CASE STUDY

Feasibility Study of Standalone Hybrid Wind-PV-Battery Microgrid Operation

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Abstract

This paper presents techno-economic analysis of hybrid wind-PV-battery based microgrid in standalone mode for technical university campus located in north-west Indian state Rajasthan. Generation unit consists of NPS100C-21 wind turbine, Tata TS250 PV module, Leonics Appolo series converter and Cellcube series battery bank. Hourly wind profile, solar data and electrical load of previous one year has been used to simulate thousands of cases to obtain optimal microgrid operation in terms of cost and number of generating units. Converter unit regulates voltage in AC and DC bus-bar. Battery acts as active power source and backup unit to meet additional power demand when wind-PV generation is deficit. This paper aims to find a feasible solution to make university campus free from fossil fuel based energy sources. Simulation results have been established under varying meteorological conditions and load data. Site lies in low wind region and maximum wind penetration is observed to be 19.5%. COE of considered generation unit is obtained as \$0.238 with renewable fraction of 100%. Obtained optimal generation unit is competitive with grid extension in terms of techno-economic feasibility.

Keywords Standalone renewable system · Energy storage unit · Converter · Techno-economic feasibility

Nomenclature

RES	Renewable energy sources
HOMER	Hybrid optimization model for electric renewable
η_{cell}	PV cell efficiency
T_{amb}	Ambient temperature
T_{NOC}	Nominal operating temperature
$P_W(v)$	Output power of wind turbine
DOD	Depth of discharge
SOC	State of charge
O&M	Operation and maintenance
I_{batt}	Battery current
σ	Battery self discharging
Φ_{batt}	Temperature coefficient
B_s	Battery storage capacity (Ah)
S_{AH}	Battery bank charge storage capacity
I_{BSU}	Battery discharge current
B_{s1} and B_{s2}	Capacities of the battery at different discharge-rate states
P_{PV}	Power of PV array
P_{WT}	Power of wind turbine
T_{life}	Rated life of component
LCC	Life cycle cost
$C_{f,rec}$	Capital recovery factor
T_{proj}	Project lifetime
$C_{tot,annu}$	Total annualized cost
CRF	Capital recovery factor
COE	Levelized cost of energy
NPC	Net present cost
E_{served}	Useful electrical load served
f_{ren}	Renewable fraction
E_{ser}	Total electrical energy served
E_{ninren}	Electrical energy generated from non-renewable sources
T_{proj}	Project tenure

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Introduction

Increasing environmental concerns and depleting conventional energy reserves has been major global challenge of this century [1, 2]. Hybrid RES based generation is supposed to feed major future energy demand [3]. Power extension of grid to isolated regions is associated with technical and economical limitation. It can be overcome by increasing dependence on RES based generation [4]. It has encouraged exploration and exploitation of RES based decentralized power generation. Complementary characteristics of wind and solar energy can be used as potential power generation source for off-grid locations [5]. Major problems associated with these sources include non-promising and intermittent nature. Standalone hybrid RES based on wind–solar generation is considered more feasible and reliable as compared to single source stand-alone systems [6]. Cost effective generation can only be ensured by overcoming hurdles like: optimal size of generator & ESU [7], power electronic converter interface control strategy, energy management policy [8] and type of generator & ESU [9]. In certain locations like hill top load stations [10], small islands [11, 12], broadcasting stations [13], satellite earth station [14], eco-tourism sites [15], hotels [16], etc.; hybrid wind-PV-storage system can provide reliable power to off-grid loads [17]. Such locations have usually low power demand restricted to lighting loads, small non-linear loads, and common household loads [18]. Speidel and Braunl reviewed feasibility and limitations of RES, ESU in context of typical household application in west Australia for off-grid and grid connected systems [19]. For standalone RES applications, solution of power security hitch can be overcome by suitable ESU [20, 21]. While planning a site for installation of RES based generation, factors needed to be considered includes meteorological data, optimal sizing of conversion equipment, load forecast, and optimization techniques [22, 23]. Literature includes application of hybrid wind-PV for electrification of off-grid community [24], rural areas [25], island [26], etc. and minimization of life cycle cost of involved conversion components [27].

Initial installation cost, intermittent/variable meteorological data and low efficiency of conversion equipment are bottleneck in widespread use of RES generation [28, 29]. Amongst reported solutions, assuring spinning reserve [30–32] and appropriate storage unit services [33–36] has been quite effective. Presently diesel generators are major source of energy for isolated loads like islands, mountain and off-grid regions [37]. Diesel generators are neither economical nor feasible in such locations for long run due to high fuel handling cost and maintenance panic incurred. Such generators have adverse impact on environment. Fortunately, such locations are generally rich in locally available natural sources like wind & solar energy and cost of generation can brought down with optimal sizing as compared to overall running cost of diesel generators [38].

The proposed standalone unit is based on real time average load of 97.8 thousand kWh load per month of Rajasthan Technical University located in Kota (Rajasthan, India) consisting of 900 students capacity student hostel, staff quarters, university departments and is spreaded over 385 acres of land. University has renewable energy department as center of excellence which aims to reduce dependency on grid connected power. HOMER (hybrid optimization model for electric renewable) software developed by United States national renewable energy laboratory has been used to obtain optimal size and economic constraints of standalone hybrid WECS-PV-Battery unit. Paper aims at finding a feasible solution to make university campus free from fossil fuel based energy source.

