Cost Effective Hybrid Energy System Employing Solar-Wind-Biomass Resources for Rural Electrification

A.D.Dhass*, S.Harikrishnan*‡

*Department of Electrical and Electronics Engineering, Rajiv Gandhi College of Engineering

(First Author Mail Address, Second Author Mail Address, Third Author Mail Address)

‡ Corresponding Author; S.Harikrishnan, Department of Electrical and Electronics Engineering, Rajiv Gandhi College of Engineering, Chennai, India, 00-8124166982, ramhkn@yahoo.co.in

Received: 16.01.2013 Accepted: 23.02.2013

Abstract- A hybrid renewable energy system combining the generation of power through solar, wind and biomass systems has been installed to meet the demand of the particular load centre. The selected site (at Pongalur in Tamilnadu, India) has an adequate solar insolation, wind velocity and biomass fuel availability. The wind velocity was varied from 2.82 to 8.04 m/s at selected site and the Biomass gasifier feed stock rates were varied as 135 and 350 kg/hr for 100 and 250 kW, respectively. The technical feasibility of photo voltaic (PV) integrated with wind and biomass systems for the required demand has been evaluated. For all the load demands, the life cycle cost (LCC) and life-cycle unit cost (LUC) for solar-biomass; wind-biomass and PV-wind-biomass hybrid system are always lower than that of stand-alone system. The PV-wind-biomass hybrid system is techno-economically feasible option for rural electrification. The effects of variation for insolation, wind velocity and biomass fuel on energy generation of the hybrid system have also been investigated.

Keywords- Solar Energy, Wind Energy, Biomass Energy, Life cycle cost, Life-cycle unit cost.

1. Introduction

Most of the countries have been focusing on renewable energy systems as they resolve issues like continuous increase in crude oil price, deficit of crude oil, emission of CO_2, etc. In India, renewable energy sources (solar, wind, biomass) play the vital role in bridging the gap between energy supply and demand to the possible extent. Standalone PV system has increased more interests amongst researchers due to increasingly viable and cost-effective candidates for providing electricity to remote areas [1-3]. Thereby, hybrid energy system was accomplished with solar, wind and biomass energy conversion systems. A great deal of research [4-6] was carried out on hybrid energy systems with respect to performance and optimization, and other related parameters of significance. Optimal sizing of standalone PV and wind energy is important to provide a satisfactory energy demand and cost [7-11]. Shen [12] had discussed on the size optimization of solar array and battery in a standalone PV system. Based on the energy efficiency model, the loss of power supply probability (LPSP) of the SPV system was calculated for different size combinations of solar array and battery. For the desired LPSP at the given load demand, the optimum size of the combination was obtained at the minimum system cost.

Elhadidy et al. [13] have studied the feasibility of wind-solar hybrid power system for Dhahran in Saudi Arabia. In this work, a 10 kW wind energy conversion system, 120 m^2 Photovoltaic panel together with a battery storage system and a diesel back-up was taken into consideration for the analysis. An integral type natural convection solar drier with the provision of biomass heating was developed for continuous drying. In another study, it was found that drying time was reduced by 54-60 and 83-84% in solar-biomass hybrid drier in comparison to only solar and open sun drying operation, respectively [14]. The combination of solar-wind hybrid system practically simplifies the storage system. The solar wind generator hybrid system may accomplish to operate under various climate conditions and different configurations [15]. An incorporated renewable energy system combining the production of energy through various types of sources like solar, wind and biomass systems might fulfill the requirement of any remote (rural) area where, grid connection is not available, as seen in Fig. 1.

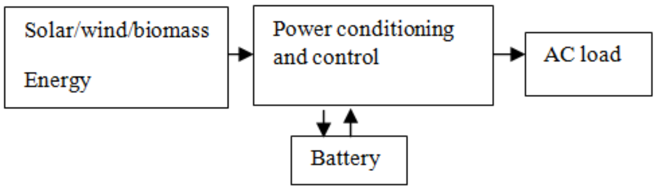

Fig. 1. Schematic diagram of PV-wind and Biomass hybrid system with battery back up

The solar-biomass combined process is feasible to use trigeneration, electricity generation and to process heat. It is economically viable as this system does not require fossil fuel and wood [16]. A new procedure was developed to measure the performance of hybrid solar-wind energy system. Luis et al., had measured power, efficiency, dc power, ac power of a hybrid system and monitored the long term assessment and performance of operation [17]. The combination of solar and wind energy electrical power production was mainly concentrated on heating and cooling under urban areas of Amman and Jordan's climate. The performance characteristics of PV panel were studied under varying load through the variable resistance [18].

