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ORIGINAL CONTRIBUTION

Planning and Optimization of Hybrid Microgrid for Reliable Electrification of Rural Region

Md Mustafa Kamal[1] · Imtiaz Ashraf[1]

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Abstract The microgrid is an economical and feasible alternative to provide the electrification of current, and future scenarios as the depletion rate of conventional fuel are high. It is essential to optimize microgrid components, including batteries, to analyze the total system cost and reliability. In the present work, a rural microgrid is planned to integrate wind, solar, diesel generator, and battery systems. The remote region of Uttarakhand (India) selected for the techno-economic and feasibility analysis of the proposed microgrid. The planned objective is concerned with determining the least per unit cost of energy and viability of the model. The optimization algorithm is applied under different cases to check its effectiveness for optimal planning. The suggested framework can be considered as part of comprehensive energy management. The simulation results indicate the high potential of saving.

Keywords Microgrid · Cost of energy · Optimization · Solar · Grid · Renewable resource

Nomenclature

$P_{s,t}^{Wind}$	Power supply to the grid by wind energy resource (kW)
$P_{s,t}^{PV}$	Power supply to the grid by the solar energy system (kW)
PV_{power}	Power output of PV array on an hourly basis (kW)
P_{rated}	PV array's rated power (kW)
f_{PV}	Derating factor (%)
I_T	Solar insolation at temperature T (kw/m^2)
I_s	Solar insolation at standard temperature
T_{cell}	PV array cell temperature (°C)
T_s	Cell temperature at 25 °C
η_{PV}	PV panel efficiency (%)
tα	Effective transmittance-absorptance
H_l	Heat transfer coefficient (kW/m^2/c)
T_α	Ambient temperature (°C)
V_1	Cut-in speed (m/s)
COE	Cost of energy
V_r	Rated speed (m/s)
f_{gen}	Fuel density (Kg/m^3)
V_2	Cut-out speed (m/s)
P_r	Rated power (kW)
Q	Initial energy of the battery
q_1	Energy status in the beginning of time t
k	Battery rate constant
c	Capacity ratio
Δt	Step length
q_{max}	Maximum charge capacity of the battery bank
q_1 and q_2	Final bound energy of the battery
P	Battery bank total power
F	Total fuel consumption
f_0	Intercept co-efficient of fuel curve
f_1	Slope of fuel curve
P_{gen}	Generator's electric output.
P_{wt}	Wind turbine output
η_w	Efficiency of wind turbine (%)

✉ Md Mustafa Kamal
mustafakamalece@gmail.com

1 Department of Electrical Engineering, Aligarh Muslim University, Aligarh, India 202002

A_w	Swift area of wind turbine (m^2)
$gen_{1t}, gen_{2t}, gen_{3t}$	Capacity of the diesel generator
$L_{1,t}$,$L_{2,t}$, $L_{3,t}$	Load demand of different categories
$S_{12,t}$,$S_{13,t}$, $S_{23,t}$, $S_{13,t}S_{24,t}$	Co-efficient of node matrix.
$E_t^{battery}$	Stored energy in the battery.
$P_{t,m}^{charge}$	Charging power of the battery
η_{charge}	Charging efficiency of the battery (%)
SOC_{charge}	State of charge of the battery (%)
$SOC_{discharge}$	State of discharge of the battery (%)
DG	Diesel generator
SPV	Solar photovoltaic
WT	Wind turbine

Introduction

Dependence on the electrical power system significantly increases over the last few decades. Electricity is the major contributing factor for the sustainable development of humanity. Conventional energy resources are depleting very fast. The growing energy demand cannot be accomplished using only traditional energy resources [1]. Clean energy resources are an option to reduce the burden on conventional fuels. These are economical, greener, resilient, and reliable sources of energy. Microgrids formed by integrating renewable resources in the area can provide a reliable supply of energy to the rural and urban communities [2]. The microgrid is the grouping of traditional power generators, renewable sources, and storage batteries to supply the area's energy demand. These types of the framework can connect with grid or work in standalone mode [3]. For the electrification of the remote regions, standalone mode of operation is widely preferred due to its low energy cost and difficulty in developing grid infrastructure. The grid-connected method extensively favors urban areas. At peak hours, electricity is provided by renewable resources and battery, and when the power tariff is low, it is supplied by the grid. The grid-connected mode of operation lowers the overall energy cost, improves power supply efficiency, and increases the penetration of renewable energy resources [4]. Diesel generators (DG) are used as the backup power source to provide uninterrupted supply. DG with renewable resources confirms the reliability in the power supply of the area. The hybrid energy system is molded by the merger of various renewable resources. The key goal of developing a hybrid energy model is to provide a cost-effective energy solution for rural residents. The planning of the hybrid energy model involves cautious and supportive algorithms to maximize customers' benefits and productivity [5].

The implementation of the hybrid power system involves meticulous planning of its elements such as the number of photovoltaic arrays, wind turbine size, DG units, converters, and the battery system. The framed system fully satisfies the energy requirement of the area [6]. The scholar extensively uses hybrid models to recommend rural and urban people's electrification. Several studies by various authors have been completed worldwide for power generation using a hybrid energy model. Renewable energy resources combined different ways to provide reliable electrification of the area. Integrating renewable energy sources such as solar, biomass, wind turbine, and DG units with or without storage have proved to be a cost-effective electrification solution [7]. [8] designed a microgrid for a small Island in Thailand and suggested the least energy cost for the electrification of the island. The model consists of PV, diesel generator, and two battery types, i.e., lithium-ion battery and lead-acid battery. The simulation was performed by using HOMER software. Results suggest that with a lithium-ion battery, energy cost is less than a system with a lead-acid battery.

[9] analyzed the hybrid energy model for the electrification of the rural community of Karnataka (India). They proposed a viable and economic electrification strategy based on genetic algorithm. Ankit et al. [10] proposed a microgrid for the Indian scenario in Uttarakhand's rural area. The suggested microgrid aims to provide the electrification of five rural villages. The techno-economic feasibility analysis is performed using HOMER software. Upadhyay et al. [11] planned an integrated hybrid system model for the unelectrified village in Uttarakhand (India) and optimized it for the least levelized cost of energy. [12] planned the microgrid system, which consists of a PV/ diesel/ battery for the rural region. The proposed model's goal is to minimize the electricity cost. Three different optimization techniques were used to analyze the model. In [13], the authors proposed a cooperative microgrid for the communities located in India's east coast zone to provide a reliable power supply using renewable resources. They performed the techno-economic analysis of the model using MATLAB simulation and compare the results of HOMER software. The developed prototype verified the simulation results. [14] proposed the electrification solution of the rural community of Jalalabad (India). HOMER software is used to analyze and calculate the cost of energy and the net present cost of the model. The sizing of components and emission of greenhouse gases is also analyzed.

Various tools are available for designing and optimization of the different objectives of microgrid modeling; the metaheuristic-based approach is widely used for cost and size optimization. [15] modeled a microgrid for the two different villages of the state of Bihar (India). Techno-economic and feasibility analysis is performed by using particle swarm optimization (PSO) and Gray wolf optimization algorithm. They suggest that the optimum value of the cost of energy is 0.17$/kWh with 93% of the renewable fraction. [16] presented an off-grid model with PV and battery systems for Uganda's rural community. The proposed objective of the model was optimized using genetic algorithm (GA). [17] suggested a hybrid model for the village hamlet in Uttarakhand (India). They estimated the available energy potential of the area. The total of energy-optimized by the discrete search optimization algorithm. Loss of power supply probability (LPSP) is considered during modeling to evaluate reliability in power supply. Das et al. [18] suggested the hybrid model using a combination of accessible renewable resources with the battery system. They used HOMER tools to study Bangladesh's rural area for optimum sizing and energy cost minimization. The renewable sources are irregular, which directly affects the system's overall production. In [19], the microgrid system with random nature is considered. The system consists of battery, PV and diesel, and wind energy system. Multi-objective particle swarm optimization (MPSO) is used for the reliability and cost analysis of three different location Iran. [20] proposed a microgrid model for the rural electrification of Almora district of Uttarakhand (Indian). They considered seasonal variation of load during modeling. Maiden cuckoo search algorithm is used for the energy cost system's size optimization. Vacari et.al [21] suggest a microgrid model considering large number of devices, deferred load, adjustable load with conventional, renewable sources, and batteries. They used sequential linear programming method to suggest the least cost of operation of the microgrid. Shezan et al. [22] suggested a microgrid considering PV/diesel/battery/wind for modeling for the rural area electrification. The study established the model has an advantage over the conventional electrification scheme. [23] suggested an efficient planning algorithm for rural microgrid in remote areas. The planning method is optimized for the least cost of operation using a mixed-integer linear programming algorithm. Two test cases have been discussed in different cost scenarios.

