Science and Technology for Energy Transition **80**, 31 (2025)

https://doi.org/10.2516/stet/2025008

Innovative Strategies and Technologies for Sustainable Renewable Energy and Low-Carbon Development
Mohan Lal Kolhe and Yang Miao (Guest Editors)

Available online at: stet-review.org

REGULAR ARTICLE OPEN ACCESS

Optimal Forecasting and credibility based Assessment of a standalone system to comprehend Biomass/Wind/Solar in contextual of rural India

Satyam Patel[1,*] and Narayan Prasad Patidar[1,*]

[1] Electrical Engineering Department, Maulana Azad National Institute of Technology, Bhopal, Madhya Pradesh 462003, India

Received: 24 December 2024 / Accepted: 12 February 2025

Abstract. Growing assets in the grid extension in rural areas originates the inspiration for a stand-alone system that is reasonably profitable and resourceful for meeting the load demand. Some places in rural areas are not reachable by the grid connectivity a demand arises for a standalone system. Various renewable energy sources such as biomass, wind, and solar are easily available and accessible in these areas for utilization and production of electricity to fulfill the energy demand. In this paper, the Integration of a biomass system along with wind and solar is considered to form a hybrid power system. This system is designed to meet the load demand of a small residential area located near a village consisting of 35–40 houses where grid supply is not accessible and has a peak load demand of around 100 kW while considering the reliability and economy of the systems. The gasification-based biomass system is integrated with solar and wind, which are used for the production of energy to process the agriculture residues and garbage available, which can be used as a fuel, that is, biomass for this system. The particle swarm optimization technique is used for the optimum size of the microgrid. The levelized cost of energy and the system's annualized cost are key parameters for the economic evaluation of the hybrid system. The levelized cost of energy for the proposed system is found to be lowest for scenario-3 (Biomass-wind) at 0.0711$/kWh while preserving the reliability at 95.0073%, which is used as a system constraint in this study.

Keywords: Biomass gasification, Wind, Solar, Reliability, Economics, Renewable energy resources.

1 Introduction

1.1 Background

The increasing population in the world leads to continuous demand for electrical energy day by day and due to the increasing trend fossil fuels are getting exhausted at a very fast rate due to which there is scarcity of electrical power. There are some factors like global warming and rapid exploitation of non-renewable energy sources for power demand, which lead to abnormal changes in the climatic condition. To deal with such abnormalities associated with the environment, research is being focused on using non-conventional sources of energy to meet the energy crises. According to the current trends, renewable sources of energy like solar, wind, and biomass can be the greatest and most suitable option for the world. Nowadays, biomass can play a great role as a source of power generation worldwide [1].

1.2 Literature review

Production of the Energy from non-conventional sources like solar-photovoltaic along with the energy storage system is found to be very much effective in remote and rural areas in India. However, according to the current scenario, solar photovoltaic along with biomass-based systems is gaining great devotion to providing energy deficiency to the isolated and rural areas where the extension of the grid is found to be very complex [2]. From the Survey, it is found that the cost of energy of each unit for PV generation is found to be high due to low conversion efficiency [3]. Due to this problem, researchers found that wind power generation can be a great option for substantial growth. Various studies and research aim to find the reliable and optimal sizing of wind-based energy production [4, 5]. However, the intermittency of wind and solar-based generation can

* Corresponding authors: satyamp849@gmail.com; nppbhopal@gmail.com

be a major weakness for the system, which leads to great concern about the reliability to meet the load requirement for energy consumers. Therefore, the hybrid system can be formed using wind and solar, which is a suitable and reliable option for one's needs.

The wind-PV-based hybrid system is found to be more economical but there will be a dependency on the energy storage system due to the stochastic and random behavior of both solar and wind energy systems [6, 7] and there is also a great concern about building the relation between the renewable sources and battery storage system for efficient supply of energy at specified load fraction [8]. Electrolytic hydrogen can also be used as energy storage for long-term renewable energy integration [9]. Previous studies found that diesel-generator or battery energy storage systems, like a flywheel, supercapacitor, batteries, fuel cell, pump storage hydro system, can be used as backup for the above hybrid system. However, battery storage system (like lithium-ion, and lead-acid) has high initial costs and raises environmental concerns due to the mining of materials like lithium, nickel, and cobalt. Recycling is one of the major drawbacks of these energy storage systems. Flywheel and supercapacitors have low energy density and high initial cost, while pump hydro storage has the geographical constraints of long lead time and diesel generators, which increases the cost and raises environmental issues, due to which it is not a feasible solution. So, due to advanced technology, the research is now focused on using Biomass or other renewable resources along with wind and solar to minimize the cost and environmental issues. Biomass has the property of carbon neutrality as there is no carbon emission and the energy can be stored in solid, liquid, and gaseous forms. It can be implemented on a small, medium, or large scale, which helps in waste management and is a cost-effective solution.

Garrido *et al.* [10] use agricultural and food processing waste products as fuel for the biomass system and integrate the solar PV-biomass gasification-based hybrid power system to analyze the levelized cost of energy and comparison of the above hybrid system with diesel generators. Chauhan and Saini [11] use Loss of Power Supply Probability (LPSP) as reliability criteria and are able to find the Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) for an integrated renewable energy system based on the Solar-wind-biogas-biomass-battery-Mini Hydro Power. The system is optimized through the discrete harmony search algorithm. M. Kolhe *et al.* [12] used the direct current permanent-magnet motor driven by a PV system tied with the centrifugal pump for the performance at different solar irradiance and equivalent cell temperature for water pumping applications and a grid-tied solar photovoltaic system performance is enhanced by incorporating the high degree of freedom voltage control loop [13]. Ahmad *et al.* [14] carried out the sensitivity and optimization analysis of hybrid power systems to find the potential of electricity generation from solar, wind, and biomass using HOMER software. The cost of energy is measured for both the populated and commercial areas. Arnab Ari *et al.* [15] investigated the hybrid system by using the HOMER software for technical and economic analysis based on reliability and net present cost. Kurukuri P. *et al.* [16] developed an optimum-size microgrid by integrating renewable energy technologies for refining cost efficacy. Pol *et al.* [17] investigated the five Ghanaian communities for technical and financial feasibility for electrification based on agricultural and local waste used as fuel for Energy Production.

1.3 Research gap and motivation

In the present scenario, the production of power from biomass technology is playing a vital role in the world. The production of energy from this technology is increasing day by day, and significantly varies by using different sources of non-conventional nature, along with it, worldwide. A recent trend in the research comprises solar, wind, and biomass to minimize the cost of energy and explore the feasible analysis for a standalone system [18]. In the last 10–15 years, biomass has emerged as a great potential for energy production. Two decades ago, it was the least prioritized and scarce source of energy because of fuel cost as compared to wind and solar, which are freely available in nature without any cost. The countries like India, which are highly populated and have a large agriculture-based economy. So, there is a great potential for residues from agriculture. Previously, agricultural residues like rice and wheat straw were burned, which caused a serious problem for the environment and a major source of pollution. Today, the usage of residues is a significant source of power production in India.

1.4 Challenges

The use of conventional sources of energy for power demand is increasing day by day, due to which there seems a drastic degradation of fossil fuel, which leads to abnormal environmental conditions such as global warming, depletion of the ozone layer, an increase in atmospheric temperature and degradation of air quality, etc. These are the major challenges that humanity is facing due to the usage of non-renewable sources of energy for the contentment of energy necessity. The integration of renewable sources like solar and wind has the challenge of intermittency, but combining these sources in a suitable combination with other renewable sources, such as biomass, can be resolved with the aforementioned combination.

1.5 Contribution

Based on the literature survey, this paper examines the integration of multiple renewable energy resources like solar-PV, wind, and biomass-based hybrid power system while considering reliability and economic evaluation (Fig. 1). The key highlights of this paper are as follows:

(i) The resource availability and power requirement for the selected load are assessed for the rural area.
(ii) Mathematical modeling of the considered system, like Biomass, Solar, and Wind, is presented and described.
(iii) The load model of the system is probabilistic in nature.