Installation cost of individual renewable energy system increases the per unit energy cost is high. So far, it has been discussed only in combinations of one or two renewable energy sources with battery backup. In the present study, a new hybrid renewable energy system has been proposed that can reduce the above problems. This proposed hybrid renewable energy system could achieve minimum per unit energy cost and also, this system can be operated in effective manner. Various combinations of renewable energy sources such as Solar-Wind, Solar-Biomass and Solar-Wind-Biomass have been analyzed for the rural electrification purpose.

2. Theory

The formulae used for calculating the amount of energy extracted from solar, wind and biomass energy sources have been discussed below. Based on this, selection of the combination is best suitable for a typical remote area under the conditions of availability of sources.

2.1. Load Estimation

The loads are main persuade of every system design that is more efficient and reliable. The entire system design is based on the load of the selected region. Also, any seasonal variation might influence the choice of tilt angle or battery size for autonomy. The seasonal variation of loads, peak power requirement, daily and hourly variation of loads, and load profile analysis are very important inputs for designing various power generating systems. Over sizing or under sizing of the system, number of days of autonomy required for battery and life of the subsystems depend mainly on load variations. For inverter selection, one of the important criteria is load variation. Proper input of the load profile is required to make the best design of the power generating systems.

2.2. 3.2. Solar Energy Output

Based on the solar radiation data integrated over a day, the daily solar energy is defined as [19].

$$DailysolarEnergy = hours(h/day)\,X1000\left(W/m^2\right) \quad (6)$$

2.3. Wind Energy

The wind turbine power per surface is given by [19]

$$P_w / S = \left(\frac{1}{2}\right)\rho V^3 \quad (7)$$

S=Swept area (m^2), V=Average wind speed (m/s), $\rho =$ air density (kg/m^3)

Power that wind turbine blades can extract from the wind is given by the following expression [14]:

$$P = 0.5 e_b K \rho A_s V^3 \quad (8)$$

The power generated by the wind machine is the function of wind velocity and it is calculated as follows [11]

$$P_w = R_{Cw}\frac{V^k - V_c^k}{V_R^k - V_c^k} \qquad V_c \le V \le V_R \quad (9)$$

$$P_w = R_{Cw} \qquad V_R < V < V_F \quad (10)$$

$$P_w = 0 \quad (11)$$

Where, R_{Cw} is the rated power for the chosen model of wind machine, V_c is the cut-in speed, V_R is the rated speed and V_F is the cut-off speed. Using equation (11), the power generated by a wind machine of a chosen model can be estimated on an hourly basis and the total power generated in a day by the wind machine, $P_{w,\ tot}$ is computed from the calculated values of P_w.

2.4. Biomass Energy

The 'Biomass Gasification – Electricity Generation' system is a technology which converts any kind of biomass energy with low heat value (such as waste from agriculture and forest and organic waste) into combustible gas and then feeds this gas to a generator for electricity generation. Discovering the method of biomass gasification for electricity generation can solve both problems of effective use of renewable energy and environmental pollution from organic waste. For this reason, the technology of biomass gasification for electricity generation attracts more and more research as well as applications.

2.4.1. Economic Analysis for Energy Generation using Biomass-Gasifier

On comparison of 250kW biomass gasifier with 100kW biomass gasifier, 250kW gasifier has been identified as least value of LCC i.e. Rs 4.08/kWh, against the 100kW gasifier having LCC as Rs 7.11/kWh, given in table 1. So, using higher rating gives lower value of LCC. From the two ranges of biomass gasifiers, the high capacity range has high initial cost but the life cycle unit is low. For the low range of capacity biomass gasifiers the initial cost is low but the life cycle unit cost is high. The capacity of 250kW and 100kW biomass gasifier, varies with feedstock rate, Life cycle cost and biomass fuel consumption per unit generation as given in Table 1. The initial investment is high in 250kW biomass gasifier, but other financial parameters are low. For low capacity of 100kW biomass gasifier, initial investment is low and financial parameters are high.