The present paper discussed the available research and found the research gap, which analyzes the electrification of the rural community of the rural area. The present study analyzes solar PV, wind, diesel generator, and grid connectivity and provides the economic, technical, and feasible microgrid configuration.

Study Area

Uttarakhand is India's northernmost state. The state shares its boarded with Himachal Pradesh in the northwest, China in the north, Nepal in the east, and Uttar Pradesh in the south. Uttarakhand state has a total installed capacity of 3487.57 MW, in which renewable energy contribution is 659.81 MW as of October 2019. Figure 1 shows the installed capacity of complete energy resources as of October 2019, in which renewable energy contribution is 18.92%. Total energy consumption per person is a significant parameter, which represents resource utilization in the region. The state's per person total energy consumption was 654.84 kWh in 2006, which was elevated to 930.41 kWh in 2010 [24].

Due to government policies and investment in the power sector, total energy consumption per person is 1454 kWh, which is higher than the national average of 1181 kWh [25]. Figure 2 shows the progress of the installed capacity of electricity in Uttarakhand from FY 2005 to 2018. Uttarakhand is a hilly state, and most of the rural populations do not have access to consistent power because of the costly expansion of grid infrastructure in the region.

As per census 2011, the total number of 123 villages and the 1966 number of village helmets are unelectrified. The Garhwal region has 58 villages, and the Pauri region has 65 villages. Out of 1966, un-electrified hamlets, 1197 are in the Garhwal region. The majority of the areas have abundant in the availability of renewable energy resources, sufficient to meet the energy demand. The state has enormous potential to tap solar energy. The area has over 300 sunny days and receives 4.5–5.5 kWh/m^2/day solar radiation during the year. Uttarakhand state renewable energy development authority (UREDA) is responsible for developing renewable energy resources [26].

UREDA divided solar power plants into five categories for power generation, grid-connected, off-grid, rooftop, canal bank, and canal top power plant. In 2015–2016, they finalized the 12 projects of grid-connected solar power plants with a cumulative capacity of 30 MW and tariff rates between 6.85 and 7.99 ₹/kWh. Nineteen number of off-grid

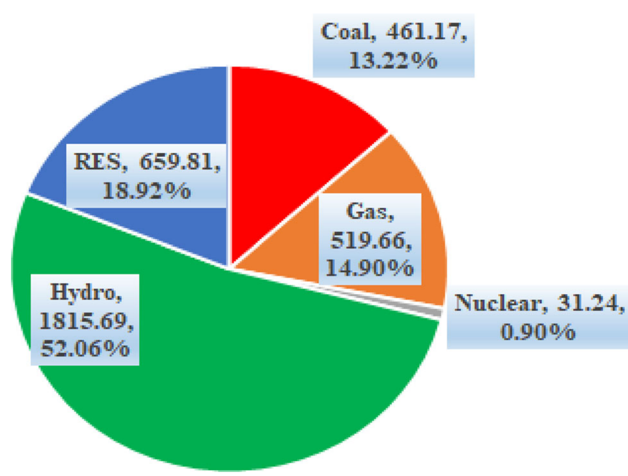

Fig. 1 Total installed capacity of Uttarakhand state (MW)[25]

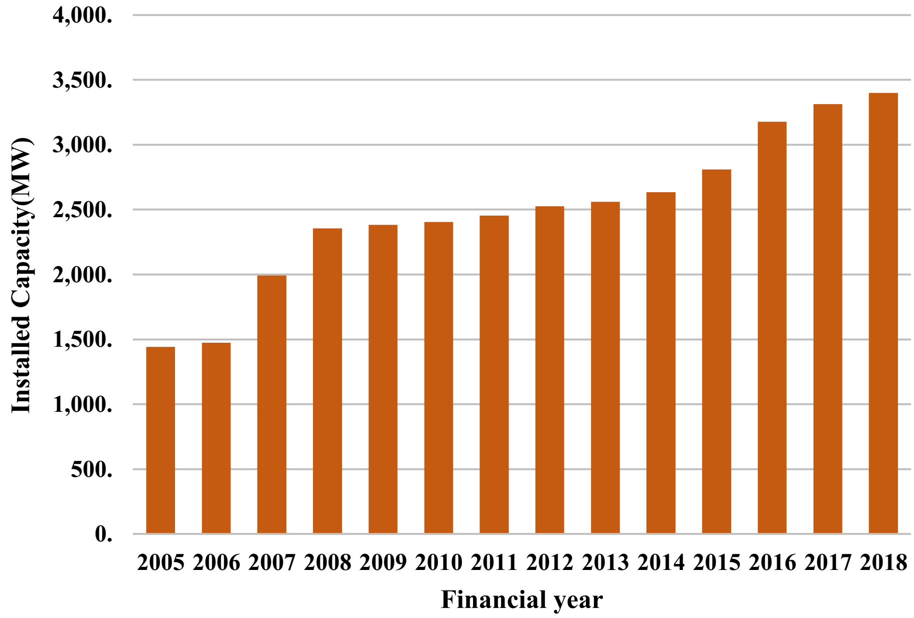

Fig. 2 Progress of installed capacity of power

projects of the collective total of 689 kWh finalize in the 214–16. Twenty rooftop projects of 30 and 20 MW projects completed in year 2015–2017. URDEA widely uses the solar modules for the electrification of rural areas. The total number of 530 remote villages and 98 village helmets is electrified using solar power, in which the maximum of 121 villages is in the Pauri Garhwal region[26]. Tehri Garhwal is one of the 13 districts of Uttarakhand selected for the proposed model's case study. The district is situated in the state's central region. New Tehri is the administrative headquarter of the district. The region covers 36,242km^2 and the population is 618,913 (2011 census) [26].

The region under investigation has abundant potential for harnessing renewable energy resources. The conceptual design to provide the electrification of the area is shown in Fig. 3. The model consists of PV, wind turbine, battery diesel generator, which operate in grid-connected mode. The battery system and DG units improve the power supply reliability. The purpose of using the battery in the model is to store excess energy and provide the supply when renewable resources are insufficient to meet the demand.

Energy Management Strategy

The suggested hybrid energy model consists of a wind energy system, solar photovoltaic system, battery, and DG units. The limitation of power delivered by the renewable energy resources is that they are intermittent; hence, power generation capacity cannot increase beyond certain limits. Due to intermittency in supply, designing power systems using renewable energy resources is challenging. Microgrid design stores excess energy via battery and supply in peak hours or when renewable energy production is insufficient. The situations come when generated power is more than the demand of area the and storage units are too charged their capacity. Hence, to protect the storage device from overcharging, it is required to implement a dump load to release unnecessary energy. The flowchart of the methodology is shown in Fig. 4. To design the microgrid system for the said area the following four cases are studied.

i. Case 1(C1): The microgrid supplied the demand of the customers depends on the diesel generators
ii. Case 2(C2): The microgrid supply energy to the customers through the combination of renewable resources
iii. Case 3(C3): The microgrid is molded by the combination diesel, battery, and renewable system
iv. Case 4(C4): Microgrid supplied in conjunction with external grid

Resource Estimation

The hybrid energy model considers the available energy resources to supply the area's energy demand. The cost of energy is determined by the working capability of renewable resources and functional components in the model. The proposed microgrid system consists of battery and PV system DG, Wind turbine with grid connectivity. In the given section, mathematical modeling of each component is considered.

