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CHARACTERIZATION AND EVALUATION OF SOLAR-BIOMASS HYBRID MODEL BASED ON THERMODYNAMIC ANALYSIS TO RUN A THERMAL POWER PLANT

Nasir Ul Rasheed Rather[1], Sheen C Moses[2], S K Singh[3], Umakanta Sahoo[4] & Umair Nazir[5]

[1]Research Scholar, Renewable Energy Engineering, Sam Higginbottom Institute of Agriculture, Technology and Sciences, Allahabad, India

[2]Associate Professor, Renewable Energy, Faculty of Engineering and Technology, Sam Higginbottom Institute of Agriculture, Technology and Sciences Allahabad, India

[3]Advisor/Scientist "G", Ministry of New and Renewable Energy, New Delhi, India

[4]Research Scientist, National Institute of Solar Energy, Gurgaon, India

[5]Research Scholar, Renewable Energy, Mewar University, Rajasthan, India

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ABSTRACT

A solar-biomass hybrid power system shall ensure continuous supply of electricity as both energy sources will complement each other. While a solar thermal shall be operated in a day time, biomass plant can be hybridized during night. An energy analysis of regenerative hybrid biomass-solar power plant has been investigated. As per availability of solar-biomass resources, an energy analysis of 5 MW regenerative solar-biomass hybrid power plant with series mode has been analyzed by using heat gain $(\%)$ *from solar & biomass. Month-wise daily average beam radiation has been considered to utilize contribution of solar heat* $(\text{i.e. } 20\%, 40\%, 60\%, 80\%)$ *in the total heat of the proposed hybrid plant. The heat transfer fluid gets heated through parabolic trough collector (PTC) field as per availability of solar resource and remaining heat will take from biomass boiler to maintain the steam at super-heated temperature of* $500\ ^{\circ}\mathrm{C}$*. The recorded regenerative overall energy efficiency of the hybrid power plant is* $35.9\ \%$*.*

KEYWORDS: *Biomass Resources, Solar DNI, Modelling of Hybrid Solar-Biomass Power Plant, Energy Analysis*

INTRODUCTION

Solar thermal power plants (STPP) do not continuously generate power due to daily & seasonal variations and low level of direct normal irradiance (DNI; short transients) for at least 100-150 days in a year in most of the places of this country. Although STPP with storage is one of the solutions to maintain the heat sources owing to DNI variations or short transients but hybridization with STPP is most important for continuous generation of power for fulfilling the energy requirements. So, the choice of Biomass resources is a judicious selection for hybridization with STPP for continuous power generation, which can supplement each other seasonally.

The present installed capacity of total power generation in energy sector of India is 252 GW as on September 2014. This includes, 31.71 GW (12.67%) from renewable energy sources & 4.78GW (1.91%) from nuclear.

Out of 31.71 GW renewable energy, solar power is 8.35% (2.65GW) [29]. To harness the solar energy potential for various applications including power generation, the Ministry launched Jawaharlal Nehru National Solar Mission (JNNSM) with a target of deploying 20,000 MW of grid connected solar power (i.e. both PV and Thermal) by 2022. The launching of the JNNSM symbolizes both and indeed encapsulates the vision and ambition for the future of solar energy. One of the aims of program is to reduce the cost of solar thermal technologies by deploying large solar thermal power generation capacity in various high potential areas of the country [1]. The STPP grid connected power projects are being installed in India. CSP based power plants of total 380 MW capacities have been completed in India using different solar thermal technologies. A 50 MW Parabolic Trough Collectors (PTC) based Solar Thermal Power Plant (STPP) has been commissioned in Rajasthan [2]. AREVA has built solar fields for two 100 MW CSP plants using its Compact Linear Fresnel Reflector (CLFR) technology. The first 100 MW units is the largest solar thermal power project under the JNNSM [3-4]. 1 MW solar thermal power plant with 16 hours thermal storage for continuous operation based on Scheffler dish solar concentrators has been designed at WRST, Mumbai in 2010 with an estimated solar to electric efficiency of about 12 %. The power plant consists of 750 nos. solar Scheffler dishes having a provision of thermal storage. Each dish has 60 m^2 of aperture area. The estimated output of the power plant is electrical power of 1 MW for 8 hrs in day time and electrical power of 800 kW for 16 hours with storage [5].

