{def}+E_{grid,sales}} \qquad \text{(iii)}$$

Where,
$C_{ann,tot}$ is the total annualized cost,
E_{prim} and E_{def} are the total amount of primary and deferrable load that the system serves per year,

5. MODELING OF POWER PLANT

5.1. Modeling of Solar PV Plant

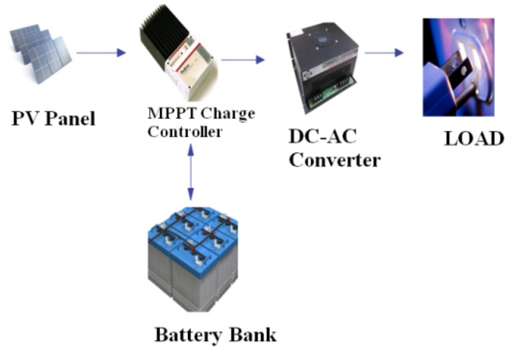

Figure 6 Modeling of Solar PV Plant

5.1.1. SOLAR PV PANEL

It converts sun's rays into electricity by exciting electrons in silicon cells using the photons of light from sun. The power output of the Solar PV panel is given by following equation [13].

$$P_{PV\,out} = P_{NPV} \times \left(\frac{G}{G_{ref}}\right) \times [1 + K_T(T_C - T_{ref})] \qquad \text{(iv)}$$

Where,
P_{PVout} = Output power from the PV cell;
P_{NPV} = Rated power at the reference conditions;
G = Solar radiation (W/m^2);
G_{ref} = Solar radiation at reference conditions (G_{ref} = 1000W/m^2);
T_{ref} = Cell temperature at reference conditions (T_{ref} = 25°C
K_T = Temperature coefficient of the maximum power
(K_T = -3.7 x 10^{-3} (1/°C) for mono and polycrystalline Si.
The cell temperature T_C is given by following equation : T_C
T_{amb} + (0.0256 x G)
Where,
T_{amb} is the ambient temperature.

Practically the Performance Ratio (PR) of the solar panel varies from 70% to 88% [10]. Slope angle for the panel is taken as 26.55 degrees. In this study, the capital cost and replacement cost of PV Panel is taken as 60,000 Rs/kW and 40,000 Rs/kW including cost of MPPT charge controller and mounting structure .

5.1.2. BATTERY BANK

For Solar plant lead acid deep-cycle storage batteries are used for storing the energy generated by PV panels for providing backup to the system when sun is not present. The Storage Capacity (C_{wh}) is calculated using following equation :

$$C_{Wh} = (E_L \times AD)\eta_{inv} \times \eta_b \times DOD \qquad \text{(vi)}$$

Where,
E_L = Total energy demand;
AD = Daily autonomy;
η_{inv} = Inverter efficiency;
η_b = Battery efficiency.
DOD = Depth of Discharge [13].

DOD is the complement of State of Charge (SOC**)**.It describes the degree to which a battery is emptied relative to its total capacity**.** This affects the length of the battery's operational life, as well as the total number of kilowatt-hours it will be able to store over its lifetime. DOD in this paper is taken as 50%. If a lead-acid battery is discharged 100% every time its electrolyte will quickly degrade compared to if it were only discharged to a maximum of 50%. In this study, the capital cost and replacement cost of 1 kWh 12V 100 Ah battery is taken as 9000 Rs.

5.1.3. MPPT CHARGE CONTROLLER

Maximum Power Point Tracker (MPPT) is a kind of charge controller that utilizes the solar panel power to its maximum potential. The MPPT fools the panels by giving output with different voltage and current which will allow more power to go into the batteries [16]. Output voltage and current from the solar panel is monitored by MPPT and operating point that will deliver that maximum amount of power to the batteries will be determined. MPPT can accurately track the always-changing operating point where the power is at its maximum, thus the efficiency of the solar cell will be increased[17]. Many algorithms have been developed for tracking maximum power point of a PV generator such as Perturb and Observe (P&O), Incremental Conductance, and fuzzy logic based tracking techniques. These algorithms vary in effectiveness, complexity, convergence speed, sensors required and cost [18].