Table 1. The biomass gasifier comparison for capacity, feed stock rate, biomass consumption, annual fixed cost, annual operational cost, no. of years of operation, cost of operation, no, of units generation and LCC.

Capacity (kW)	Feed Stock Rate (kg/hr)	Biomass Consumption Rate (kg. of wood/kWh)	Fixed cost (in lakhs)	Operating cost (Lakhs/year)	Life Time (Years)	Costof operation (Lakhs/year)	No. of Units Generation (Kwh/year)	Life cycle cost (Rs/kWh)
250	350	1.4	69.52	0.48	7	3.68	9,00,000	4.08
100	135	1.35	60	0.48	7	2.56	3,60,000	7.11

2.5. Life -Cycle Cost Estimate

Life cycle cost (LCC) analysis is the systematic, analytical process of evaluating alternative courses of action early on in a project, with the objective of choosing the best alternative to employ scarce resources. The courses of action are for the entire life of the project and are not for some arbitrary time span (e.g, the 20 –year plan).

2.6. Life Cycle Cost Analysis Methods

For LCC analysis, escalation and discount rates should be considered. The most used method of LCC analysis uses the net present worth method. In this method, costs are estimated in current values, and escalated to the time when they are spent, and then corrected to a present worth using a discount rate. When the inflation and discount rates are equal, LCC can be computed as current values, totaled for the project life and compared. When the escalation and discount rate are different, the escalation and present worth calculations should be performed

$$LCC = \text{Installation Cost} + \text{Maintenance cost} + \text{Insurance cost} \quad (12)$$

3. Results and Discussion

The various design parameters considered for the typical village nearby selected site (Pongalur) in this study are load data, type of wind machine, solar panel, and biomass gasifier, battery and site specifications like wind velocity, biomass fuel availability and solar insolation.

3.1. Load Data

Table 2. Load Data of a Typical Remote Village

Particulars of Load	Power (W)	Quantity	Average Operation(Hrs)	Energy(kWh/day)
House hold Lighting	50	400	12	240
Community Centre Lighting	50	50	6	15
Street Lighting	60	100	12	72
Health Centre	1500	10	6	90
Water Pumps	3700	20	10	740
			Total	1200.00

The energy consumption is depending on the electrical load. Let us consider, one day energy requirement is 1200kWh per day for the selected site (Pongalur). The energy level of electrical load, number of hours of operation as given in Table 2 used on this parameter LCC, and life cycle unit cost has been determined for solar-biomass-wind hybrid combination. The consumption of energy level is different, which depends upon the types of load employed. For example energy consumed for house hold and lighting value is 240kWh/day and for water pumps, 740kWh/day.

3.2. *Capacity of Solar-Biomass hybrid system*

Table 3. Cost for solar and biomass system

Capacity of Biomass gasifier (kW)	Cost of biomass gasifier (Lakhs)	Capacity of solar panel (kW)	Cost of solar panel (lakhs/kW)
100	60	162	3

From the Table 3, it is observed that the capacity of biomass gasifier and solar PV is 100kW which is comparatively high with biomass gasifier. The mixing of combined ratio is (1:1). Fig.2 shows the Life cycle cost analysis for solar-biomass hybrid system energy ratio. Total energy is the combination of solar and Biomass energy. Solar energy contribution increases left to right on x-axis. Similarly, biomass energy fraction increases from 0 to 1 right to left on x- axis, right side of x-axis biomass contribution is zero initially, it is vice versa for solar energy contribution. In this analysis, LCC is Rs 590 lakhs due to the contribution of the solar PV panel and biomass energy contribution is zero. It includes the battery and balance of system components and as a result, it increases the cost. This method can be adopted only if there is more solar irradiation availability in the site. From the Fig. 2, it is noticed that the minimum life cycle cost is observed as 532 lakhs. At this point biomass energy contribution is maximum but, solar PV energy contribution is zero.