Scope of Hybrid Biomass-Solar Power Generation

Hybrid biomass-solar power generation has been studied and investigated at several ranges between 5 MW to 110 MW [6-9]. The studies mainly focused on the integration of biomass combustion boiler with solar thermal water vapor cycle [10-13]. The solar field (PTC) energize heat transfer oil to a maximum temperature up to 290 ^oC which is directly supplied to the boiler for making saturated steam. Biomass combustion is used to superheat the steam at 31 bar [14]. A hybrid power plant case study was investigated [15] to provide electricity as well as process heat for running a cold storage. The plant capacity of the boiler is 3 Tons. In another biomass-solar hybrid system, water gets converted into saturated steam at 40 bars and superheat at 520 ^0C through biomass combustion [16]. A grid interactive hybrid solar power plant built by Thermo solar Borges having a capacity of 22.5 MW in Spain is using heat from solar DNI of 18 MJ/m^2/day and remaining heat comes from biomass residue [17-18].

This chapter is mainly focussed on the biomass and solar hybridization where, the biomass boiler is running continuously at full load capacity and solar field is utilizing additional heat to water fluid using heat transfer fluid during sunshine hours. Besides the hybridization, attention is also paid on the state-wise availability of biomass resources and DNI at selected places in India. Solar thermal technologies selection and site selections are most important factor for hybrid CSP-Biomass power generation to supplement with each other seasonally. A case study on solar thermal technologies was carried out for Gujarat [19]. The compact linear Fresnel reflector is the most preferred technology after compound parabolic trough. In India about 380 MW of PTC based power plants have been installed as part of the JNNSM (Phase-II) [20]. Temperature up to 391^{0}C is achieved by using single-axis parabolic trough reflectors on North–South tracking [21].

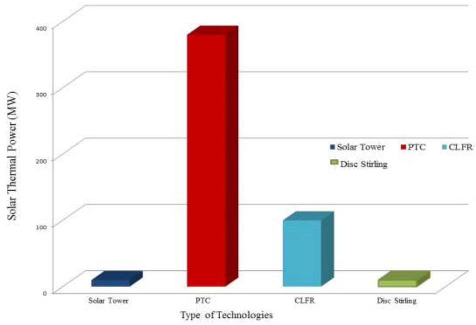

Figure 1: Installation of Solar Thermal Technologies for Power Generation and Process Heat in India

During off-season, the feed stock biomass residue will be used as boiler fuel to generate power from CSP-Biomass hybrid power system for continuous power supply. Biomass fuels are utilized in off-season due to integration of solar thermal power plant with the biomass power. The month wise harvesting period of major biomass production are considered to minimize the savings of biomass fuels [22-23]. It is seen that the harvesting period of rice husk is maximum among major available biomass types. The harvesting period of rice husk is from April to December of every year and Maize stalks harvesting period is from January to March. Therefore, biomass fuels utilization is comparatively high during the low solar DNI period, i.e. January, July, August, September, and December.

For assessing the solar energy potential only, 10% of the total waste land area availability has been considered in the major biomass energy contributing states like Punjab, Uttar Pradesh, Haryana, Maharashtra, Madhya Pradesh, Karnataka, Tamil Nadu, Gujarat, Rajasthan, Kerala, Bihar, Andhra Pradesh, West Bengal, Odisha & Assam. All these States have a potential of 90% biomass power against the total national biomass power in the country.

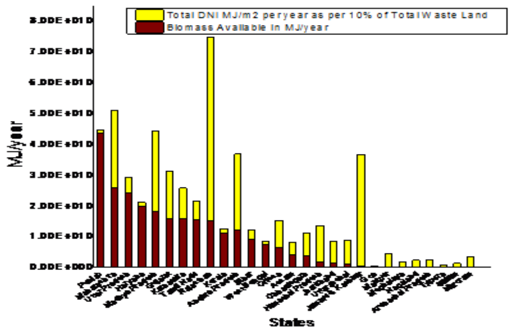

Figure 2: State Wise Solar DNI and Biomass Resources Available in MJ/Year

Taking in the view, UNDP-GEF under MNRE is planning support the hybrid biomass with solar thermal back up for sustainable power supply. About 150 MW of hybrid solar-biomass thermal projects are likely to be taken up initially [24]. The relative utilization of solar and biomass system to run the hybrid power plant is also depicted. The main objective of the plan is to assess the global policy and technological scenario in the commercial scale Biomass-Solar thermal hybrid technologies for power generation in India.

Energy Analysis

First law of thermodynamics is used to analyze the performance of hybrid power plant. The energy equation is mainly defined for the major components of the power plant. The energy, technical, financial analysis has been investigated by several authors [9,28-32].