5.1.4. POWER CONVERTER

HES that contains both AC and DC elements requires a converter. It acts as both rectifier and inverter accordingly. In this study, capital cost and replacement cost of power converter is taken as 7,000 Rs.

5.2. Modeling of Biomass Plant

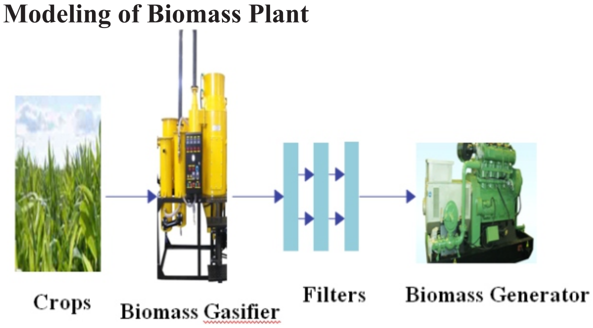

Figure 7 Modeling of Biomass Plant

5.2.1. GASIFICATION

Gasification means the conversion of biomass into mixture of combustible gasses called producer gas by partial oxidation of biomass at high temperatures of about 800°C-900°C The producer gas (with low calorific value) can be directly burned or can be used as a fuel for gas engines [21]. The system consists of updraft or downdraft gasifier[22], gas cleaning filters, and an engine that generates electricity from producer gas. In this paper, cost of biomass generator is considered to be 96000 Rs./kW.

5.2.2. MAJOR BIOMASS IN RAJASTHAN

Biomass dispatch ability depends on the seasonality. Propis Juliflora Wood grows throughout the year and also grows on wasteland, thus suits well for Biomass Energy production. Table 3 represents generation, consumption surplus quantity, and other parameters of four major biomass available in Rajasthan[15].

Table 3 Major Biomass in Rajasthan

Name of Biomass	Mustard Stalks and Husk	Guar Stalks	Propis Juliflora Wood	Cotton Stalks
Generation Point	Agro-Field	Agro-Field	Waste Land	Agro-Field
Generation(tons/year)	61,55,994	45,78,265	2,92,36,340	9,34,938
Consumption(tons/year)	47,36,157	34,10,774	2,56,42,750	5,26,886
Surplus(tons/year)	14,19,837	11,67,491	35,93,590	4,08,052
Cost(Rs./ton)	2,632	2,436	3,020	2,050
Seasonality	Feb-May	Oct-Dec	Throughout the year	Nov-Jan
Calorific Value(Kcal/kg)	3,363	3,784	3,217	3839
Moisture (%)	10.07	11.78	26.21	21.90

5.3. HYBRID SOLAR PV – BIOMASS POWER PLANT

Both Solar Energy and Biomass Energy have their individual strengths and weaknesses. Solar energy requires very less maintenance but is limited only for 5-6 hours per day on an average. Biomass energy has an advantage of dispatch ability but biomass prices vary on a wide scale every year. Solar PV-Biomass Hybrid power plant which will enhance the potential of the plant by balancing their individual strengths and weaknesses.

6. IMPLEMENTATION ON HOMER

6.1. MODEL OF HYBRID SYSTEM

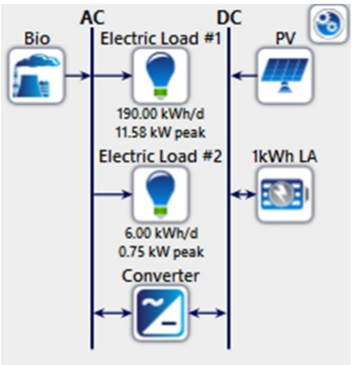

Figure 8 Model of Hybrid System

Figure 8 shows a schematic diagram of Hybrid Solar PV-Biomass-Battery power plant model of HOMER Pro software. As indicated, scaled annual energy consumption is 190 kWh/day with peak load of 11.58 kW for village houses and 6 kWh/day with peak load of 0.75 kW for school and street lights. PV is connected on the DC bus while Biomass Generator is connected to the AC bus and converter acts as both rectifier and inverter. Whenever battery gets discharged below DOD i.e. 50% and there is not sufficient solar energy, then the battery will be charged from Biomass Generator through a rectifier.