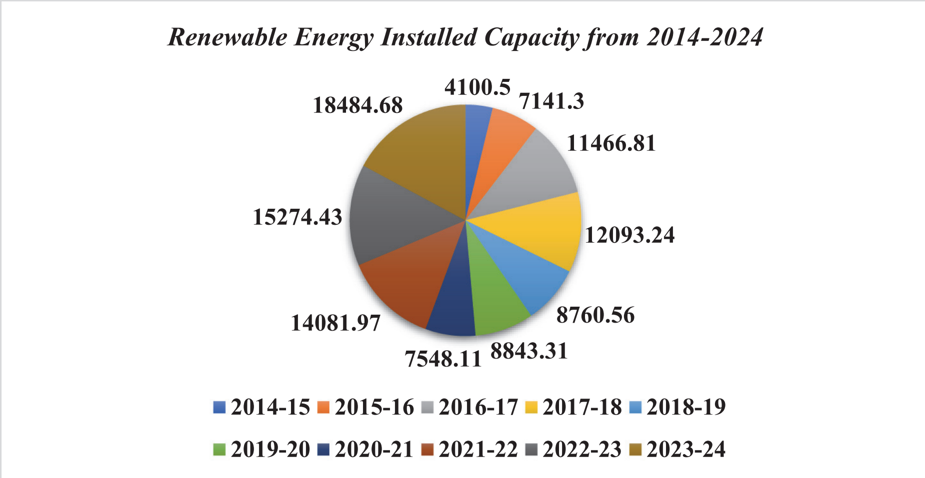

Figure 1. Yearly attainments of renewable energy installed capacity (MW) excluding Large Hydro Power [19].

(iv) The standalone hybrid power system is able to meet the load demand while preserving the economic and reliability criteria.

1.6 Paper organization

The rest of the manuscript is systematized in the following manner. Section 2 of this paper defines the methodology involved in the investigated study. Section 3 deals with the mathematical modeling of the sources that are involved in forming a proposed hybrid power systems. Section 4 provides details about the problem formulation by selecting the appropriate objective function with system constraints. Section 5 discusses the results of the proposed hybrid power archived with a detailed discussion. In the last Section 6, concluding this study with its contribution and significance.

2 Methodology

This work deals with the integration of a Gasifier-based Biomass system along with the Wind and Solar system to fulfill the load criteria of the selected village whose peak load is around 100 kW. The selected load of the small village is located in the Indian states, which have a population of around 1200 persons according to the Election Commission of India (ECI) list. The selected area comes under rural India, having a great potential for agriculture-based residues and cow dung for fulfillment of biomass needs. The area has agricultural land of around 500 acres. This region has great seasonal crops of wheat and grams that are harvested during summer, majorly green gram (also known as kidney bean) which is harvested at the start of the rainy season, and Paddy crops are harvested during winter which can be a great source for our biomass need. Around 2.25 tons of wheat residues and 5–6 tons of paddy crop are available per acre according to certain investigations done in different rural areas of Indian states [20, 21].

On a certain investigation, it is found that some people (around 35–40 houses) from this area moved away from the village due to scarcity of land for housing. These houses are located away from village areas where grid supply is not accessible and near agricultural land where electricity is not available 24/7. So, there is very much demand for electricity for their household purposes. While investigating it is found that each house requires approximately 1.5–2 units per house for their usage. The load profile for this small village area is shown in Table 1. It is also found that daily agricultural residues of approximately 2–2.5 tons per day (*i.e.* from wheat straws, rice husk and straws, maize straws, barley straws, sugarcane residues, grown garbage in the agricultural field, leaves from different plants, soybean husk, banana steam and leaves, tomato plant wastes, leaves from the papaya plants, *etc.*) can be easily available and around 1 ton of cow-dung for biomass as fuel can be utilized.

3 Mathematical modeling of proposed hybrid system

In this paper, biomass, solar-PV, and wind-based standalone hybrid systems are considered for the load fulfillment of a small residential area located near a village. The mathematical component of each is described as follows (Fig. 2).

3.1 Gasifier based biomass system modeling

Energy production from the gasification-based biomass system is an attractive method to generate power from agriculture-based residues, garbage, and other biodegradable waste from houses. As this method utilizes the above-mentioned residues and garbage as a fuel, which costs a low amount for electrical energy production, it becomes economical and environmentally friendly as it does not cause pollution. The fuel for this technology can be stored at a particular place so that there will not be any scarcity in need.

Table 1. Load profile of a small village (consisting of approx. 35–40 houses) [22].

S. No.	Category	Equipment	Power rating (W)
1	Lighting	Indoor lighting	60
		Outdoor lighting	50
2	Cooling	Fans and coolers	200
3	Appliances	Refrigerators and freezers	300
4	Electronics	Television and chargers	160
5	Heaters	Cooking and water	400
6	Miscellaneous	Water pumps	350
		Iron	170
		Music system	60
7	Total estimated load of a house (approx.)		1750

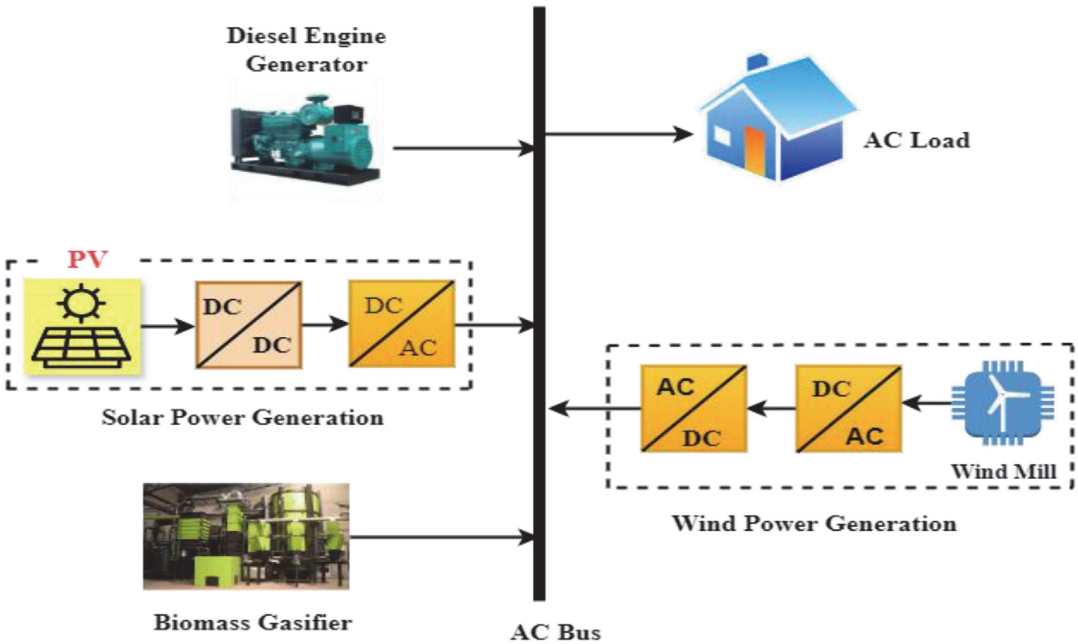

Figure 2. Various components of the proposed standalone hybrid power system.

Gasification, Pyrolysis, and Combustion are the three thermal energy conversion processes from biomass energy production. Out of the above three, gasification is found to be more effective for energy production as it transforms the carbonaceous material into the gaseous product at high temperatures (800–900 °C). The gas produced during this method is called Synthesis Gas, commonly known as Syngas. The Syngas contain Hydrogen (H_2, 30–40%), Carbon monoxide (CO, 20–30%), Carbon dioxide (CO_2, 15–20%), and Methane (CH_4, 10–15%). Gasification can be a direct or indirect process. In the direct gasification process, there is a requirement for a gasification agent (other gaseous compound) to produce the syngas whereas steam is used in indirect gasification for syngas production. The amount of energy generated depends on the caloric value of the fuel, *i.e.* residues from various crops [22–24].