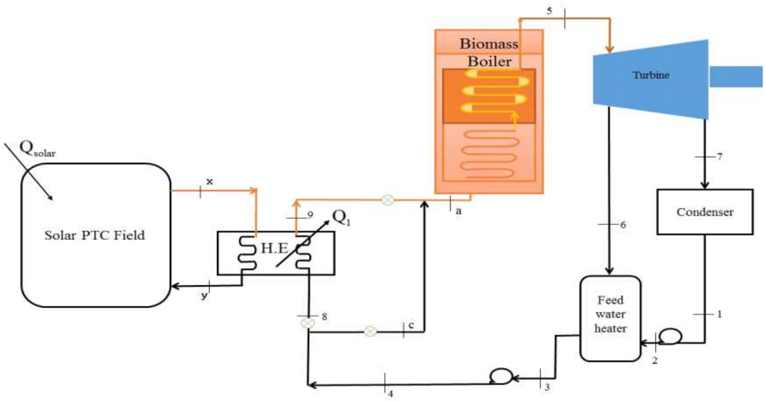

Figure 3: Modelling of Regenerative Hybrid Solar-Biomass Power Plant

Parabolic trough collector transfers the solar beam radiation (I_{bm}) into useful heat (Q_1) at specific mass flow rate of heat transfer fluid (m_{oil}) which circulates through absorber tube. PTC specifications used in this analysis, is shown in Table 1.

Table 1: System Specifications of Parabolic Trough Collector are Used in this Study

Equipment	Input Parameters	Value	Units
Parabolic Trough Collector Field	Area, A_{ap}	31339	m^2
	Optical Efficiency, η_{opt}	0.65	
	a_1	0.1	$W/m^2-{}^0C$
	a_2	0.001	$W/m^2-{}^0C^2$
	Mirror reflectance	0.94	
	Flow rate	28	$kg/\sec$

Useful heat gain (Q_1) from the solar field is expressed as

$$Q_1 = F_R\left[\left(S\times A_{ap} - A_r\times U_L\left(T_x - T_{amb}\right)\right)\right] \quad (1)$$

Where, $S = I_{bm}\times IAM$ (2)

Beam radiation is defined as, $\mathrm{I}_{bm} = DNI\times\cos\theta$ (3)

Generally, the optical efficiency (η_{opt}) of the parabolic trough reflector at normal incidence varies from 0.6 to 0.75. The instantaneous energy efficiency $(\eta_{I,E})$ of the parabolic trough collector is expressed as

$$\eta_{I,E} = \eta_{opt} - a_1 \frac{(T_m - T_{amb.})}{I_{bm}} - a_2 \left[\frac{(T_m - T_{amb.})^2}{I_{bm}} \right] \qquad (4)$$

Where, a_1 is first order coefficient of the collector efficiency $(W/m^2\ {}^0C)$ & a_2 is second -order coefficient of the collector efficiency $(W/m^2\ {}^0C^2)$. Mean temperature of the heat transfer fluid (T_m) defined as

$$T_m = \frac{T_y + T_x}{2} \qquad (5)$$

So, the useful heat gain (Q_1) is also defined as

$$Q_1 = A_{ap} \times I_{bm} \times \eta_{I,E} \qquad (6)$$

The mass flow rate of heat transfer fluid is defines as

$$m_{oil} = \frac{\eta_{I,E} \times A_{ap} \times I_{bm}}{\Delta T \times c_p} \qquad (7)$$

Where, (ΔT) is the temperature difference of heat transfer fluid from PTC field

$$\Delta T = (T_x - T_y) \qquad (8)$$

For Turbine: $W_T = m_w \left[(h_5 - h_6) + (1-\alpha)(h_7 - h_1) \right]$ (9)

Where, 'α' is fraction of steam bleed from turbine.

Condenser: $Q_{C1} = m_w \cdot (1-\alpha) \cdot (h_7 - h_1)$ (10)

Pump: $W_p = m_w \left[(h_3 - h_4) + (1-\alpha) \cdot (h_2 - h_1) \right]$ (11)

HE : $Q_1 = m_w (h_9 - h_8) = m_{oil} (h_x - h_y)$ (12)

Biomass Boiler: $Q_{boiler} = m_w (h_5 - h_a)$ (13)

The overall efficiency of the hybrid solar-biomass (HSB) power plant is expressed as the ratio of output energy to input energy.

$$\eta_{o,HSB} = \frac{W_{net}}{Q_1 + Q_{biomass}} \tag{14}$$

Where the net-work output (W_{net}) of the plant is defined as the difference of turbine work output and pump work input.