6.2. OPTIMIZATION RESULTS AND ANALYSIS

HOMER Pro software simulates every possible system configuration and sorts the feasible ones and arrange them in decreasing order of NPC. Figure 9 represents Optimization Results and the most optimal Hybrid Solar PV-Biomass power plant and only Biomass power plant. Most optimal Solar PV-Biomass hybrid power plant comprises of 4.75 kW solar array, 9 kW biomass generator, 20 lead-acid batteries and 6.9 kW converter with NPC and COE of Rs.11.2M and Rs.12.15. While most optimal Biomass system comprises of 9 kW biomass generator, 32 lead-acid batteries 2.26 kW converter with NPC and COE of Rs. 11.8M and Rs. 12.72. Table 5 represents NPC of the hybrid system considering capital cost, replacement cost, fuel cost and salvage value of all the equipments used.

Architecture						Cost		
PV (kW)	PV-MPPT (kW)	Bio (kW)	1kWh LA	Converter (kW)	Dispatch	COE (₹)	NPC (₹)	Operating cost (₹)
4.75	1.00	9.00	20	6.90	CC	₹12.15	₹11.2M	₹762,739
		9.00	32	2.26	CC	₹12.72	₹11.8M	₹819,711

Figure 9 Optimization Results

Table 5 NPC of Hybrid Solar PV-Biomass power plant

Component(Rs.)	Capital(Rs.)	Replacement(Rs.)	Fuel(Rs.)	Salvage(Rs.)	Total(Rs.)
PV system	285,006	0	0	0	285,006
Biogas Genset	864,000	2,352,792	7,268,851	-5,390	10,480,253
1 kWh Lead Acid Battery	180,000	250,416	0	-22,976	407,439
Converter	48,268	20,479	0	-3,854	64,893
System	1,377,274	2,623,687	7,268,851	-32,221	11,237,591

6.3. Simulation Results of Hybrid Solar PV-Biomass power plant

6.3.1. PV Output

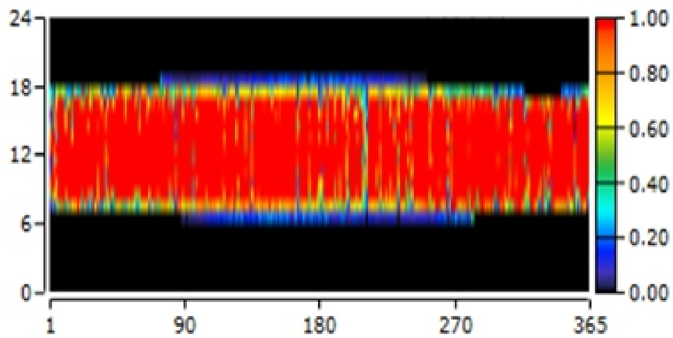

Figure 10 PV Output

Table 6 PV Output Constraints

Quantity	Value
Rated Capacity	4.75 kW
Mean Output	0.42 kW
Mean Output	9.89 kWh/d
Minimum Output	0.00 kW
Maximum Output	1.00 kW
Capacity Factor	8.68 %
Total Production	3611.39 kWh
Hours of Operation	4373 hours/yr

6.3.2. Biomass Generator Output

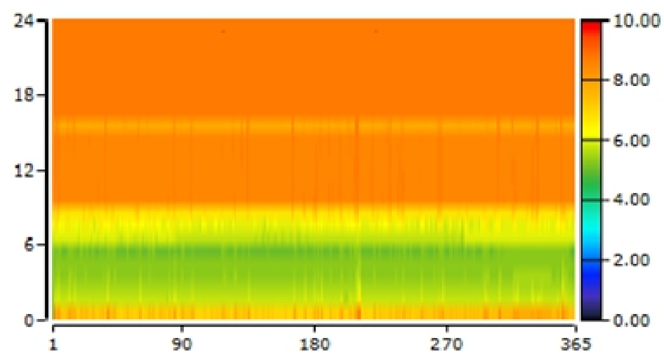

Figure 11 Biomass Generator Output

Table 7 Biomass Generator Output Constraints

Quantity	Value
Rated Capacity	9 kW
Mean Output	7.87 kW
Minimum Output	5.15 kW
Maximum Output	9 kW
Capacity Factor	87.5 %
Total Production	68,946 kWh
Fuel Consumption	208 tons/yr
Specific Fuel Consumption	2.11 kg/kWh