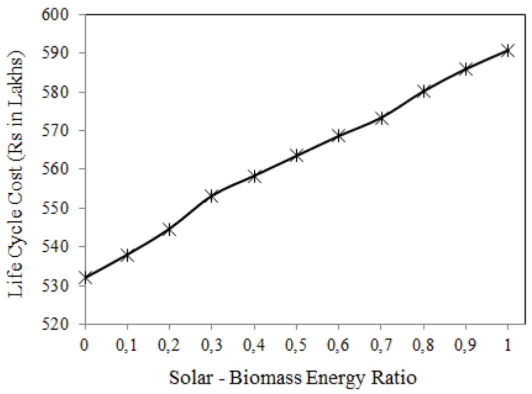

Fig. 2. Variation of Solar to Biomass Energy Ratio

Fig. 3 shows the life cycle unit cost for solar-biomass hybrid energy system. The total energy is the combination of solar and biomass energy and solar energy contribution increases left to right on x-axis. Similarly, biomass energy fraction increases from right to left on x- axis. From the result, it shows that the minimum life cycle unit cost is observed as Rs, 7.34. Solar PV system has high initial cost and low maintenance cost. In biomass gasifier, initial investment is low and running cost is high due to the maintenance for life cycle span of biomass gasifier.

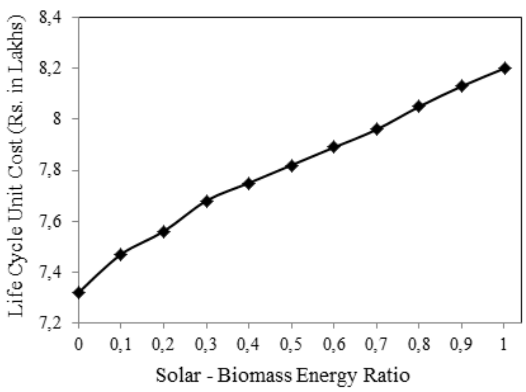

Fig. 3. Variation of Solar to Biomass Energy Ratio

3.3. *Capacity of Biomass-Wind Hybrid System*

Table 4. Cost for biomass and wind system

Capacity of biomass gasifier(kW)	Cost of biomass gasifier (lakhs)	Capacity of wind machine (kW)	Cost of wind machine (lakhs/kW)
100	60	150	67.5

In biomass-wind hybrid system, biomass gasifier and wind machine capacity are 100kW and 150kW, respectively as shown in Table 4. The cost of the wind machine is too high and its maintenance cost is low. The initial investment of the biomass gasifier is low but, maintenance is required for entire life span.

3.3.1. Life Cycle Cost

Fig. 4 shows the life cycle cost of wind-biomass hybrid system. The total energy is the combination of Biomass and wind energy, Biomass energy contribution increases left to right on x-axis. Similarly, Wind energy fraction increases from right to left on x- axis. The cost of the wind machine considered in this study is high and energy generation is also a seasonal one, because unavailability of wind speed level, life cycle cost is high. Biomass gasifier is minimum cost and availability of fuel source is massive. The result shows that the minimum life cycle cost is observed as 85 lakhs. This low life cycle cost is due to the combination of biomass gasifier along with wind machine.

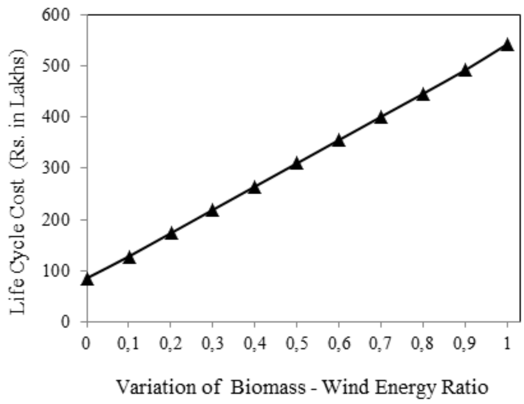

Fig. 4. Variation of Biomass to Wind Energy Ratio

3.3.2. Life Cycle Unit Cost

Fig. 5 shows the life cycle unit cost of wind-biomass hybrid system. The total energy is the combination of Biomass and Wind energy, Biomass energy contribution increases left to right on x-axis. Similarly, Wind energy fraction increases from right to left on x- axis. The result reveals that the minimum life cycle unit cost is found as Rs. 1.18. One unit of energy generated through biomass gasifier is low, because of cheaper availability of wood, rice husk, timber saw and also low labor maintenance cost.