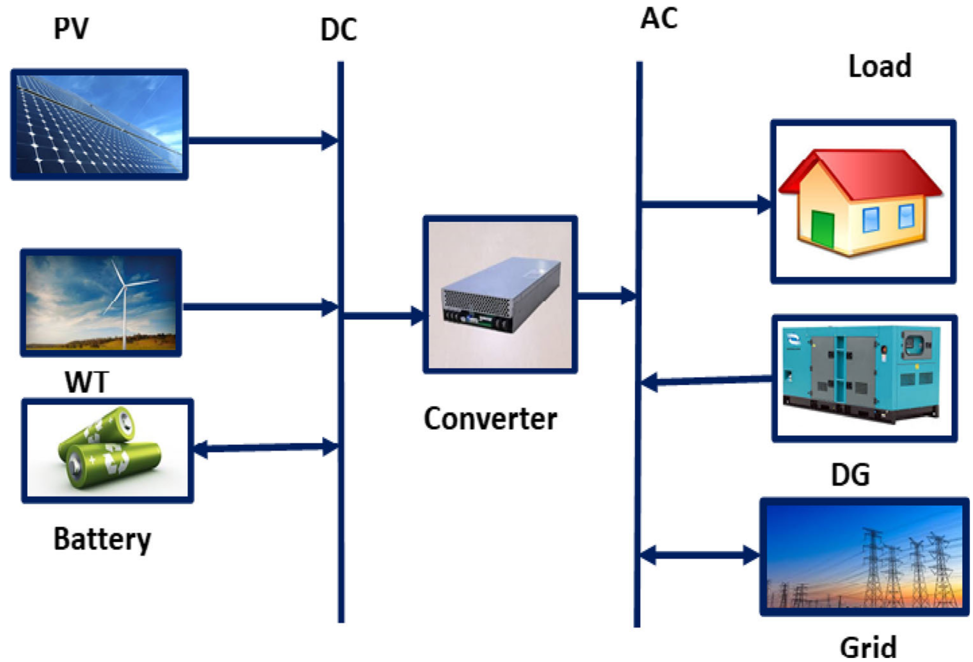

Fig. 3 Microgrid model of the area

Solar Photovoltaic System (SPV)

The SPV comprises several PV units. The power output of the solar module is influenced by the incident solar radiation and environmental conditions. The output PV array varied with the incident solar radiation on the surface of the nodule. It is evident that with the increase of 0.1 °C temperature co-efficient, the production of the solar module may increase [27]. The equation can calculate PV power output

$$PV_{power} = P_{rated} f_{pv} \left(\frac{I_T}{I_{st}}\right) \left[1 + \alpha_p (T_{cel} - T_s)\right] \quad (1)$$

The cell temperature T_{cel} °C can be formulated as

$$t\alpha I_T = \eta_{PV} I_T + H_l (T_{cel} - T_\alpha) \quad (2)$$

$$T_{cel} = T_\alpha + I_T \left(\frac{t\alpha}{H_l}\right) \left(1 - \frac{\eta_{PV}}{t\alpha}\right) \quad (3)$$

The coefficient $\left(\frac{t\alpha}{H_l}\right)$ is difficult to measure. Hence based on the report provided by the manufacturer on the nominal cell temperature 20 °C and incident radiation 800 W/m^2 under the no-load condition the equation is rewritten as

$$\frac{t\alpha}{H_l} = \frac{T_{cel,nom} - T_{\alpha,nom}}{I_{T,nom}} \quad (4)$$

The final PV cell temperature can be obtained for the value of $(\alpha t) = 0.90$

$$T_{cel} = T_\alpha + I_T \frac{T_{cel,nom} - T_{\alpha,nom}}{I_{T,nom}} \left(1 - \frac{\eta_{PV}}{0.90}\right) \quad (5)$$

The geographical location of the area is 28.47 latitude to 78.14 longitudes. Solar radiation data are collected from the above location directly from the National Aeronautics and Space Administration (NASA) surface meteorology and solar energy database. The region receives annual mean solar radiation of 5.32 kWh/m^2 and a clear index of 0.5. The maximum radiation was recorded as 7.420 kWh/m^2 in the month of May and clear index 0.7 in the month of October. C is clearness of sky measured in terms of clearness index. It signifies the volume of solar radiation that strikes the earth's surface. The region has a huge solar energy harness capacity with more than 300 sunny days. 22,369 kWh/m^2/yr recorded as the total annual potential of solar capacity. Figures 5, 6, and 7 show the study area's monthly average radiation and clearness index [28]. The area has a variable temperature throughout the year maximum average temperature recorded in the month of June is 22.5 °C and the minimum in January 7.5 °C.

Wind Energy System

Wind turbines convert the kinetic energy of wind into electrical energy. The wind turbine's shaft is rotated with the flow of wind over the rotor, which can be used to generate electrical power. Wind turbine is manufactured in variety of sizes from small rooftop to large commercial application. In the present work, the BWC EXCEL 1-R wind turbine model is considered according to the wind velocity profile in the area. Wind turbines' selection depends on the hub height, service height, types of components, and cost, cut-in speed, and type of electricity

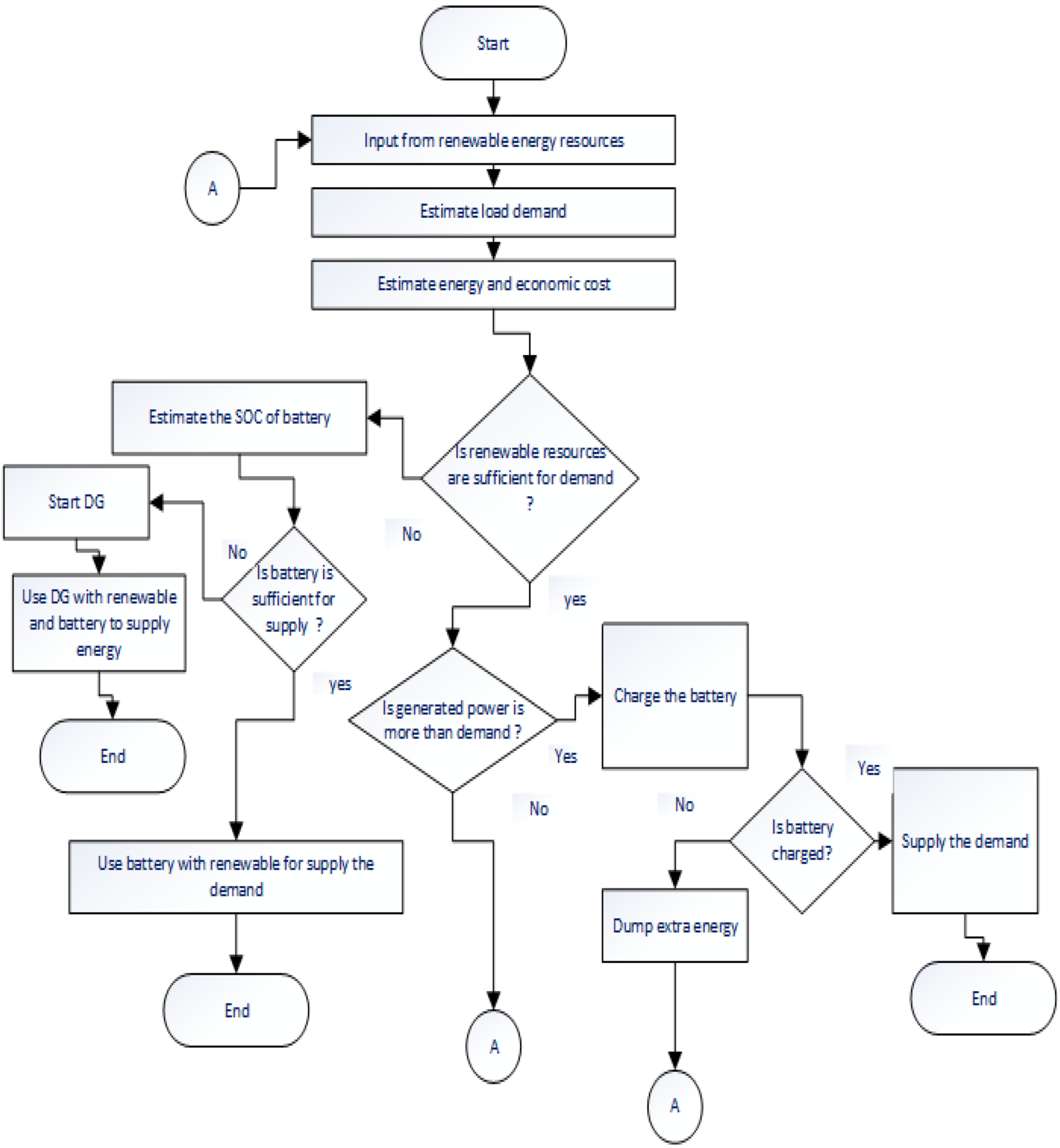

Fig. 4 Flowchart of methodology

generated. The power characteristics of wind turbines are shown in Fig. 8.