6.3.3. Battery State of Charge

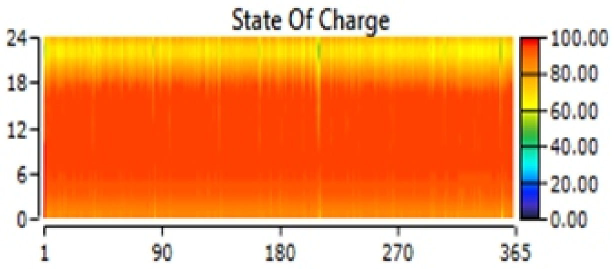

Figure 12 Battery State of Charge

Table 8 Battery Constraints

Quantity	Value
Batteries	20
String Size	4
Strings in parallel	5
Bus Voltage	48
Autonomy	1.23 hour
Energy In	2,475.50 kWh/yr
Energy Out	1,984.72 kWh/yr
Storage Depletion	4.82 kWh/yr
Losses	495.61 kWh/yr
Annual Throughput	2,218.98 kWh/yr

6.3.4. Converter Output

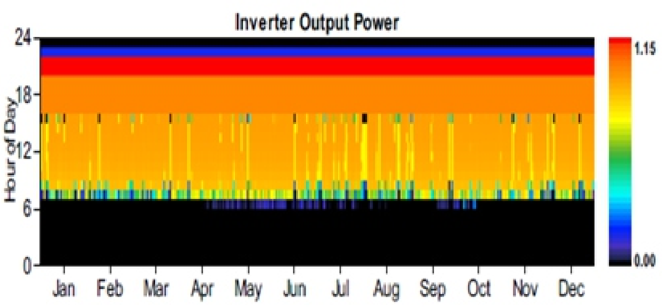

Figure 13 Inverter Output

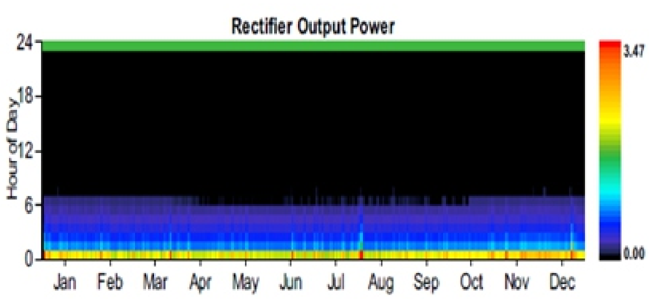

Figure 14 Rectifier Output

Table 9 Converter Output Constraints

Quantity	Inverter	Rectifier
Hours of operation	5,924 hrs/yr	2,829 hrs/yr
Energy In	5,420 Kwh/yr	2,554 Kwh/yr
Energy Out	5,149 Kwh/yr	2,299 Kwh/yr
Losses	271 Kwh/yr	255 Kwh/yr

7. CONCLUSION

In this research work, Hybrid Solar PV/Biomass Plant is modeled, simulated and optimized for Jaiprakashpura village in Rajasthan. HOMER Pro software is used in designing and modeling the optimal system. To serve the daily load requirement of the village the optimal system consists of 4.75 kW PV, 9 kW Biomass generator, 20 Lead-Acid batteries (12V,100Ah) and 6.90 kW Converter. NPC and COE for the optimal system are Rs.11,237,591 and Rs.12.15. Hybrid configuration of the plant is Rs. 0.57 cheaper than only Biomass plant. Thus, it is clearly seen that the hybrid system is feasible and can deliver reliable power at lower rates with zero unmet load.

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