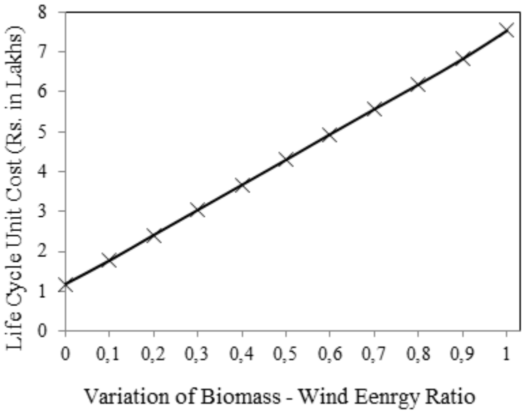

Fig. 5. Variation of Biomass to Wind Energy Ratio

3.4. Variation of Solar and (Wind + Biomass) Energy Ratio

The combination ratio of solar-wind-biomass hybrid system is 1: (0.75+0.25). The capacities of solar PV, biomass, and wind machine are 160kW, 100kW, and 100kW respectively. The life span of operation of this combination is 20 years. The cost analysis details are furnished in Table 5.

Table 5. Cost for solar and (wind + biomass) system

Period of operation	No. of units generated (kWh/20 years)	Solar panel capacity (kW)	Biomass gasifier capacity (kW)	Wind machine capacity (kW)	Cost of solar panel (Rs.in lakhs)	Cost of biomass gasifier (Rs in lakhs)	Cost of wind machine (Rs in lakhs)	Ratio of solar to (wind+ biomass)
20	72,00,000	160	100	100	480	60	45	1: (0.75 +0.25)

3.4.1. Life Cycle Cost

Fig. 6 shows the life cycle cost for Solar to (wind + Biomass) hybrid photovoltaic system. The total energy is the combination of solar and (Wind + Biomass) energy, solar energy contribution increases left to right on x-axis. Similarly, (Wind + Biomass) energy fraction increases from right to left on x- axis. Solar energy contribution is 50% only, and the remaining 50% of contribution from wind and biomass energy. Wind energy of 75% and biomass energy of 25% are contributed to meet the remaining 50% of energy. The result indicates that the minimum life cycle cost is 197 lakhs, at which solar energy Contribution is zero. Contribution of biomass energy is very low and hence LCC of this combination gives the moderate value.

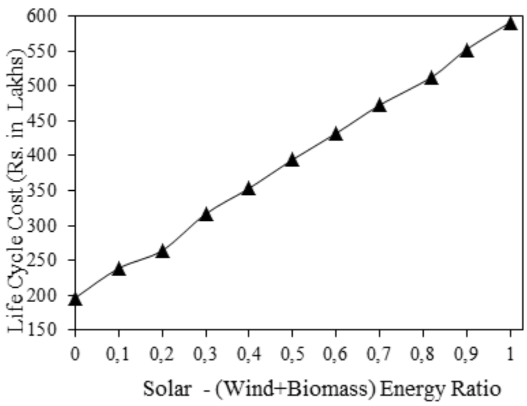

Fig. 6. Variation of Solar to (Wind + Biomass) Energy Ratio

3.4.2. Life Cycle Unit Cost

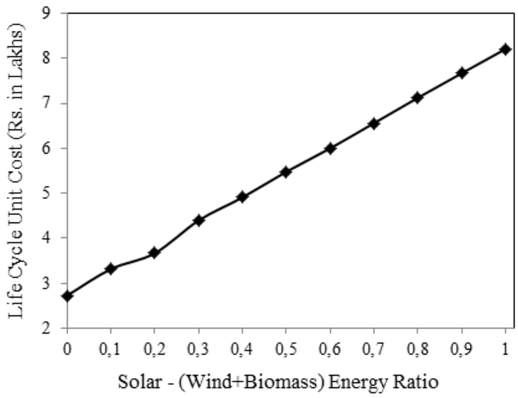

Fig. 7. Variation of Solar to (Wind + Biomass) Energy Ratio

Fig. 7 represents the life cycle unit cost of hybrid photovoltaic system. The total energy is the combination of solar and (wind + biomass) energy, solar energy contribution increases left to right on x-axis. Similarly, (wind + biomass) energy fraction increases from right to left on x- axis. From the Fig. 7, it is observed that the minimum life cycle unit cost is Rs. 2.70. One unit of electrical energy generation cost is high, because it is the combination of solar energy, wind energy and biomass.