$$Wnet = W_T - W_P \tag{15}$$

In this analysis, isentropic efficiency of the pump and steam turbine is considered to be 0.8. The water gets heated in HE and remaining heat is taken from biomass boiler $(Q_{biomass})$ to maintain the quality of steam in superheated condition.

$$Q_1 = m(h_9 - h_4) = m_{oil}(h_x - h_y) \tag{16}$$

The heat is taken from biomass boiler $(Q_{biomass})$ to maintain the quality of the steam at superheated condition (state point $a-5$). At intermittency of day / night cycles, the by-pass arrangement has taken (state point $4-c$) the operation of biomass boiler at full load (100% utilization of heat from biomass boiler).

$$Q_{biomass} = \frac{Q_{boiler}}{\eta_{I,b}} \tag{17}$$

Where;

$$Q_{boiler} = m(h_5 - h_a) \tag{18}$$

The first law efficiency of the biomass boiler is expressed in this study.

$$\eta_{I,b} = \frac{Q_{boiler}}{m_{boiler} \times H.V.} \tag{19}$$

The expanded steam is extracted from the turbine and mixed with condense water to preheat in feed water heater. The steam is expanded at state point 6 and fraction of steam $'\alpha'$ bleed off and was taken into feed water heater. The remaining fraction of the steam $'(1-\alpha)'$ is expanded to the condenser pressure at state point 7. And total flow rate of the mixture leaves from the feed water heater to state point 3 and pumped to the PTC solar field. In intermittency of day / night cycles, the by-pass arrangement has taken at state point $c-a$ to direct pump to the biomass boiler.

RESULTS AND DISCUSSIONS

A detailed study of availability of solar-biomass resources for hybrid power plant with energy analysis of new regenerative hybrid power plant are carried out in this paper. State wise daily average hourly DNI with biomass resources has been used to analyze the variation in the power output. A 5 MW solar –biomass power plant has been analyzed for Gurgaon region, India. For these calculations, the annual average hourly beam radiation is taken from NREL, Ram swami et al &tyagi et al [25-27]. It is observed that, months of January, July, August, September, December are having low level of beam radiation. The heat input from the solar and biomass arrangement are taken in series mode. Fig. 4 represents monthly average hour utilization of heat gain from solar and biomass. The PTC field will heat the heat transfer fluid and pump to the receiver depending upon the availability of beam radiation (i.e.20%, 40%, 60% & 80%) and remaining heat will come from biomass boiler (i.e. 80%, 60% & 40%) for making steam at superheated condition. The monthly daily average utilization of heat taken from solar and biomass are 20-30% and 70-80% respectively. It is seen that, in the month of November solar radiation decreases compared to May due to cosine losses [28]. In this case, remaining heat is used to maintain the hot water to superheated condition from biomass boiler.