The output power ($P_{\text{BM}}\ (t)$) from the biomass gasifier system can be given as below:

$$P_{\text{BM}}(t) = [\text{BM(tons/year)} * CV_{\text{BM}} * {}_{\text{BM}}{*}1000]/ \\ [365 * 860 * (\text{operating hour/day})], \quad (1)$$

where, BM is the total amount of availability of biomass per year in tons, CV_{BM} is the calorific value of designated biomass, *i.e.* depends on the type of available residues from agricultural crop or garbage, ${}_{\text{BM}}$ is the overall generation efficiency of the gasifier system. So, the annual energy production ($E_{\text{BM}}\ (t)$) of the biomass can be estimated as;

$$E_{\text{BM}}(t) = E_{\text{ac}}(t) \\ = \text{P}_{\text{BM}}(t) * \{365 * 24 * \text{Capacity Factor}\}. \quad (2)$$

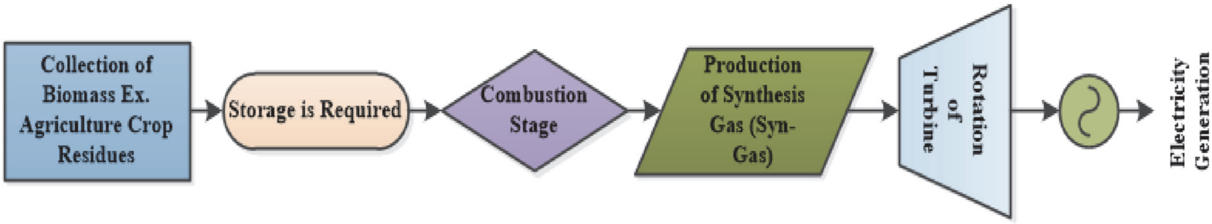

Figure 3. Process of energy generation from the biomass system.

The capacity factor of the gasifier can be calculated as the ratio of the number of hours of operation in a day to the total number of hours in a year, based on that, the total output power and energy can be calculated (Fig. 3).

3.2 Wind system modeling

The speed from the wind turbine is stochastic in nature and is sturdily associated with the time frame. Due to this random behavior in wind speed, the calculation in the evaluation of the reliability of the system becomes a very tedious work. As the speed of the wind is intermittent, so there is a complexity in finding the reliability of the system consisting of renewable sources as compared to that of non-renewable resources. So, to avoid such issues, the study time period is further divided into different time frames and each frame is considered as the time segment of the study. So, each segment of the wind speed can be modeled by a specific probability density function (PDF) which can take the wind speed intermittency into consideration [25–27].

While taking the wind speed as a random variable, each segment of the wind speed can be modeled by using the two-parameter Weibull distribution function:

$$f_{\mathrm{wb}}(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^{k}} \quad \text{for } v > 0,\ c > 1 \text{ and } k > 1, \quad (3)$$

where,

v = Speed of wind (m/s),
$f_{\mathrm{wb}}(v)$ = PDF of Weibull for speed v,
c = Scaling Parameter of Weibull PDF (m/s),
k = Shaping Parameter Weibull of PDF (constant).

μ_{wb} is the mean and the σ_{W} is the standard deviation the Weibull probability density function can be calculated as

$$\mu_{\mathrm{wb}} = c \cdot \Gamma\left(1 + \frac{1}{k}\right), \quad (4)$$

$$\sigma^2_{\mathrm{wb}} = c^2 \cdot \left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)\right]. \quad (5)$$

where Γ represents the gamma function.

As the Weibull distribution is a continuous function discretization is necessary for each segment of time. Let us consider that W_{wb} is the discrete form of $f_{\mathrm{wb}}(v)$ and is given as [27]:

$$W_{\mathrm{wb}} = \{v_r,\ P(v_r) : r = 1 : N_v\}, \quad (6)$$

where

$\mathrm{W_{wb}}$ = Discrete form for wind speed PDF,
V_r = rth state of wind speed (m/s),
$P(v_r)$ = rth state probability for speed of wind,
N_v = Number of states considered for discretization of wind speed.

rth state probability of wind speed can be estimated as [27]:

$$P(v_r) = \begin{cases} \displaystyle\int_0^{\frac{(v_r + v_{r+1})}{2}} f_{\mathrm{wb}}(v)\cdot \mathrm{d}v & \text{for } r = 1 \\ \displaystyle\int_{\frac{(v_{r-1} + v_{r+1})}{2}}^{\frac{(v_r + v_{r+1})}{2}} f_{\mathrm{wb}}(v)\cdot \mathrm{d}v & \text{for } r = 2 \text{ to } N_{v-1} \\ \displaystyle\int_{\frac{(v_{r-1} + v_{r+1})}{2}}^{\infty} f_{\mathrm{wb}}(v)\cdot \mathrm{d}v & \text{for } r = N_v. \end{cases} \quad (7)$$

3.2.1 Power output from the wind turbine

The output power of a wind turbine depends on its rated capacity generating unit (WT_{rated}), rated speed (V_r), cut-in-speed (V_{ci}) and cut-out-speed (V_{co}). The output power of the wind turbine is characterized by a wind speed *versus* power output curve, shown in Figure 4 (Tab. 2).

The mathematical formulation for power output (WT_{power}) from the turbine corresponding to V can be given as [26]:

$$WT_{\mathrm{power}} = \begin{cases} 0 & \text{for } 0 \le V \le V_{\mathrm{ci}} \\ \left(a + bV + cV^2\right) WT_{\mathrm{rated}} & \text{for } V_{\mathrm{ci}} \le V \le V_r \\ WT_{\mathrm{rated}} & \text{for } V_r \le V \le V_{\mathrm{co}} \\ 0 & \text{for } V \ge V_{\mathrm{co}} \end{cases} \quad (8)$$

where,

$a,\ b,\ c$ are constant,
V_{ci} = cut-in speed,
V_{co} = cut-out speed,
V_r = rated value of speed,
V = speed at some particular instant.

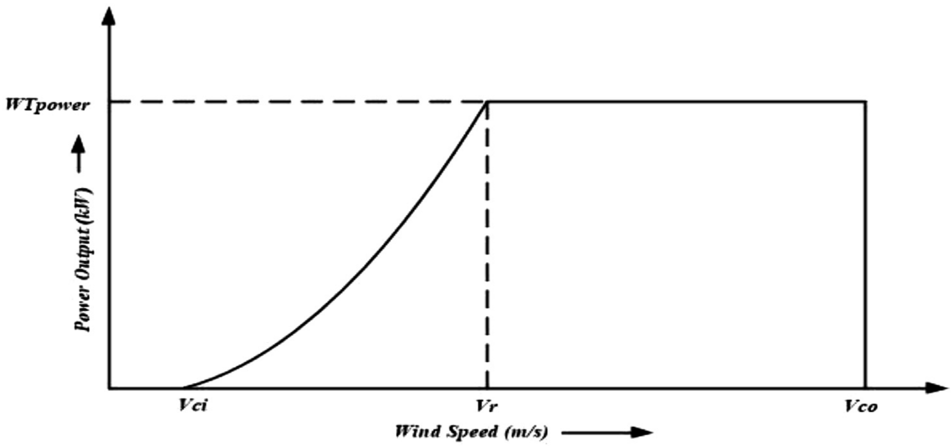

Figure 4. Wind speed characteristic [26].

Table 2. Specification of wind turbine unit.

S. No	Wind turbine module characteristic	Values
1	Rated power (kW)	20
2	Cut-in speed (m/s)	2.5
3	Rated speed (m/s)	10
4	Cut-out speed (m/s)	25
5	Hub height (m)	50

3.3 Solar system modeling

The solar irradiance from the sun is random in nature so it can be modeled using a suitable probability density function. Therefore, solar irradiance from the sun for a particular time frame can be modeled using the beta distribution [11, 14, 17, 28]:

See the Equation (9) bottom of the page

where,

si = radiations from the sun $(\mathrm{kW/m^2})$,
$f_{\mathrm{BD}}(\mathrm{si})$ = PDF of beta for si,
$a,\ b$ = parameters of beta distribution,
Γ = Gamma function.