3.5. Variation of Solar to (Wind + Biomass) Energy Ratio

The combination of solar, wind and biomass ratio is 1: (0.25+0.75). The capacity of these renewable sources is 160kW for solar, 100kW for wind, and 100kW for biomass gasifier. The total amount of electrical energy generated from this combination is 72 lakh units for 20 years life span. The combination details are furnished in Table 6.

Table 6. Cost for solar and (wind + biomass) system

Solar to (Wind + Biomass) Ratio	No. of units generation (kWh/20 years)	Solar panel (capacity/lakhs)	Biomass (capacity/Lakhs)	Wind machine (capacity/Lakhs)
1:(0.25+0.75)	72,00,000	160/480	100/60	100/45

3.5.1. Life Cycle Cost

Fig. 8 shows the life cycle cost of Solar to (wind + biomass) hybrid photovoltaic system. Total energy is the combination of solar and (wind + biomass) energy, solar energy contribution increases left to right on x-axis. Similarly, (wind + biomass) energy fraction increases from right to left on x- axis. The LCC is not increased gradually, it has some deviation from actual value because of initial cost of both solar and wind energy, while comparing to biomass energy. From this result, the minimum life cycle cost is observed as 428 lakhs, and herein, solar energy contribution is zero.

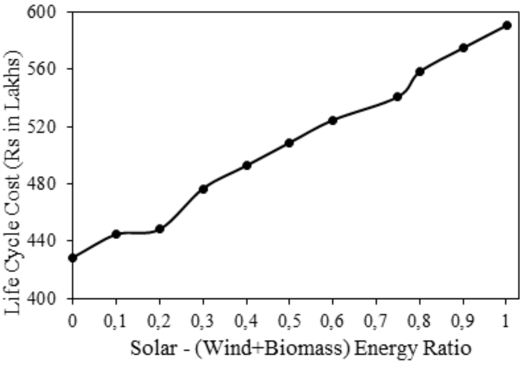

Fig. 8. Variation of Solar to (Wind + Biomass) Energy Ratio

3.5.2. Life Cycle Unit Cost

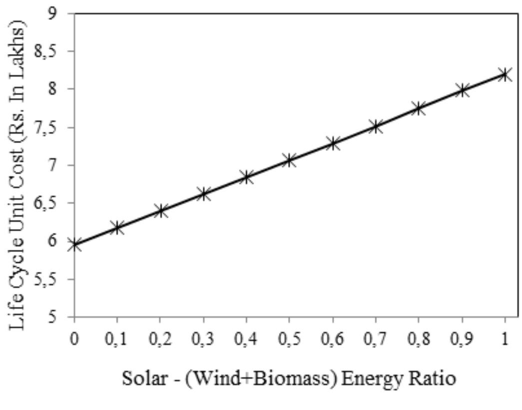

Fig. 9. Variation of Solar to Variation of Solar to (Wind + Biomass) Energy Ratio

Fig. 9 shows the life cycle unit cost of hybrid photovoltaic system. The total energy is the combination of solar and (wind+ Biomass) energy, solar energy contribution increases left to right on x-axis. Similarly, (wind +Biomass) energy fraction increases from right to left on x- axis. This gives the maximum amount for per unit generation of electrical energy. It is found that the minimum life cycle unit cost is Rs. 5.90. At this point, wind energy contribution dominates over the biomass energy.