The characteristic suggests that V_1, V_2 and V_r is the cut-in, cut-out, and rated wind turbine speed. The required wind speed at a specific height is obtained by Eq. (6). V and V_{ref} denote the wind speed at reference height h and h_{ref}, respectively, γ is the ground surface friction whose value varies from 0.10 for flat land to 0.25 for the heavily forested area [29].

$$V = V_{ref}\left\{\frac{h}{h_{ref}}\right\}^{\gamma} \tag{6}$$

The wind turbine output is represented by equation

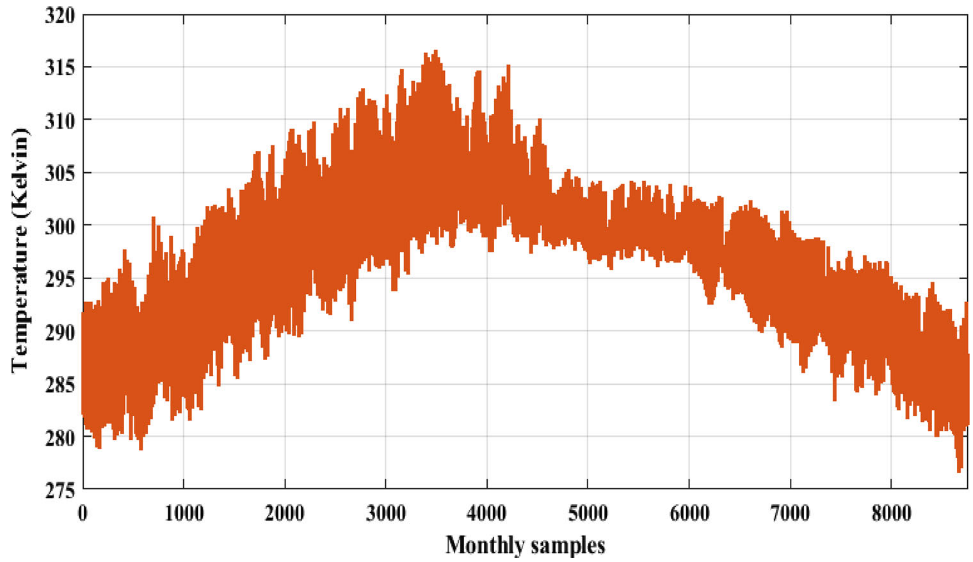

Fig. 5 Temperature variation of the study area

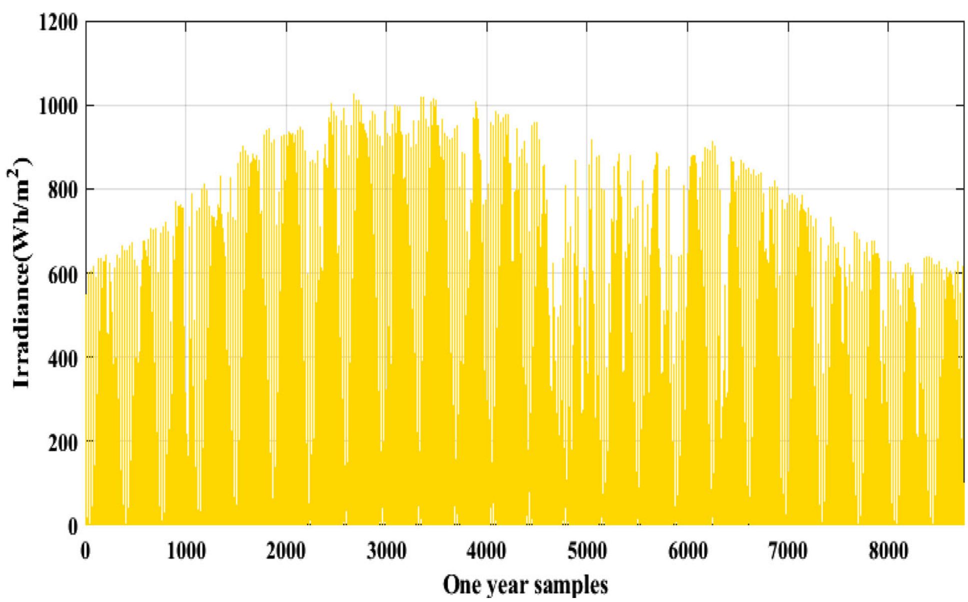

Fig. 6 Variation of solar irradiance

$$P_{wind}(V) = \begin{cases} 0\,for\; V < V_1 \\ aV^3\,for\; V_1 < V < V_r \\ P_r\,for,\;\; V_r < V < V_2 \end{cases} \tag{7}$$

$$a = \frac{P_r}{\left(V_r^3 - V_1^3\right)} \tag{8}$$

$$b = \frac{V_1^3}{\left(V_r^3 - V_1^3\right)} \tag{9}$$

The V_1 ranges 2.5 -3.5 m/s, while V_2 lies between 20 and 25 m/s. The power output of the wind turbine is represented by Eq. (10)

$$P_{wt} = P_{wind}A_{wind}\eta_{wind} \tag{10}$$

Wind turbines in India are designed at 10 m/s wind speed. The study area's wind speed is (4–16 m/s), suitable for low-speed designed wind turbines. Figures 9, 10 show the study area's monthly average wind speed. These data of wind speed variation and average monthly wind speed are directly taken from NASA surface metrology and solar database [28].

Battery storage system (BSS)

The storage unit is used in the energy model to store the extra power and delivers the power when PV and wind turbines fail to provide the required energy to the consumers. The diesel generator is also used in the model to ensure consistency in the power supply. Hence when all three cannot meet, the demand for diesel generators started.