μ_{BD} is the mean and σ_{BD} is the standard deviation of the beta PDF and written as:

$$\mu_{\mathrm{BD}} = \frac{a}{a+b}, \tag{10}$$

$$\sigma_{\mathrm{BD}} = \sqrt{\frac{ab}{(a+b+1)(a+b)^2}}. \tag{11}$$

From the above two equations a and b can be given as:

$$b = (1-\mu_{\mathrm{BD}})\left[\frac{\mu_{\mathrm{BD}}\,(1+\mu_{\mathrm{BD}})}{\sigma^2} - 1\right], \tag{12}$$

$$a = \frac{\mu_{\mathrm{BD}} \cdot b}{(1-\mu_{\mathrm{BD}})}. \tag{13}$$

As the beta distribution is a continuous function discretization is necessary for each segment of time. Let us consider that S_{BD} is the discrete form of $f_{\mathrm{BD}}(\mathrm{si})$ and is given as [25, 26]:

$$S_{\mathrm{BD}} = \{s_q,\ P(s_q) : q = 1 : N_{si}\}, \tag{14}$$

S_{BD} = discrete from of solar radiations PDF,
s_q = qth state of solar radiations (kW/m),
$P(s_q)$ = qth state Probability of solar radiations,
N_{si} = number of states considered for solar radiations.

qth state probability of solar irradiance can be estimated as:

$$P(s_q) \begin{cases} = \displaystyle\int_0^{\frac{(s_q+s_{q+1})}{2}} f_{\mathrm{BD}}(\mathrm{si})\cdot \mathrm{d}s & \text{for } q=1 \\ = \displaystyle\int_{\frac{(s_{q-1}+s_q)}{2}}^{\frac{(s_q+s_{q+1})}{2}} f_{\mathrm{BD}}(\mathrm{si})\cdot \mathrm{d}s & \text{for } q = 2 \text{ to } N_{\mathrm{si}}-1 \\ = \displaystyle\int_{\frac{(s_{q-1}+s_q)}{2}}^{\infty} f_{\mathrm{si}}(\mathrm{si})\cdot \mathrm{d}s & \text{for } q = N_{\mathrm{si}} \end{cases}. \tag{15}$$

$$f_{\mathrm{BD}}(\mathrm{si}) = \begin{cases} \dfrac{\Gamma(a+b)}{\Gamma(a)\cdot\Gamma(b)}\mathrm{si}^{(a-1)}\cdot(1-\mathrm{si})^{(b-1)} & \text{for } 0 \le \mathrm{si} \le 1,\ a>0, \text{and } b>0 \\ 0; & \text{otherwise} \end{cases}, \tag{9}$$

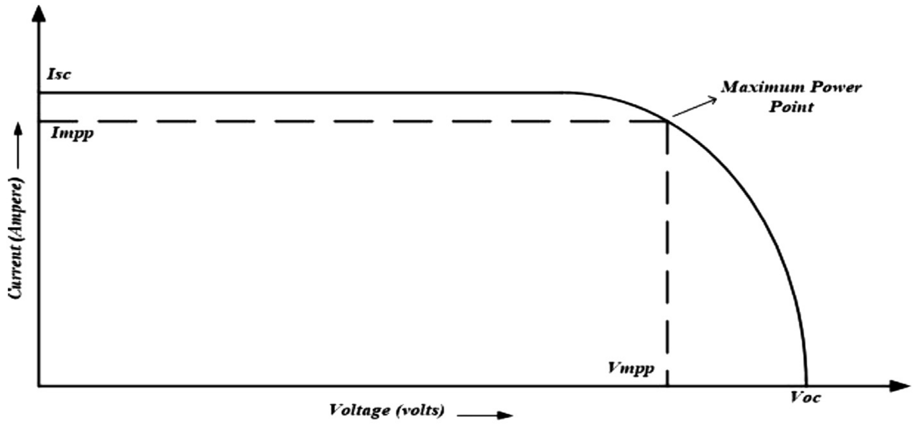

Figure 5. *I-V* characteristics of PV module [27].

3.3.1 Power output from solar irradiance

The output power of a solar cell depends on the number of solar radiations that fall on the solar cell. The process converts the sun irradiance into a basic unit called a photovoltaic cell, which is responsible for converting irradiance into electrical energy. In this conversion system, photons from the sun are absorbed by a solar cell and release the electron to provide the electrical direct current in a closed path. In a PV module commonly known as a solar cell, a large number of PV cells are connected in series, which has a typical low voltage of around 0.5 V.

The power output of solar PV is given by the current-voltage (*I-V*) characteristic curve. The parameters listed below are given in the datasheet provided by the constructor of the PV module (Fig. 5, Tab. 3):

I_{SCC} = short circuit current (A),
V_{OCV} = open circuit voltage (V),
I_{mpp} = current at maximum power point (A),
V_{mpp} = voltage at maximum power point (V).

Current and voltage for corresponding radiation and temperature can be calculated by using the following relations mentioned below:

$$T_{\text{cell}} = T_{\text{Amp}} + s \cdot \frac{N_{\text{OT}} - 20}{0.8}, \tag{16}$$

$$I(s) = s[I_{\text{SC}} + K_{\text{isc}}(T_{\text{cell}} - 25)], \tag{17}$$

$$V(s) = V_{\text{OC}} - K_{\text{VOC}} T_{\text{cell}}, \tag{18}$$

where,

T_{cell} = cell temperature (°C),
T_{Amb} = ambient temperature (°C),
s = solar radiation (W/m^2)
I_{SC} = short circuit current of PV module (A),
K_{isc} = short circuit current temperature coefficient (A/(°C)),
V_{OC} = open circuit voltage (V),
K_{VOC} = open circuit voltage temperature coefficient (V/°C).

Now, from the above relations it can be said that the current and voltage are varying in accordance with the solar radiation. Therefore, the value for maximum power consisting of the N number of arrays can be calculated as:

$$P_{\text{PV}}(s) = N \cdot \text{FF} \cdot V \cdot I, \tag{19}$$

where FF represents the fill factor characterized by the materials of PV modules

$$\text{FF} = \frac{V_{\text{mpp}} \cdot I_{\text{mpp}}}{V_{\text{OC}} \cdot I_{\text{SC}}}. \tag{20}$$

3.3.2 Renewable resources modeling

Now, the Renewable Energy Source Model (RESM) can be obtained by combining the probabilistic model generated by taking all the possible combinations of solar irradiance and wind speed discretization.

Therefore, the renewable energy source model for a particular *i*th time segment can be stated as:

$$\text{RESM}^i = \left[R_k^i,\ P\left(R_k^i\right) : k = 1 :\ N_{\text{RESM}}\right]. \tag{21}$$

The number of states in RESM is given by:

$$N_{\text{RESM}} = N_s * N_v, \tag{22}$$

where,

RESM^i = discrete PDF RESM for *i*th time frame,
R_k^i = vector consisting of solar radiation and wind speed in *k*th arrangement of RESM^i,
$P\left(R_k^i\right)$ = probability associated with R_k^i.

3.3.3 System hardware availability model

The System or Complete Hardware Availability Model for renewable resources can be formed by combining the individual availability model of the wind turbine unit and the PV array unit. These availability models are based on the Forced Outage Rate (FOR) of both types of generating units and hold as it is for all-time segments.

Table 3. Specification of PV module.

S. No	PV module characteristics	Value
1	Peak wattage (W)	75.00
2	O_C voltage (V)	21.98
3	S_C voltage (A)	5.32
4	Voltage at MPP (V)	17.32
5	Current at MPP (A)	4.76
6	Coefficient of temperature at O_C voltage (mV/°C)	14.40
7	Coefficient of temperature at S_C current (mA/°C)	1.22
8	Nominal temperature of operating cell (°C)	43.00

The availability model for wind turbine units can be given as:

$$A_{W_i} = \left[C_{W_{i,j}},\ P\left(C_{W_{i,j}}\right) : j = 1 : N_{W_i}\right] \qquad (23)$$

where,

A_{W_i} = availability model of ith WTG,
$C_{W_{i,j}}$ = output power corresponding to jth capacity state of ith WTG,
$P\left(C_{W_{i,j}}\right)$ = probability associated with $C_{W_{i,j}}$,
N_{W_i} = number of output states of ith WTG,

The availability model for N_{WT} states:

$$A_W = A_{W1} * A_{W2} * \ldots..A_{W_{N_{\mathrm{WT}}}}, \qquad (24)$$

N_{WT} = Number of WTG units.

Similarly, the availability model for PV array unit can be stated as:

$$A_{\mathrm{PV}_i} = \left[C_{\mathrm{PV}_{i,j}},\ P\left(C_{\mathrm{PV}_{i,j}}\right) : j = 1 : N_{\mathrm{PV}_i}\right] \qquad (25)$$

where,

A_{PV_i} = Availability model of ith PV array,
$C_{\mathrm{PV}_{i,j}}$ = output power corresponding to jth capacity state of ith PV array,
$P\left(C_{\mathrm{PV}_{i,j}}\right)$ = Probability associated with C_{PV_i},
N_{PV_i} = Number of output states of ith PV array.

The availability model for N_{PV} states can be stated as:

$$A_{\mathrm{PV}} = A_{\mathrm{PV1}} * A_{\mathrm{PV2}} * \ldots..A_{\mathrm{PV}_{N_{\mathrm{PV}}}}, \qquad (26)$$

N_{PV} = Number of PV arrays.