3.6. Variation of Solar Energy Percentage

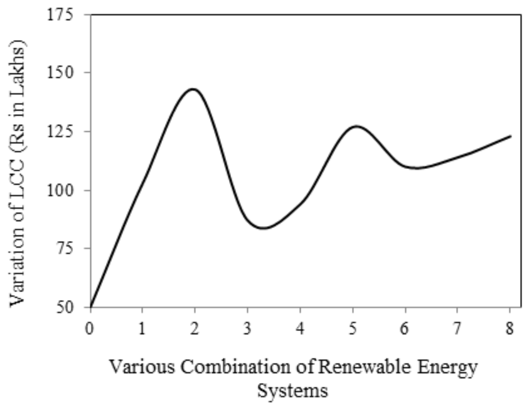

Fig. 10. Variation of Solar Energy Percentage

1. Stand-alone Solar Energy
2. Stand-alone Wind Energy
3. Stand-alone Biomass Energy
4. Solar - Biomass Hybrid System
5. Solar - Wind Hybrid System
6. Solar to (Wind + Biomass) = 1: (0.25 + 0.75)
7. Solar to (Wind + Biomass) = 1: (0.5 + 0.5)
8. Solar to (Wind + Biomass) = 1: (0.75 + 0.25)

The relationship between various combination of renewable energy with respect to solar energy and variation of LCC is shown in Fig. 10. Solar energy contribution varies for each interval of various types of hybrid renewable energy systems which in turn, the LCC of the system is also varied. For example, Solar to (Wind + Biomass) = 1 :(0.25+0.75) hybrid system has achieved low LCC as compare to that of other renewable energy combination. This combination can be implemented in places where the power grid connections are not economically viable. In between the 1 and 2 points, curve attains the maximum peak Rs 140 Lakhs, in addition of stand-alone solar, stand alone wind energy, which gives the electricity, and none of combination has been taken place. Other than this, all are ranges between Rs 100 Lakhs to Rs 125 Lakhs. The lowest range of variation is due to stand-alone biomass energy system is Rs 80 Lakhs.

4. Conclusion

A new methodology has been developed to determine the per unit energy cost of the SPV, wind and biomass hybrid system. Solar and (wind + biomass) hybrid energy system is the ratio of 1: (0.75 + 0.25); the minimum LCC is Rs 194 lakhs and the minimum Life cycle unit cost is Rs 2.74. For the hybrid combination, the range of solar to (wind +

biomass) energy system is the ratio of 1: (0.25 + 0.75); the minimum LCC is Rs 424 lakhs and the minimum Life cycle unit cost is Rs. 5.84 By analyzing the various contribution of hybrid system, wind-biomass gives minimum LCC of Rs, 85lakhs and minimum Life cycle unit cost of Rs, 1.18. From the result, it clearly signifies that there is a variation of contribution of solar energy for each combination of hybrid system. From the various combination of renewable energy system, it can be concluded that the LCC for the Solar to (Wind + Biomass) = 1 :(0.25+0.75) has achieved the low value. Thus, this new hybrid combination system can be suggested to implement in remote places where installation of power grid is too expensive.

Nomenclatures

A	-Area of each panel in m^2
A_s	-Swept area of the wind machine in m^2
E_s	-Daily total energy generated from solar PV panels in kWh
e_b	-Blade efficiency
I_b	-Hourly beam radiation in kW/m^2
I_{bn}	-Solar radiation for beam flux in kW/m^2
I_d	-Hourly diffused radiation in kW/m^2
I_g	-Hourly global radiation in kW/m^2
I_{sc}	-Solar constant in kW/m^2
I_T	-Hourly total radiation in kW/m^2
I_{mp}	-Maximum current (A)
P_f	-Packing factor
P_w	-Power generated by a wind machine in kWh
$P_{s,tot}$	-Energy produced per panel per day for specific type in kWh
$P_{w,tot}$	-Total power generated in a day by the wind machine in kWh
R_b	-Tilt factor for beam radiation
R_d	-Tilt factor for diffuse radiation
R_r	-Tilt factor for reflected radiation
V	-Wind velocity at a specific hub height in m/s
$\bar{V}$	-Mean wind velocity in m/s
V_R	-Rated speed in m/s
V_F	-Cut-off speed in m/s
V_c	-Cut-in speed in m/s
V_r	-Wind velocity at reference height in m/s

Greek Symbols

δ	-Declination
γ	-Surface azimuth angle
β	-Tilt angle
ρ	-Density of air in kg per m^3
η_b	-Battery efficiency
η_m	-Module efficiency
η_{pc}	-Conditioning efficiency

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