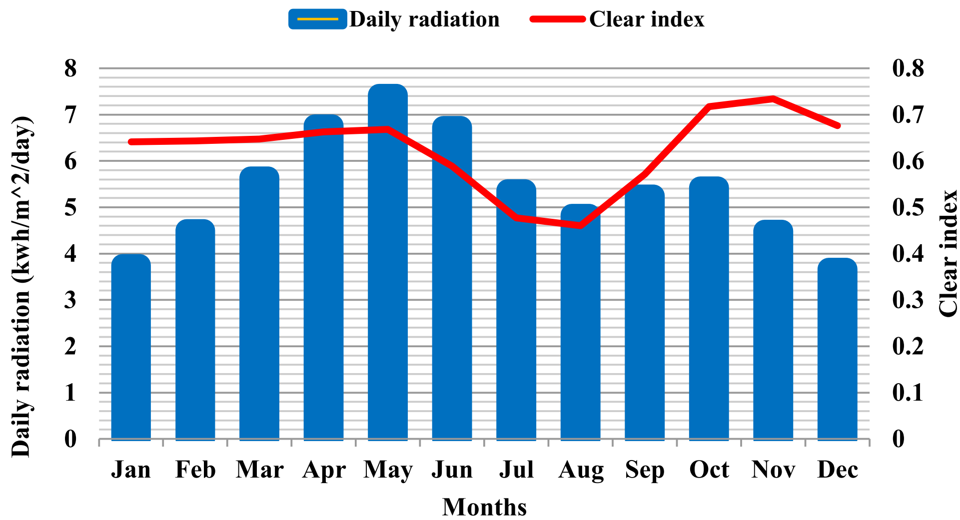

Fig. 7 Monthly average radiation and clear index of the region

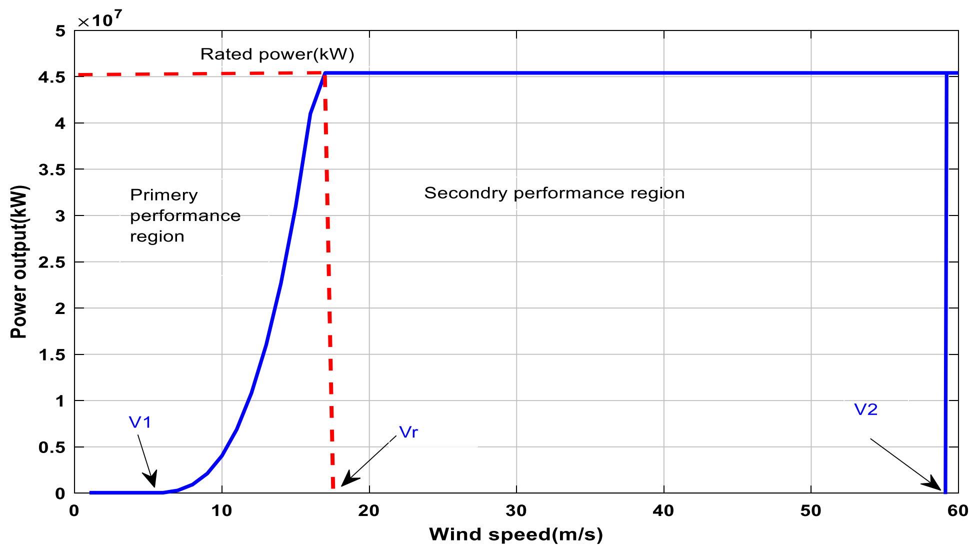

Fig. 8 Characteristics curve of wind turbine

For the battery's long life, regular maintenance of the battery is necessary [30]. The round-trip efficiency of the battery considers 80%. The stored energy in the battery is expressed as

$$q_{bat} = q_{bat,0} + \int_{0}^{\xi} V_{bat} I_{bat} dt \tag{11}$$

The state of battery charge is defined as

$$Bat_{soc} = \frac{q_{bat}}{q_{bat,max}} \times 100(\%) \tag{12}$$

The battery's kinetic model can calculate the extreme permissible charge and discharge power. The maximum absorbed energy by two-tank system is given by

$$P_{bat(cmax)kbm} = \frac{kq_1 e^{-k\Delta t} + qkc\left(1 - e^{-k\Delta t}\right)}{1 - e^{-k\Delta t} + c\left(k\Delta t - 1 + e^{-k\Delta t}\right)} \tag{13}$$

The maximum discharge power of the battery in the given time is represented by the equation.

$$P_{bat(dmax)kbm} = \frac{-kcq_{max+}kq_1 e^{-k\Delta t} + qkc\left(1 - e^{-k\Delta t}\right)}{1 - e^{-k\Delta t} + c\left(k\Delta t - 1 + e^{-k\Delta t}\right)} \tag{14}$$

The energy capacity which absorbed or withdrawn from a battery bank in each time step can be calculated by the following equations

$$q_{1\_end} = q_1 e^{-k\Delta t} + \frac{(qkc - p)\left(1 - e^{-k\Delta t}\right)}{k} + \frac{pc\left(k\Delta t - 1 + e^{-k\Delta t}\right)}{k} \tag{15}$$

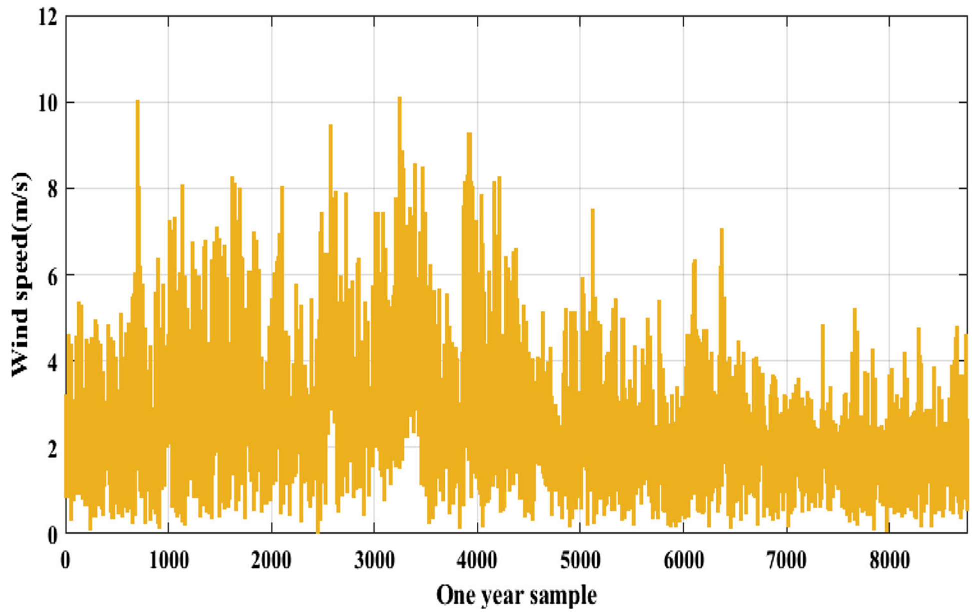

Fig. 9 Variation of wind speed in the study area

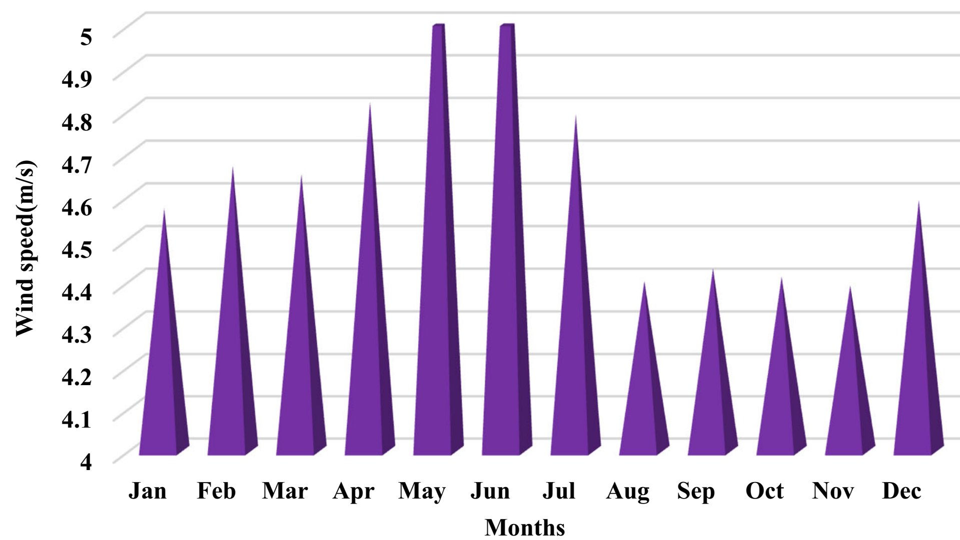

Fig. 10 Monthly average wind speed of study area

$$q_{2\_end} = q_2 e^{-k\Delta t} + q(1-c) + \frac{pc\left(k\Delta t - 1 + e^{-k\Delta t}\right)}{k} \quad (16)$$

Diesel Generator

Diesel generator is the widely used source of generation of electricity in remote areas. Its application ranges from the community, telecommunication, individual, hospital, and educational institution due to its reliability, costs, and ability to produce electricity when other sources are not available. The diesel generator's capacity is calculated based on the peak electrical load. Two generator sets were used in the present modeling, GEN1 and GEN 2, with a power of 10 kW and a lifetime of 15000 h. The generator's efficiency and maximum load capacity are considered 35 and 25%, respectively. The fuel consumption of the diesel generator is calculated as

$$F = f_{0,gen} y_{gen} + f_{1,gen} P_{gen} \quad (17)$$

The density and the lower heating value of diesel fuel are 820 kg/m^3 and 43.3 MJ/kg.