A Complete Hardware Availability Model (CHAM) can be generated by combining the wind turbine and solar array availability models, the above two models:

Therefore;

$$\mathrm{CHAM} = [F_t,\ P(F_t) : t = 1 :\ N_{\mathrm{CHAM}}], \qquad (27)$$

$$F_t = [F_{\mathrm{PV}_t}\ F_{\mathrm{WTG}_t}], \qquad (28)$$

where,

F_t = vector comprising of output states of WTG units and PV array in tth combination of CHAM,
F_{PV_t} = capacity level of PV arrays in tth combination of,
F_{WTG_t} = capacity level of WTG units in tth combination of,
$P(F_t)$ = probability corresponding to with $F_{t,}$
N_{CHAM} = Number of states in CHAM.

3.3.4 Probabilistic load modeling of a small residential area located near the village

The modeling of the probabilistic load is divided into different time segments, and each segment of time consists of multiple states and their corresponding probabilities (Fig. 6). For each state of load, the probability is computed by dividing the number of occurrences of each state of load by the total number of load points:

$$\mathrm{Load}^m = \left\{\mathrm{Load}_i^m,\ P\left(\mathrm{Load}_i^m\right) : i = 1 : N_i\right\}, \qquad (29)$$

where,

$\mathrm{Load}^{\mathrm{m}}$ = vector corresponding to probabilistic load point,
Load_i^m = load of state ith during mth time segment,
$P(\mathrm{Load}_i{}^m)$ = probability corresponding to $\mathrm{Load}_i{}^m$
N_i = number of states in $\mathrm{Load}^{\mathrm{m}}$.

Table 1 represents the load profile of a particular house and the electricity demand of a single house is analyzed and found that it has a demand of approximately 1.5–2 kW for each house. There are around 35–40 houses and the peak demand of the area is around 100 kW.

4 Problem framework

The key objective of this work is to reduce the LCOE for the proposed standalone system while maintaining the reliability of the proposed hybrid system. For optimal configuration of renewable resources integrated hybrid power system, three main deciding factors, *i.e.*, the rating of the biomass gasifier, the number and rating of the wind turbine generator, and the solar PV panels. This study mainly deals

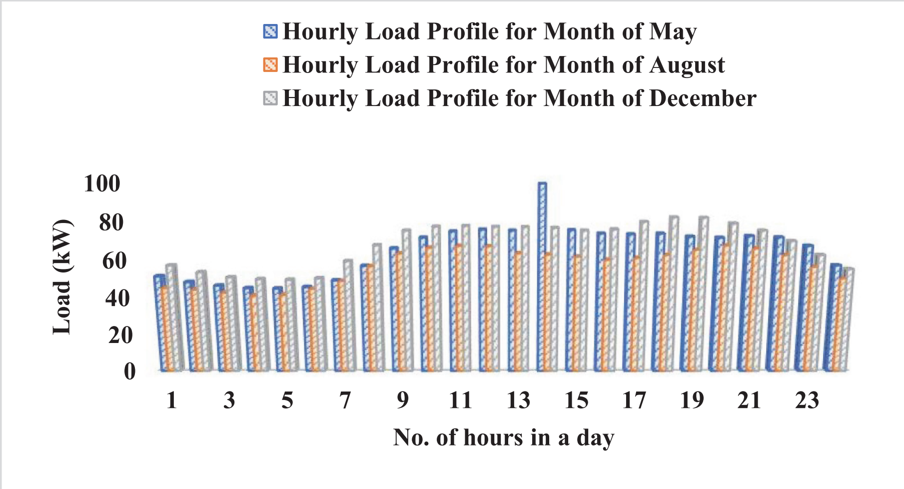

Figure 6. Probabilistic load demand profile for a particular day for different months.

with technical and economic analysis while preserving reliability with optimum generating capacity. From a technical point of view, the system well-being criteria are considered. This includes probabilities associated with the risk state, the marginal state, and the healthy state of the standalone system. For economic analysis, the concept of Annualized System Cost (ASC) or Net Present Cost (NPC) is to be considered.

4.1 Objective function

The objective function can be stated as

Minimize LCOE

$$\text{LCOE} = \frac{T_{\text{LCC}}}{\sum_{r=1}^{N_I} Q_r (1+d)^r}, \tag{30}$$

where,

LCOE = Levelized Cost of Energy (\$/kWh),
T_{LCC} = present worth of total costs incurred during project lifespan (\$),
N_{I} = lifespan of the project (in years),
Q_r = provided energy by standalone system in rth year (kWh).
d = nominal discount rate.

The following components are included in the total life cycle cost T_{LCC} *i.e.*,

$$T_{\text{LCC}} = C_{\text{CC}} + C_{\text{OM}} + C_{\text{RC}} + C_{\text{UOC}} - C_{\text{SV}}, \tag{31}$$

C_{CC} = capital cost (\$),
C_{OM} = operation and maintenance cost (\$),
C_{RC} = replacement cost (\$),
C_{UOC} = utility outage cost (\$),
C_{SV} = salvage value (\$).

This T_{LCC} function applies to each generating unit of the biomass gasifier system, the solar system module unit, the wind turbine generating unit, and the converter unit.

4.2 Operating constraint

The operating constraints include the reliability constraints and the optimal number of generating units.

4.2.1 Constraints on system reliability

Following the reliability constraints are applicable to a standalone system

$$P_{\text{R}} \leq P_{R_{\max}},$$
$$P_{\text{H}} \geq P_{\text{H}_{\min}},$$

where,

P_{R} = Percentage of risk state probability,
$P_{R_{\max}}$ = Maximum permissible percentage of risk state probability,
P_{H} = Percentage of healthy state probability,
$P_{H_{\min}}$ = Minimum permissible percentage of healthy state probability.

4.2.2 Constraints on generating units

The standalone system consists of at least one unit of a solar and wind-generating unit

$$N_{\text{BM}_{\min}} \leq N_{\text{BM}} \leq N_{\text{BM}_{\max}},$$
$$N_{\text{PV}_{\min}} \leq N_{\text{PV}} \leq N_{\text{PV}_{\max}},$$
$$N_{\text{WT}_{\min}} \leq N_{\text{WT}} \leq N_{\text{WT}_{\max}},$$

where,

N_{BM}, N_{PV}, N_{WT} = number of biomass, pv, and wind generating unit respectively,