Monthly Average of Hourly Heat Utilization from Solar and Biomass

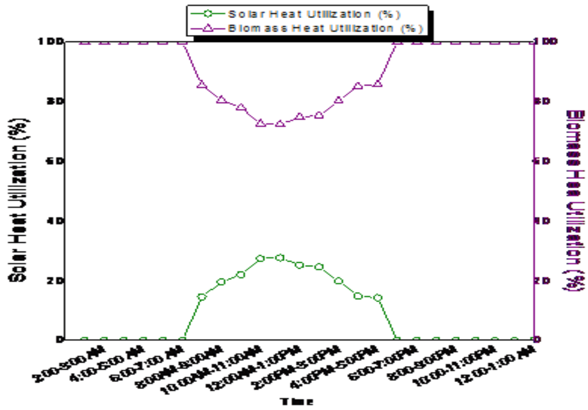

Figure 1: January

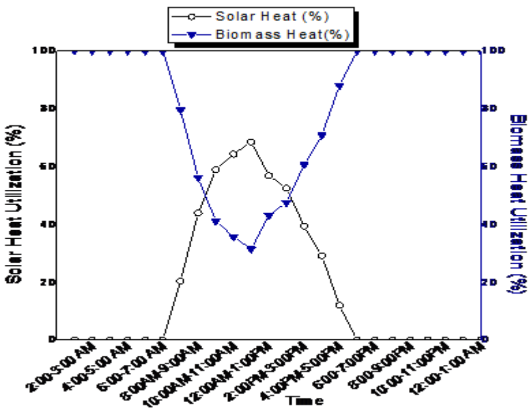

Figure 2: February

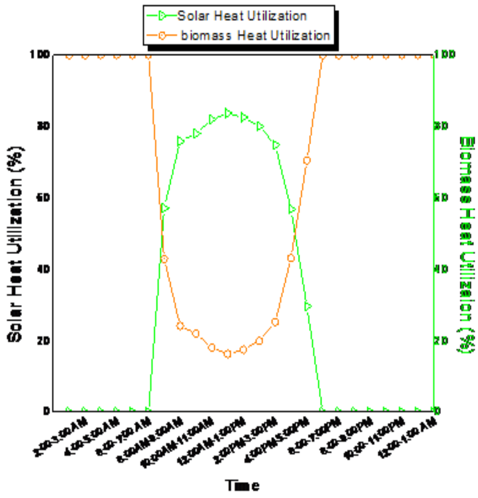

Figure 3: March

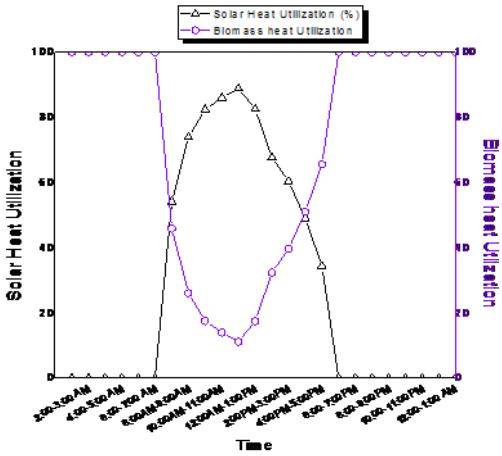

Figure 4: April

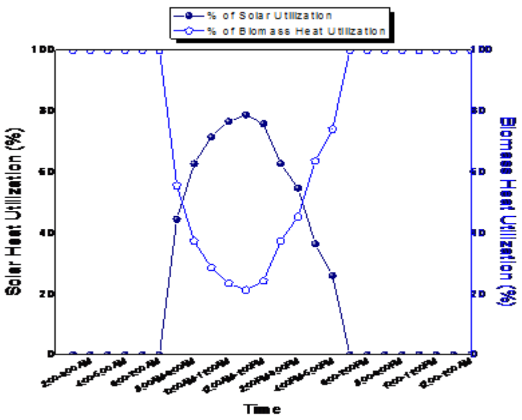

Figure 5: May

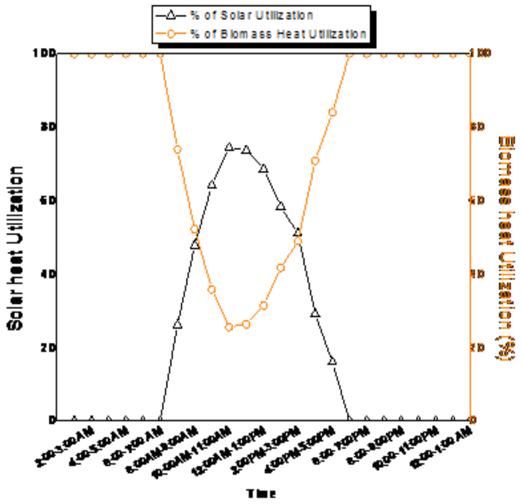

Figure 6: June

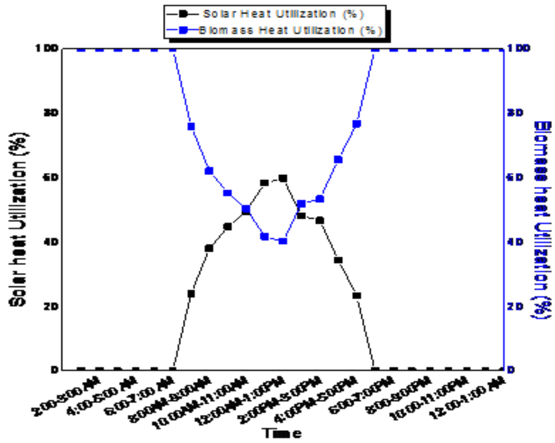

Figure 7: July

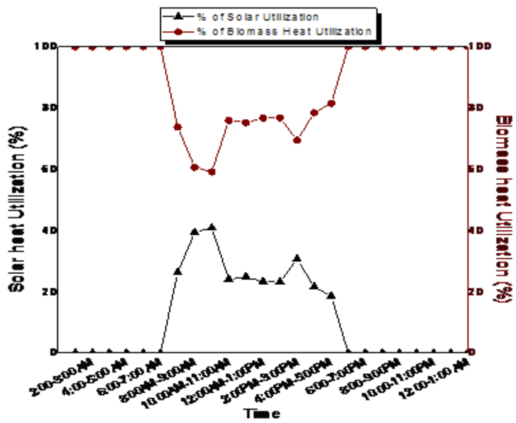

Figure 8: August

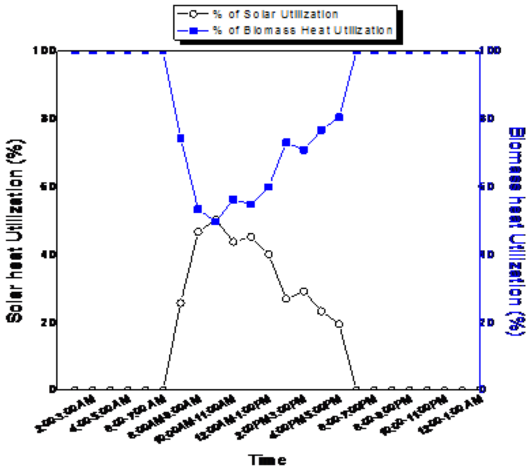

Figure 9: September

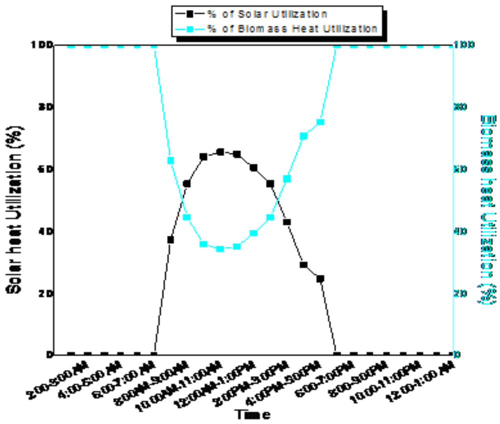

Figure 10: October

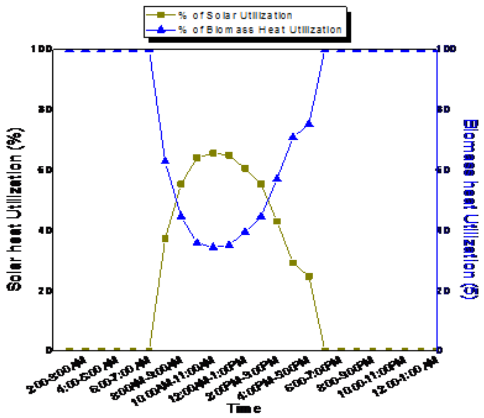

Figure 11: November

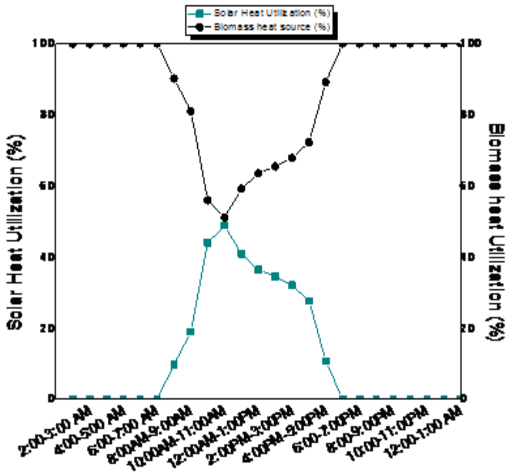

Figure 12: December

CONCLUSIONS

Biomass is an important energy source for hybrid with solar thermal for enhancing power generation capacity in the country. Hybrid solar-biomass power plant becomes a good solution to overcome the obstacles of solar thermal energy. Taking in the view, Govt. of India is making biomass policy to minimize the biomass feed stock in the hybrid power plant for establishing the market for the systems. Apart from financial benefits to the promoters of these projects, the society also benefits due to intangible advantages such as employment generation in rural areas, environmental benefits, distributed power generation, etc. The potential estimated for power generation from the present surplus biomass could be further increased with development of technology and consequent increase in hybrid solar-biomass conversion efficiencies. Further, intensive cultivation of waste and marginal lands for energy crops, with use of advanced plantation techniques, could enable the country to increase its hybrid power potential even more. Government of India has been promoting hybrid solar-biomass based power generation, which will result in commercialization as well as developmental activities in the country for enhancing indigenous capability in this area.

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