Economic Modeling

The microgrids viability is represented in terms of overall net present cost (NPC) and the cost of energy (COE). These two parameters are described as:

The hybrid system's economic analysis is carried out in terms of COE. The COE can be represented as the system's yearly cost ratio to the generated energy [31].

$$\mathrm{COE} = {}^{A_c}/_{G_e} \quad (18)$$

A_c is the total annualized capital cost, and G_e is the energy generated. The generated power is the actual demand, excluding excess supplied energy. The total yearly cost comprises yearly capital cost, O&M cost, and replacement cost. The cost A_c is calculated as

$$A_c = C_c + OM_c + R_c \quad (19)$$

where, C_c denotes yearly capital cost,OM_c is the O&M cost,R_c represents yearly replacement cost. The net present cost is a critical factor for analyzing the energy system, which consists of current values of all initial costs, O&M cost, the fuel cost of generator and replacements cost, with the deduction of the present value of all revenues [32]. The other revenues included the value of system components for the entire lifetime of the projects

$$C_{NPC} = {}^{A_c}/_{CRF(j,N)} \quad (20)$$

where $CRF(j,N)$ representing the capital recovery factor j is the rate of interest and N denotes the number of years.

$$CRF(j,N) = {}^{j(j+j)^N}/_{(1+j)^N - 1} \quad (21)$$

Problem Formulation

The area has a rich source of renewable resources. Hence, the supply of energy in the microgrid is formed by combining available resources in the locality. The microgrid proposed for the area consists of a solar/wind/diesel generator and storage device that works on grid-connected mode. The objective of the suggested model is to provide reliable and least-cost electricity to the area. The total cost of energy minimization is formulated by the following objective function:

$$\begin{aligned} \text{Min J(X)} = \sum_{t=1}^{t=24} & [(\delta gen_{1,t} + \rho) + (\vartheta gen_{2,t} + \sigma) \\ & + (\alpha gen_{PV} + \gamma) + (\beta gen_{wt} \\ & + V_{cr}(Z_1 + Z_2 + Z_3) \end{aligned} \quad (22)$$

The above minimization fulfills the following constraint. The node balancing constraints are

$$\begin{aligned} -S_{12,t} - S_{13,t} + gen_{1,t} + Z_{1,t} &= L_{1,t} \\ S_{12,t} - S_{24,t} - S_{23,t} + Z_{2,t} &= L_{2,t} \\ S_{13,t} + S_{23,t} + gen_{2,t} + Z_{3t} &= L_{3,t} \\ S_{24,t} + gen_{3,t} &= 0 \end{aligned} \quad (23)$$

The constraints, which satisfy the DC power, flow in each branch of the suggested microgrid.

$$\begin{bmatrix} S_{12,t} + 10 \\ S_{13,t} + 10 \\ S_{23,t} + 10 \\ S_{24,t} + 10 \end{bmatrix} \cdot \begin{bmatrix} \theta_{1,t} - \theta_{2,t} \\ \theta_{1,t} - \theta_{3,t} \\ \theta_{2,t} - \theta_{3,t} \\ \theta_{2,t} - \theta_{4,t} \end{bmatrix} = 0 \quad (24)$$

The generator capacity is listed as.

$$gen_{1t} \le 10,\ gen_{3t} \le 10,\ gen_{4t} \le 10 \quad (25)$$

The load curtailment constraints are

$$Z_{1t} \le L_{1,t},\ Z_{1t} \le L_{2,t},\ Z_{1t} \le L_{3,t} \quad (26)$$

With the integration of renewable resources, objective function remains the same only a few constraints changed.

$$\begin{aligned} [-S_{12,t} - S_{13,t} + gen_{1,t} + Z_{1,t} &= L_{1,t} \\ S_{12,t} - S_{24,t} - S_{23,t} + Z_{2,t} + P_{wind,t} + P_{pv,t} &= L_{2,t} \\ S_{13,t} + S_{23,t} + gen_{3,t} + Z_{3t} &= L_{3,t} \\ S_{24,t} + gen_{4,t} &= L_{4,t}] \end{aligned} \quad (27)$$

Battery units are included in the modeling to provide reliable electrification to the area. The area demand of energy cannot be accomplished by renewable resources alone. Hence storage and DG units are used when renewable sources are not sufficient to provide electricity to the area. The battery cannot be charged by renewable resources. As a result, the storage unit was designed to store excess energy during low demand and provide power during peak hours.

$$\begin{aligned} [-S_{12,t} - S_{13,t} + gen_{1,t} + Z_{1,t} + P_{dischrging} + P_{charge} &= L_{1,t} \\ S_{12,t} - S_{24,t} - S_{23,t} + Z_{2,t} &= L_{2,t} \\ S_{13,t} + S_{23,t} + gen_{3,t} + Z_{3t} &= L_{3,t} \\ S_{24,t} + gen_{4,t} &= L_{4,,t}] \end{aligned} \quad (28)$$

$$\begin{bmatrix} E_{t+1,m}^{battery} = E_{t,m}^{battery} - \dfrac{E_{t,m}^{discharge}}{\eta_{discharge}} + P_{t,m}^{charge}\eta_{charge} \\ E_t^{battery}.SOC_{discharge} \le E_t^{battery}.SOC_{charge} \\ 0 \le P_{t,m}^{discharge} \le P_{t,m}^{charge} \end{bmatrix} \quad (29)$$

To analyze the microgrid, planning efforts are made to properly mix the available energy resources so that the total cost of operation and the levelized cost of energy (LCOE) are the least.

Optimization Algorithms

For the optimization microgrid problem such as size optimization, cost of energy optimization numerous pieces of literature is available. The modern optimization problem is