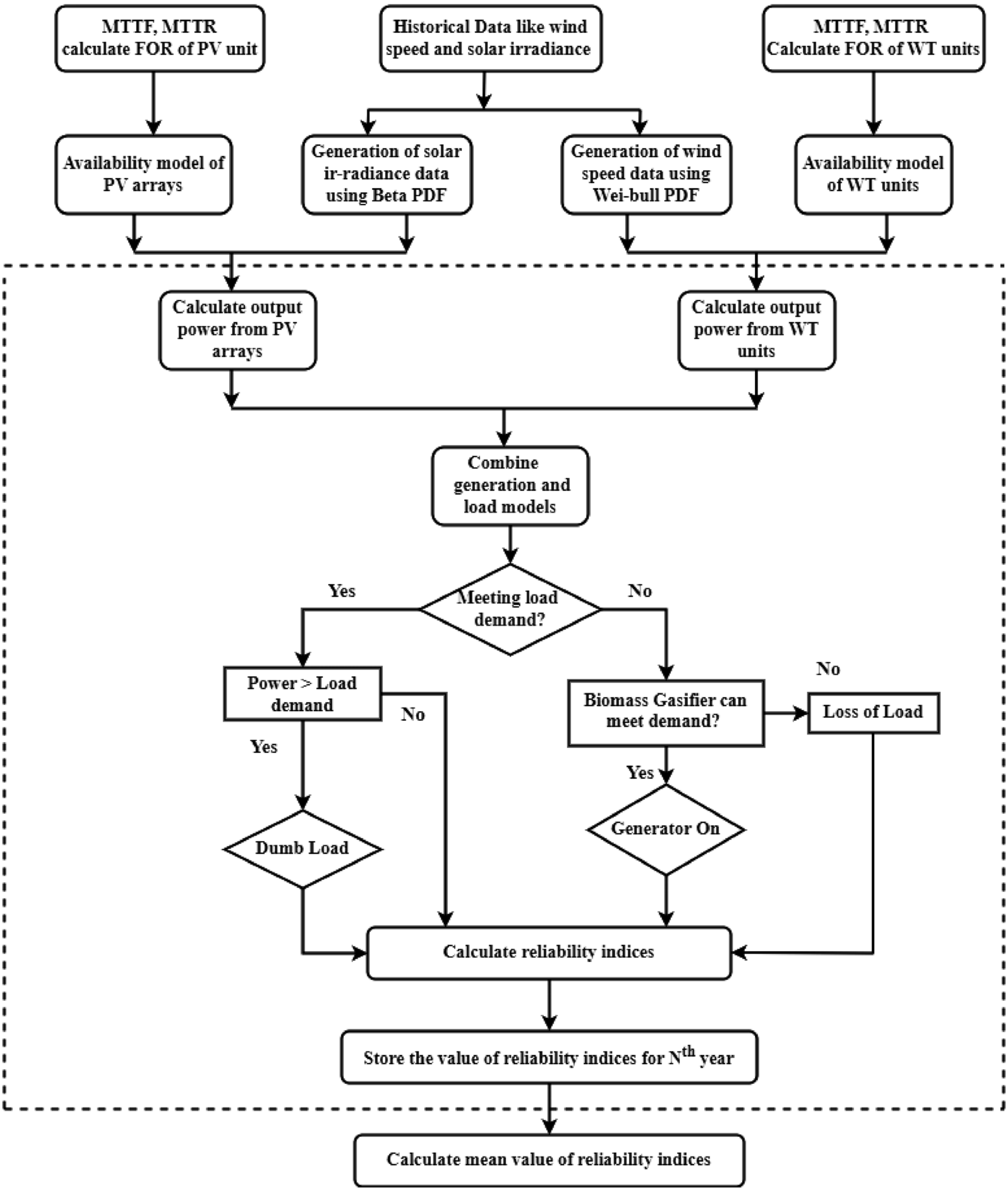

Figure 7. Flow chart for calculating reliability indices.

$N_{\mathrm{BM_{min}}}$, $N_{\mathrm{BM_{max}}}$ = minimum and maximum generating units of biomass respectively,

$N_{\mathrm{PV_{min}}}$, $N_{\mathrm{PV_{max}}}$ = minimum and maximum generating units of pv system respectively,

$N_{\mathrm{WT_{min}}}$, $N_{\mathrm{WT_{max}}}$ = minimum and maximum generating units of wind respectively.

For the calculation of the reliability, which is taken as a system constraint, there is a need to model the appropriate generation model, load model, and combination of these generation and load models to create the suitable model to obtain the required competence indices. The generating units are modeled by Mean Time To Repair (MTTR) and Mean Time To Failure (MTTF). MTTR of a system or component is defined as the average time taken to make it operational from the abnormal and faulty state, and a lower MTTR leads to higher system reliability. MTTF is an equivalent time of an entity or a particular system that

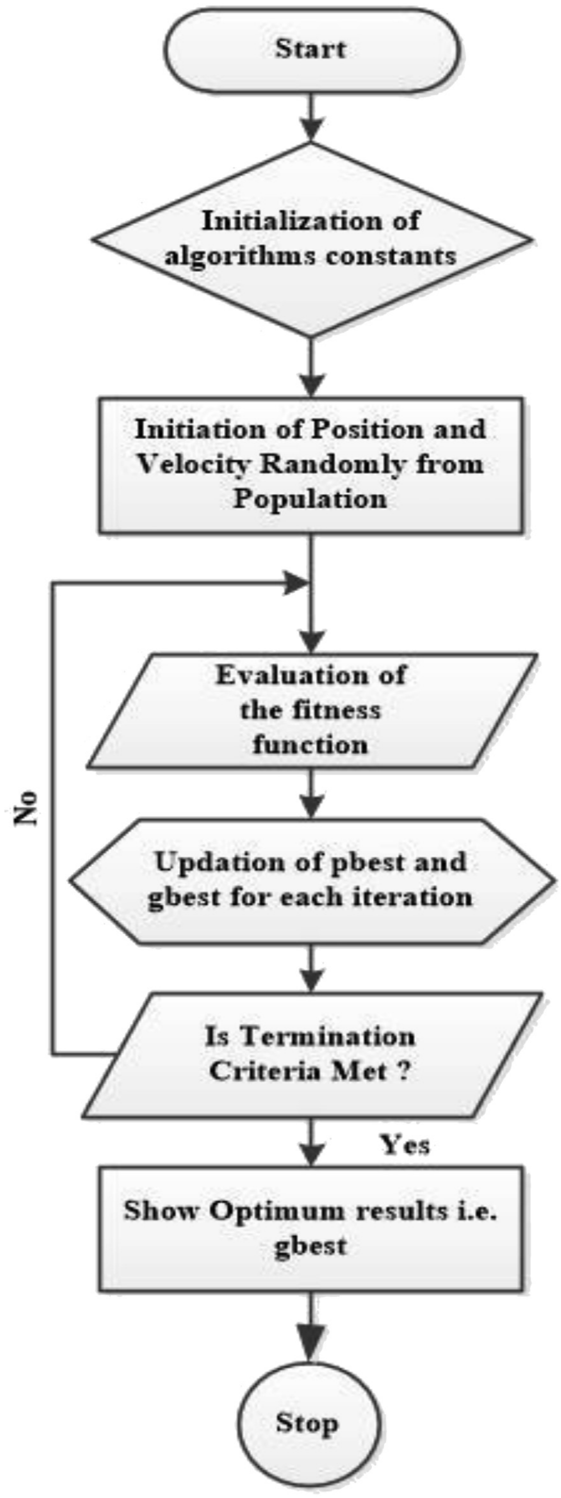

Figure 8. Flow chart of PSO algorithm.

is functional appropriately before it goes into a failure state for the first time, and a system is highly reliable with more MTTF. The forced Outage Rate (FOR) for a system can be calculated based on the MTTR and MTTF. FOR can be represented by:

$$\mathrm{FOR} = \frac{\mathrm{MTTR}}{\mathrm{MTTF} + \mathrm{MTTR}}. \quad (32)$$

Figure 7 represents the calculation of reliability indices for the proposed stand-alone hybrid power system.

4.3 Particle swarm optimization algorithm

The particle swarm optimization algorithm is inspired by the supportive behavior of social animals like birds, ants, or fish. This technique is applicable for both continuous and discrete optimization problems as it is very effective and simple in nature. Russel and James Kennedy invented this algorithm in 1995. It is a metaheuristic and an intelligent optimization technique, which gathers great attention from researchers due to its glitch-resolving capability (Fig. 8).

The algorithms include the following steps:

1. Initialize the constants of the algorithm.
2. Initialize the population for the position and velocity of particles.
3. Velocity vector is to be generated.
4. Evaluation of fitness function for each particle
5. For every iteration, update the values of personal best (pbest) and global best (gbest).
6. Update the velocity and position of each particle.
7. If the criteria for termination are met, then show the optimum results, otherwise repeat from step 4.

5 Results and discussion

Particle Swarm optimization algorithm code is developed for the different combinations of the considered system in the MATLAB environment, and the optimum solution is obtained by taking the units of different rating. The obtained solution for each configuration is economical and reliable.

During the analysis, different configurations are analyzed based on the system' annualized cost for optimal configuration while meeting the constraints. The following scenarios are taken into consideration for investigation:

1. Diesel Generator (DG) only
2. Wind and DG units
3. Wind and biomass
4. Solar and DG
5. Solar and biomass
6. Wind-solar-DG
7. Wind-solar biomass

Figure 9 represents the daily wind profile for the year 2023. The data for wind speed is taken from the POWER data access viewer by *NASA* for the comprehensive analysis of renewable energy resources.

Figure 10 represents the solar radiation profile for PV module for power generation. The data of solar radiation is on a daily basis and taken from the POWER data access viewer by NASA for analysis and estimation purposes.

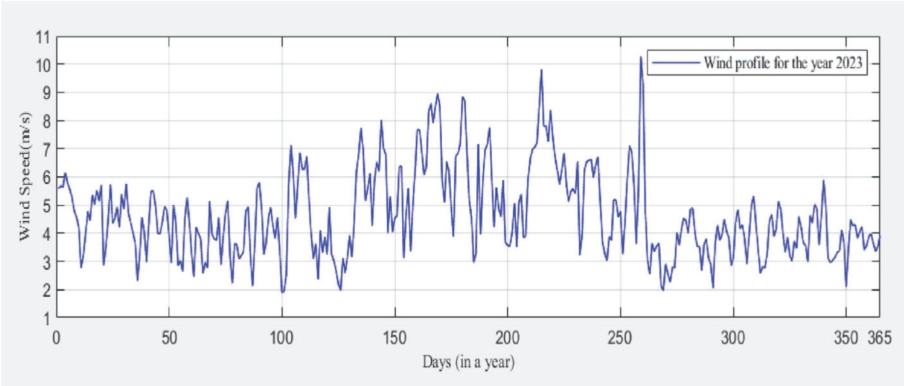

Figure 9. Typical yearly wind profile.