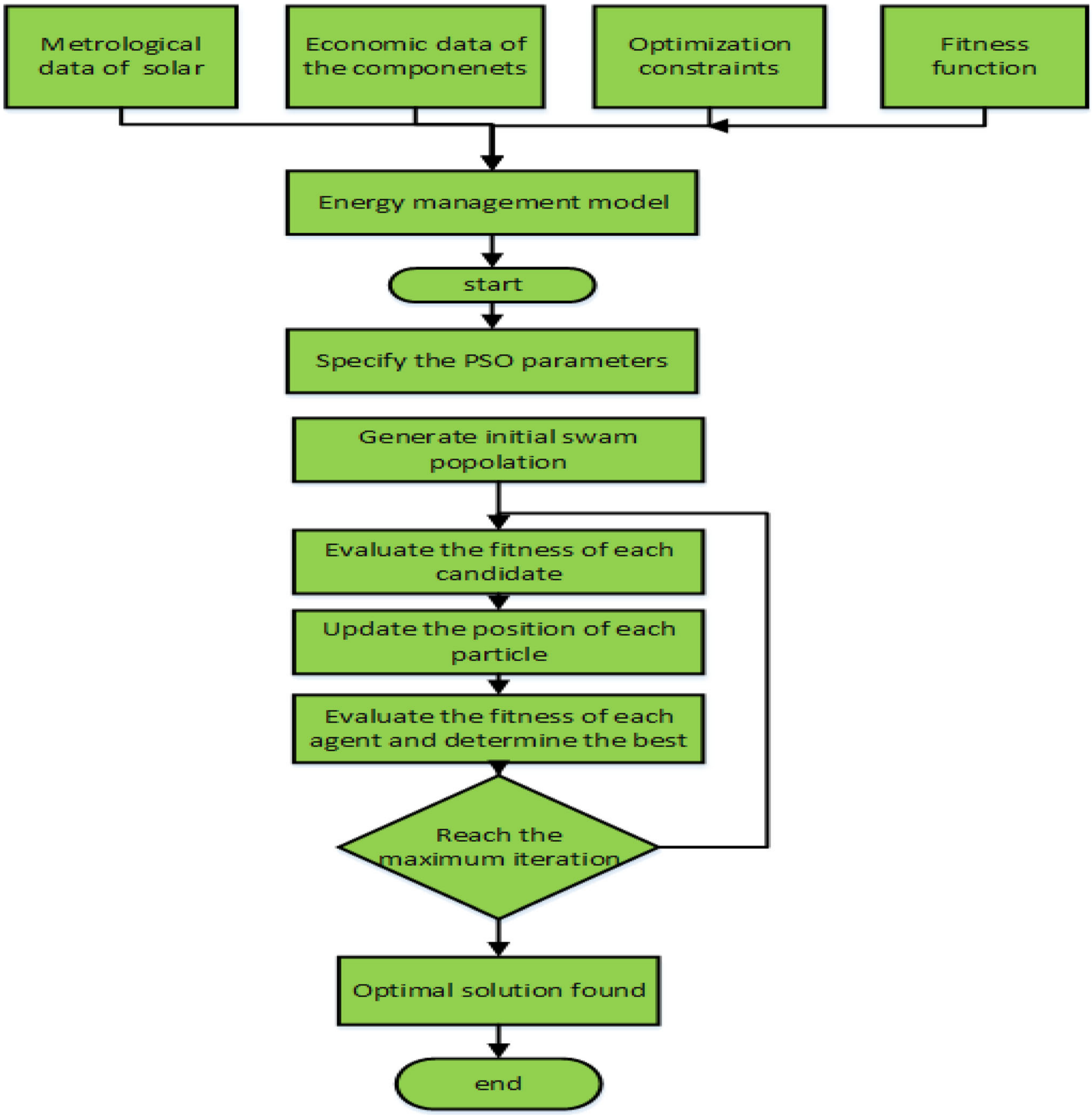

Fig. 11 Optimization algorithms

widely used. Algorithms are genetic algorithm (GA), Gray wolf optimization (GWO), cuckoo search algorithm, particle swarm optimization (PSO), etc. Particle swarm optimization is used in various engineering optimization problems due to simplicity in use and excellent optimization results. In the present work, we used PSO for the optimization of the energy cost of the rural microgrid.

For the above-suggested model, the optimization of the cost of operation is used by PSO. In 1995, Kennedy and Eberhart developed PSO, which is based on swarm behavior in nature, such as bird flocking and fish schooling. It is widely used in a range of problems because of its simplicity and flexibility. It used genuine number randomness and global communication among the swarm rather than mutation, crossover. So, it is easy to implement and requires no encoding and decoding of the problem [33]. Flowchart of optimization is shown in Fig. 11.

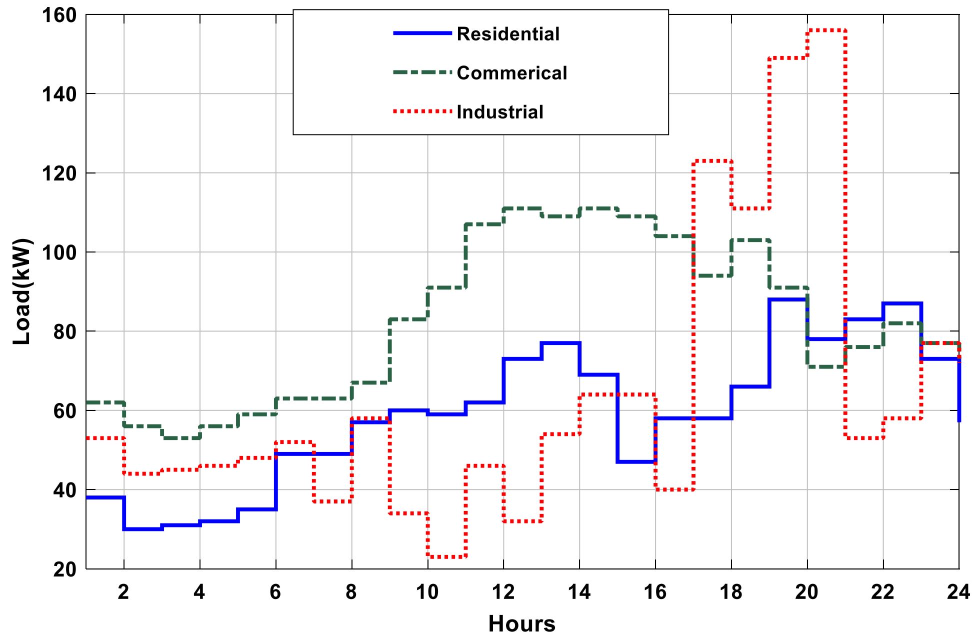

Fig. 12 Demand load of the area

Table 1 Parameter used in microgrid planning

PV module capital cost	$3100/kW
O&M for PV module	$1/kW/yr
Life time of PV module	25 years
Capacity of each module	327 W
WT capital cost	$4152
WT O&M charge	$3798
Capacity of each WT	1 kW
Capital cost (DG)	$700
O&M (DG)	$0.0056/h
Capacity of each DG	20 kW
WT efficiency	90%
Battery charge	82%
Rating of each battery	12 V, Lead acid, 1kWh
Electricity sells	$0.06/kWh
Electricity purchase	$0.135/kWh
Interest rate	5%
Battery self-discharge	1%
Population of PSO swarm	50
Inertia rate	0.02
Social parameter	0.50
Number of iterations	200

Demand Analysis

The area's demand is estimated considering commercial, industrial, and residential loads. The collected data combined the load of area, which is varying from 11 to 160 kW. The load variation is considered unchanged for 24 h during the model's simulation. The overall consumption of yearly load is for further analysis (Fig. 12).

Total load of the area denoted as

$$\text{Total Load} = P_{s,t}^{Wind} + P_{s,t}^{PV} - Demand \tag{30}$$

Intermittency of the renewable resources forced the additional energy resources in the modeling. Renewable energy resources are not sufficient to supply the demand of the area. Hence, DG units with a battery system are provided to give the power when needed. The excess power is stored by the battery when the production of renewable resources is more than enough to the demand of the area.

Results and Discussion

The proposed microgrid is optimized for the reliable electrification of the region using particle swarm optimization. The algorithm mentioned above deals with the objective function for the least operation cost. The algorithm initializes with the population size of 50, and the number of iterations is 200. The load profile of area varying may be possible to add hourly load variation due to customers' requirement. Parameters used in the above-proposed microgrid simulation are listed in Table 1.

Simulation of the above-proposed microgrid is carried out in the MATLAB environment. Figures 13, 14, and 15 show the power generated by each module, WT and DG.

For the electrification of the community and analyze the microgrid, different cases have been considered. For the proper planning of microgrids, a minimum number of components should be used. The sizing of components

Fig. 13 Power generated by each PV module

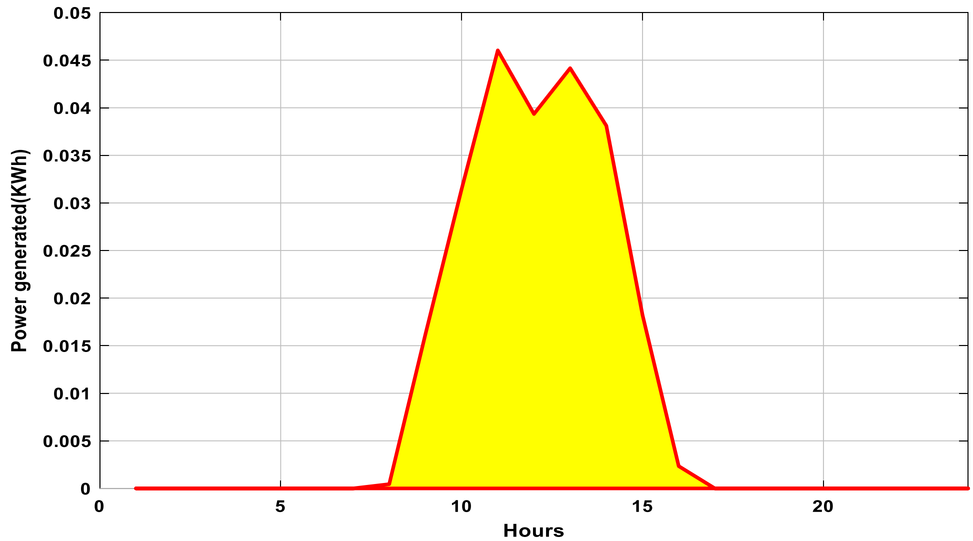

Fig. 14 Power generated by each DG unit

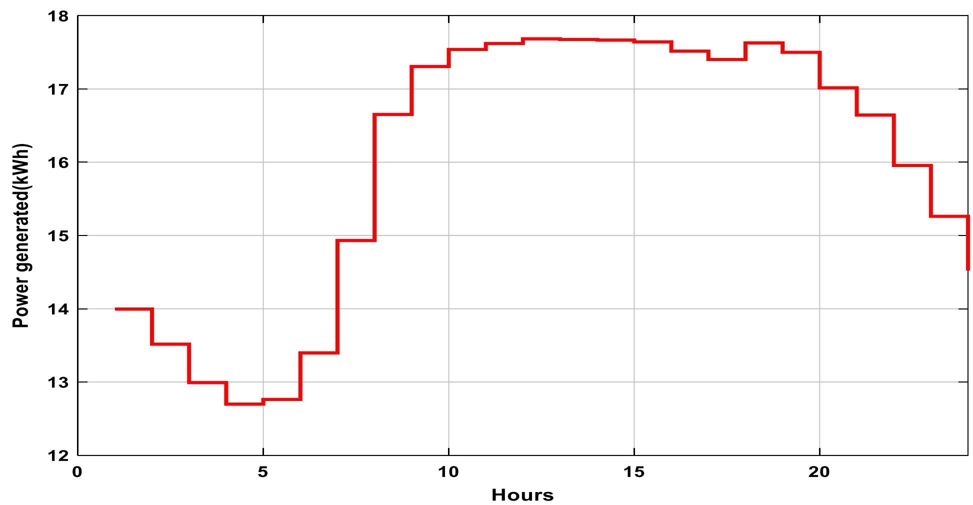

Fig. 15 Power output of each wind turbine

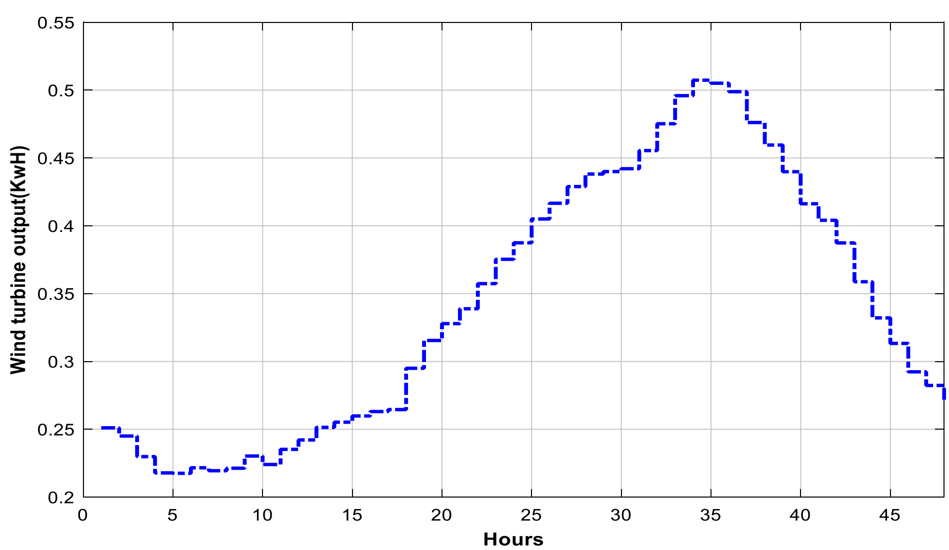

Table 2 Optimal number of components for different cases

Apparatuses	C1	C2	C3	C4
DG (20 kW)	8	0	3	0
Solar PV	0	50	36	0
WT	0	40	35	0
Battery	0	25	18	0
Grid supply (kW)	0	0	0	50

Table 3 Total cost of operation and LCOE for different cases

Cases	Total cost of operation ($)	LCOE($/kWh)
C 1	280,998.65	4.00
C2	130,635.60	1.65
C3	98,649.87	1.28
C4	2,100,345.98	0.25

Table 4 Energy production by various components

Components	C1	C2	C3	C4
DG	80,000	0	11,244	0
SPV	0	15,369	12,424	0
WT	0	149,461	123,118	0
GRID	0	0	0	80,000

reduces the cost burden on the planning. For optimization of the number of components PSO used, Table 2 suggests the optimal number of components used in each case. In each case, the number of components are calculated. It is evident from the table the C3 is maximum harnessing the renewable energy resources and a smaller number of DG sets are used. Hence, greenhouse gas emissions can minimize, and the reliability of the power supply is increased.

The fuel price for the DG sets is considered $0.79/L for the calculation in the present planning of microgrids. The development of grid infrastructure appeals to additional costs. Hence, we assume the cost of electricity from the grid is $0.30/kWh, and the cost of grid extension is $ 2500/KM. The total optimal cost and COE calculated are shown in Table 3.

It can be observed from the table the case 1 and case 4 cost more to realize the demand of energy. The value of LOCE is lower in case 4. The best way to supplied energy is to provide energy using renewable energy resources and battery systems, so that load on the grid and the environment can be reduced. The extension of the grid and operation of the diesel generator are not environmentally friendly. Hence the energy planner always emphasized the maximum utilization of renewable energy resources and proper mixing of the battery unit for the total load of the area. In terms of the contribution of renewable resources, C2 used 100% renewable penetration to fulfill load without DG sets. The intermittent nature of renewable supply does not guarantee the whole production from renewable resources. Hence C2 is not a reliable option for electrification. C3, in which renewable penetration is 85%, works with DG to provide a more efficient electrification method. The surplus generated electricity can be stored in the battery to use in peak hours or no supply.

From Table 4 excess energy produced by renewable energy resource evident, which can be allowed to store in the battery. Renewable energy supply depends on the weather condition and the location of the area. Hence some conditions may arise when renewable may not fully meet the demand. In this regard, in case 3, all the needs can be met by the renewable resources and battery system investigated for the capacity shortage. The analysis was carried out by varying 10% to 40%.

The most optimal design of standalone system for electrifying the rural population is formed by the fusion of available energy resources and DG sets shown in Table 5. The microgrid configuration combining PV, WT, DG, and battery is an effective option for the rural community's electrification. The proposed planning method has economic benefits compared to the system with other

Table 5 Variation of unmet energy for C3

Components	Unmet=10%	Unmet=20%	Unmet=30%	Unmet=40%
Demand of area (kW/yr.)	80,000.00	80,000.00	80,000.00	80,000.00
Cost function value	83,355.45	5694.96	42,174.95	38,126.07
DG (kWh/yr.)	7905.06	00	00	00
SPV (kWh/yr.)	14,711.10	12,454.89	00	00
Wind (kWh/yr.)	162,432.79	155,431.70	112,768.79	359,879.65
Unserved power(kWh/yr)	8032.95	16,979.89	25,989.70	35,989.69
RE input (kWh/yr.)	186,944.60	165,896.35	114,987.75	69,744.85

combinations in LCOE, the total cost of operation, and greenhouse emission. The suggested system benefits India's rural population to provide a reliable supply of power.

Conclusion

In an emerging nation like India, a significant portion of the population lacks reliable electricity access. The proposed work analyzed such areas and suggested the optimal planning for the rural population's electrification. The microgrid model with the optimal design is designed by a combination of energy resources in the locality. The energy model investigated the rural region of Uttarakhand state of India. Four cases have been discussed for finding the optimal cost of energy using the particle swarm optimization algorithm. The model suggests the optimum number of energy resources for the area's reliable electrification. According to the findings, the net present cost of microgrid operation in grid-connected mode is $2,100,345.98, with per unit cost of energy is $ 0.25, which is least compared to other modes of operation. The intermittency of renewable sources is analyzed for the optimum case by varying 10 to 40% of total production. The finding indicates that maximum renewable penetration is achieved when the energy is 10%. It is necessary to reduce the total energy cost the participation of renewable resources increased. The suggested model can improve microgrid planning's economic and technical aspects with lower deficiency of demand management.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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