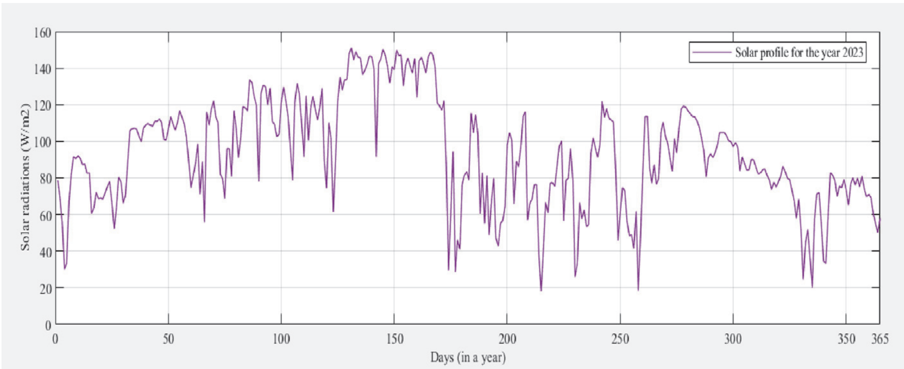

Figure 10. Yearly solar irradiance.

Comparisons of the above-considered system are done based on LCOE while meeting the reliability as a constraint.

Scenario 1: Only the diesel generator source is taken into account for the fulfillment of the power demand of the considered probabilistic load. Further, the annual simulation in this scenario is taken for the best probable optimal arrangement of the system components. In this system, generators of different capacities like 20 kW, 40 kW and 70 kW units are taken into the accounts for meeting the load demand but optimal combination shows that there is no requirement for a 70 kW generator but 5 units of 20 kW and 1 unit 40 kW is sufficient to meet the load demand with LCOE of 0.7733$/kWh and the System Annualised Cost (SAC) is calculated as $415,787.58. Energy Not Served (ENS) for the considered system is negligible, *i.e.* $1.17e^{-10}$ per year.

Scenario 2: In this configuration, a wind turbine system is implemented with the diesel generator to meet the load demand, as wind is a natural source for power generation for which there is no requirement for fuel. For this scenario again the generators of different capacities are considered and the optimal configuration as 4 units of diesel generators 20 kW each and 2 units of wind turbines 40 kW each is able to meet the requirement with LCOE of 0.5680$/kWh and SAC is estimated to be $307,662.85. ENS for the above system is found to be 2.41 units per year.

Scenario 3: Now integration of the wind turbine system with the biomass-based gasifier system is done for load requirement. Wind and biomass are both great renewable sources of energy, and there is no emission from the above system, and it does not pollute the environment. The optimal combination shows that the load demand can be met by 1 unit biomass generator rated 20 kW and 3 units of wind turbines rated 40 kW each and found the LCOE for the given system is 0.0711$/kWh and having the SAC for the above hybrid system is $57,349.163. ENS for the year comes out to be 582.061 units.

Scenario 4: In this hybrid system, a solar-PV system is integrated with the diesel-based generator system. As in this system, solar is renewable and the diesel generator is a non-renewable source of energy, so there will be some emission from the diesel system, which leads to pollution in the environment. But solar doesn't have any fuel requirement, so the system is feasible for the load requirement. The optimal combination shows that 6 units of solar rated 15 kW each and with the 6 units of diesel rated 20 kW each is able to meet the load demand with LCOE of 0.5861$/kWh and the SAC is found to be more than the wind and solar hybrid system *i.e.* $316,787.43 and the ENS comes out to be 68.18 units for the optimal combination.

Scenario 5: Now the solar system is integrated with a biomass system to remove the use of conventional sources as it increases the system cost and is not environmentally

Table 4. Comprehensive analysis based on economic of the investigated systems.

S. No.	Integrated system	LCOE ($/kWh)	SAC ($)
1.	Diesel Generator (DG) only	0.7733	415,787.58
2.	Wind and DG units	0.5680	307,662.85
3.	Wind and biomass	0.0711	57,349.163
4.	Solar and DG	0.5861	316,787.43
5.	Solar and biomass	0.1308	70,250.31
6.	Wind-solar-DG	0.4514	242,224.31
7.	Wind-solar biomass	0.1172	62,901.28

Table 5. Reliability analysis of the system under consideration.

S. No.	Integrated system	P_R (Risk state probability)	P_H (Healthy state probability)
1.	Diesel Generator (DG) only	0.0062	99.9980
2.	Wind and DG units	0.0124	99.7499
3.	Wind and biomass	0.0134	95.0073
4.	Solar and DG	0.1105	98.7138
5.	Solar and biomass	0.9422	92.3792
6.	Wind-solar-DG	0.1422	96.5310
7.	Wind-solar biomass	0.1458	95.8241

friendly. So, the use of natural sources of energy is very advantageous and economical to meet the load requirement. In this configuration, two natural sources *i.e.* solar and biomass gasifier systems a used and the same optimal combination is used as that of the solar-diesel hybrid system and found that the LCOE comes out to be 0.1308$/kWh which is mo economical than the solar-diesel configuration and the SAC comes out to be $70,250.31

Scenario 6: Now both the renewable sources of energy, *i.e.* solar and wind, are now integrated with a diesel generator for the best possible configuration. In this scenario, the optimal combination shows that three units of solar, 30 kW each, two units of wind, 20 kW each, and four units of diesel generator are presenting the best results. In this hybrid system, the SAC for the system found to be $242,224.31, and the LCOE comes to be 0.4514$/kWh. ENS for the system is 1050.80 units, *i.e.*, a little bit higher due to the intermittency of renewable energy sources.

Scenario 7: In this hybrid power system, all the natural sources of energy are used for power production. In this configuration, a solar, wind and biomass gasifier-based generator is used to meet the load demand. This hybrid standalone system completely use sources as a fuel, which are freely available in nature or have very low cost like biomass for power generation due to which it is very much nature friendly and has no emission to the environment. The optimal configuration shows that the LCOE for the system is 0.1172$/kWh and has a SAC of $62,901.28.

From Table 4, it can be concluded that biomass is best comprehended with solar and wind. As a greater number of intermittent sources are included with biomass, it will become more economical as compared to the diesel generator system.

Table 5 shows the reliability of the considered system which is taken as a constraint. P_R and P_H are the Risk state and Healthy state probabilities associated with the system under consideration. In the above work, P_H of the system should be greater than 90% and P_R of the system should be less than 1% while calculating the economics of the system. The system under consideration was found to be in acceptable ranges. From the above, it can be seen that the non-renewable source (*i.e.* diesel generator) is showing the highest reliable system with the least probability of risk. Integration of renewable sources with the diesel generator is more reliable than the system having only intermittent nature of sources or use of a biomass generator with solar and wind.

6 Conclusion

Various case studies have been performed to analyze the system's optimum performance by optimizing the hybrid system component size. The optimal component sizes of the standalone hybrid system are optimized through a technique known as particle swarm optimization, which is an artificial intelligence algorithm inspired by the communal behavior of creatures like birds and fish. From the above-considered scenarios, it is observed that the only diesel generator has the highest system annualized cost, which leads to a bigger levelized cost of energy. When the diesel generator is integrated with renewable sources of energy, it is found that there is a significant decrement in the system annualised cost along with an improvement in the LCOE. The reliability of the system is higher with conventional sources of energy and relatively less economical but when there is an integration of more than one renewable source like wind-solar-biomass in the hybrid power, the system becomes more economical with comparatively less reliable due to the intermittent nature of renewable sources of energy as compared to conventional sources and also gratifying the reliability as a constraint. A biomass gasifier generator system is integrated with these other sources to make the system more economical, and it is evident from the above scenarios that there is a significant decrement in the LCOE which is profitable for a standalone hybrid power system. The biomass gasifier generator is integrated along with the wind turbine and wind-solar hybrid system results in LCOE of 0.0711$/kWh and 0.1172$/kWh respectively, which is lowest among all the considered cases, and compared the results with the system having Pumped Storage Hydro (PSH) along with solar and wind. The LCOE of the PSH-wind and PSH-wind-solar comes out to be 0.283 $/kWh and 0.268$/kWh respectively [26] that are highly uneconomical as compared to the proposed biomass-wind and biomass-wind-solar hybrid system respectively. Saiket Saha *et al.* [23] got the least LCOE of 0.0712 $/kWh where reliability is not a system constraint, whereas the best LCOE of 0.0711 $/kWh is attained in this study while meeting the reliability constraint. The future aspect includes the integration of multiple natural sources like tidal energy, geothermal energy, ocean energy, *etc.* for enhancement of system economy and consistency.

References

1 Baruah D., Baruah D.C. (2014) Modeling of biomass gasification: A review, *Renew. Sustain. Energy Rev., Elsevier* **39-C**, 806–815. https://doi.org/10.1016/j.rser.2014.07.129.

2 Singh S., Singh M., Kaushik S.C. (2016) Feasibility study of an islanded microgrid in rural area consisting of PV, wind, biomass and battery energy storage system, *Energy Convers. Manag.* **128**, 178–190. https://doi.org/10.1016/j.enconman.2016.09.046.

3 Abouzahr I., Ramakumar R. (1990) Loss of power supply probability of stand-alone wind electric conversion systems: a closed form solution approach, *IEEE Trans. Energy Convers.* **5**, 3, 445–451.

4 Elhadidy M.A., Shaahid S.M. (2004) Role of hybrid (wind+diesel) power systems in meeting commercial loads, *Renew. Energy* **29**, 109–118.

5 Elhadidy M.A., Shaahid S.M. (1999) Optimal sizing of battery storage for hybrid (wind+diesel) power systems, *Renew. Energy* **18**, 77–86.

6 Patil A.B.K., Saini R.P., Sharma M.P. (2010) Integrated renewable energy systems for off grid rural electrification of remote area, *Renew. Energy* **35**, 6, 1342–1349.

7 Bhattacharjee S., Acharya S. (2015) PV-wind hybrid power option for a low wind topography, *Energy Convers. Manag.* **89**, 942–954.

8 Kolhe M. (June, 2009) Techno-economic optimum sizing of a stand-alone solar photovoltaic system, *IEEE Trans. Energy Convers.* **24**, 2, 511–519. https://doi.org/10.1109/TEC.2008.2001455.

9 Agbossou K., Kolhe M., Hamelin J., Bose T.K. (2004) Performance of a stand-alone renewable energy system based on energy storage as hydrogen, *IEEE Trans. Energy Convers.* **19**, 3, 633–640. https://doi.org/10.1109/TEC.2004.827719.

10 Garrido H., Vendeirinho V., Brito M.C. (2016) Feasibility of KUDURA hybrid generation system in Mozambique: Sensitivity study of the small-scale PV-biomass and PV-diesel power generation hybrid system, *Renew. Energy, Elsevier* **92-C**, 47–57.

11 Chauhan A., Saini R.P. (2016) Discrete harmony search-based size optimization of Integrated Renewable Energy System for remote rural areas of Uttarakhand state in India. *Renew. Energy* **94**, 587–604. ISSN 0960-1481, https://doi.org/10.1016/j.renene.2016.03.079.

12 Kolhe M., Joshi J.C., Kothari D.P. (2004) Performance analysis of a directly coupled photovoltaic water-pumping system, *IEEE Trans. Energy Convers.* **19**, 3, 613–618. https://doi.org/10.1109/TEC.2004.827032..

13 Jalan S.K., Babu B.C., Kolhe M.L. (2020) High-flexibility DC-link voltage control for grid-tied solar PV systems: maximizing performance and power quality, *IEEE Trans. Consumer Electron.* https://doi.org/10.1109/TCE.2024.3479329.

14 Ahmad J., Imran M., Khalid A., Iqbal W., Ashraf S.R., Adnan M., Ali S.F., Khokhar K.S. (2018) Techno economic analysis of a wind-photovoltaic-biomass hybrid renewable energy system for rural electrification: A case study of Kallar Kahar, *Energy, Elsevier* **148-C**, 208–234.

15 Ari A., Bohre A., Chaturvedi P., Kolhe M., Singh S. (2022) Techno-economic analysis of hybrid renewable energy systems – a review with case study, in: *Planning of hybrid renewable energy systems, electric vehicles and microgrid. Energy systems in electrical engineering*, Bohre A.K., Chaturvedi P., Kolhe M. L., Singh S.N. (Eds.), Singapore: Springer, pp. 227–264. https://doi.org/10.1007/978-981-19-0979-5_11.

16 Kurukuri P., Mohamed M.R., Raavi P.H. (2024) Optimal planning and designing of microgrid systems with hybrid renewable energy technologies for sustainable environment in cities, *Environ. Sci. Pollut. Res.* **31**, 32264–32281. https://doi.org/10.1007/s11356-024-33254-5

17 Arranz-Piera P., Kemausuor F., Darkwah L., Edjekumhene I., Cortés J., Velo E. (2018) Mini-grid electricity service based on local agricultural residues: Feasibility study in rural Ghana, *Energy, Elsevier* **153-C**, 443–454.

18 Ling J., Zhengping L., Yuxuan W., Guohe H. (2022) Techno-economic feasibility analysis of optimally sized a biomass/PV/DG hybrid system under different operation modes in the remote area. *Sustain. Energy Technol. Assessm.* **52-B**, 102117. ISSN 2213-1388, https://doi.org/10.1016/j.seta.2022.102117.

19 *Year wise Achievements: Installed Renewable Energy Capacity, "Ministry of New and Renewable Energy India"*. https://mnre.gov.in/year-wise-achievement.

20 Anurag C., Subho U., Gaurav S., Senthilkumar N. (2022) Agricultural crop residue based biomass in India: potential assessment, methodology and key issues, *Sustain. Energy Technol. Assessments* **53-B**, 102552. ISSN 2213-1388, https://doi.org/10.1016/j.seta.2022.102552.

21 Dennis C., Piyush J., Ludo D., Priyangshu M.S., Deepak P. (2015) Agriculture biomass in India: Part 1. Estimation and characterization, *Resour. Conserv. Recycl.* **102**, 39–48. ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2015.06.003..

22 Arashdeep S., Prasenjit B. (2021) Conceptualization and techno-economic evaluation of microgrid based on PV/Biomass in Indian scenario, *J. Clean Prod.* **317**, 128378. ISSN0959-6526.

23 Saikat S., Gaurav S., Anurag C., Subho U., Rajvikram M.E., M.S. Hossain Lipu (2023) Optimum design and techno-socio-economic analysis of a PV/biomass-based hybrid energy

system for a remote hilly area using discrete grey wolf optimization algorithm, *Sustain. Energy Technol. Assessments* **57**, 103213. ISSN 2213-1388, https://doi.org/10.1016/j.seta.2023.103213.

24 Naoufel E., Asmae B., Anisa E., Jamil A., Rachid E.M. (2024) Optimization of an off-grid PV/biogas/battery hybrid energy system for electrification: A case study in a commercial platform in Morocco. *Energy Convers. Manage.: X* **21**, 100508. ISSN 2590-1745, https://doi.org/10.1016/j.ecmx.2023.100508.

25 Arun R., Patidar N.P. (2021) Optimal sizing and allocation of renewable based distribution generation with gravity energy storage considering stochastic nature using particle swarm optimization in radial distribution network, *J. Energy Storage* **35**, 102282. ISSN 2352-152X.

26 Rathore A., Patidar N.P. (2020) Reliability constrained socio-economic analysis of renewable generation based standalone hybrid power system with storage for off grid communities, *IET Renew. Power Gener.* **14**, 2142–2153 https://doi.org/10.1049/iet-rpg.2019.0906.

27 Arun Rathore N.P.P. (2019) Reliability assessment using probabilistic modelling of pumped storage hydro plant with PV-Wind based standalone microgrid, *Int. J. Electric. Power Energy Syst.* **106**, 17–32. ISSN 0142-0615.

28 Abisoye B., Miguel C.B. (2021) Solar PV systems to eliminate or reduce the use of diesel generators at no additional cost: A case study of Lagos, Nigeria, *Renew. Energy* **172**, 209–218. ISSN 0960-1481, https://doi.org/10.1016/j.renene.2021.02.088.