This paper is organized so as to first introduce problem followed by literature reported in research field and then after define the solution in terms of standalone and hybrid generation. In methodology section, method adopted to perform this case study in terms of simulation steps and component modeling of system. Consecutive section describes technical and economical consideration made to execute this case study. It is followed by technical and economical results obtained for considered load conditions.

Methodology

Literature includes a number of available optimization software tools used for RES based generation [4]. System analysis
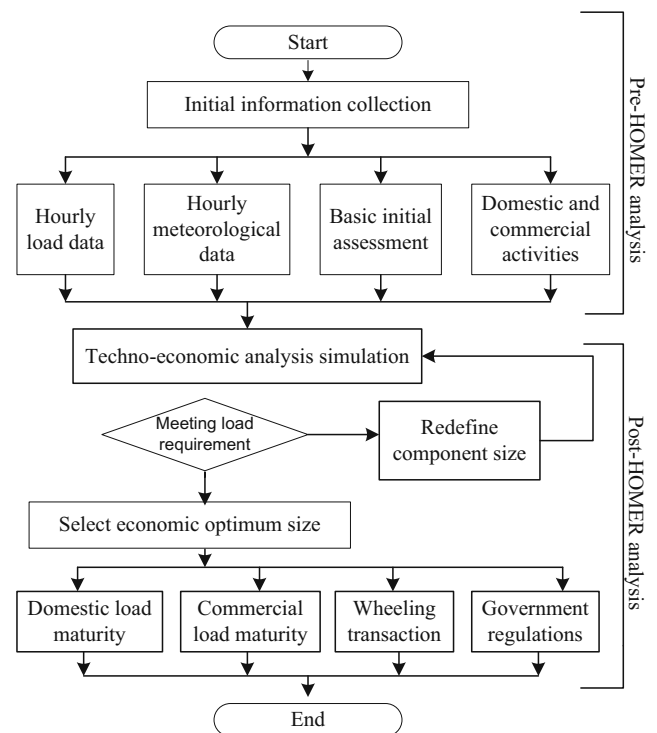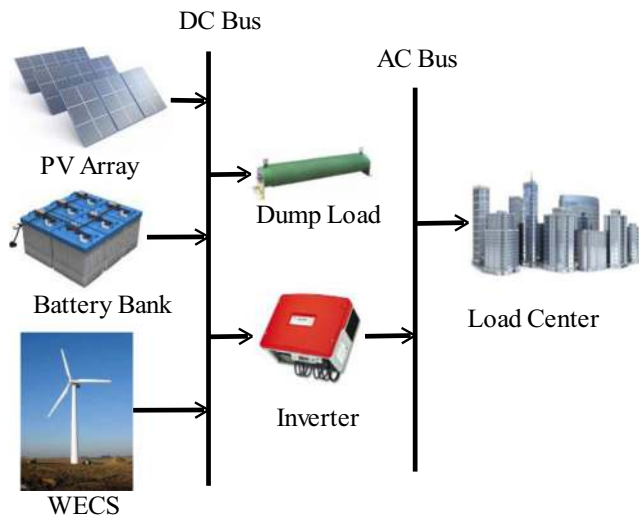

Fig. 1 Methodology adopted

Fig. 2 Schematic architecture of hybrid system

is done in terms of pre and post HOMER analysis as shown in Fig. 1. In pre-HOMER analysis, hourly load data, hourly meteorological data and site layout are collected for university campus. Load data consists of street lighting load, staff quarters, hostels, university central services, sport services and university departments. Generation unit and storage unit capacity depends on load demand. In post HOMER analysis best configuration is selected depending on type of load, wheeling transactions and issues like weather condition, site location and government policies.

Component Sizing Parameters

Component sizing parameters of hybrid model has been reported for optimal configuration [39–41]. This paper considers wind and solar PV to provide base power to the load, and battery acts as backup unit. Each component is simulated in terms of cost and size to obtain low cost power solution.

Photovoltaic Unit

PV unit consists of PV modules consisting of series-parallel configured PV cells to generate electrical energy from solar
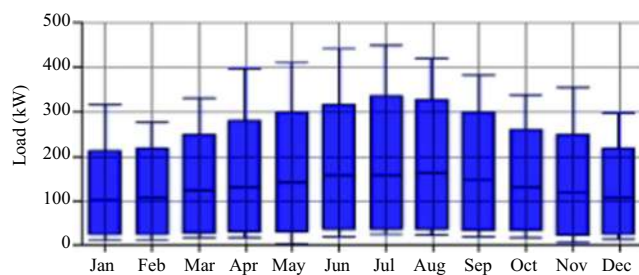

Fig. 3 Hourly load during year 2014

Table 1 Summary of considered load site

Particulars	Details
Site name	Rajasthan Technical University
Location	Akelgarh
District	Kota
State	Rajasthan
Country	India
Latitude	25° 8.5'N
Longitude	75° 48.6′E
Height from sea level (meters)	251.1
Total area (acres)	385
Rivers available	1
Water wells	7
Total habitates	3200
Medical facilities	1
Post office	1
Bank	1
Guest house	1

irradiance and meet load parameters. Energy output of PV unit is calculated as:

$$P_{PV} = K_{df}.P_{PV,rated}.\frac{I_g}{I_{em}} \tag{1}$$

$$P_{PV,rated} = \eta_{PV}A_{PV}I_{PV} \tag{2}$$

Where, K_{df} is derating factor, $P_{PV,rated}$ is the rated capacity of PV array (kW), I_g is actual solar irradiance incident on solar array
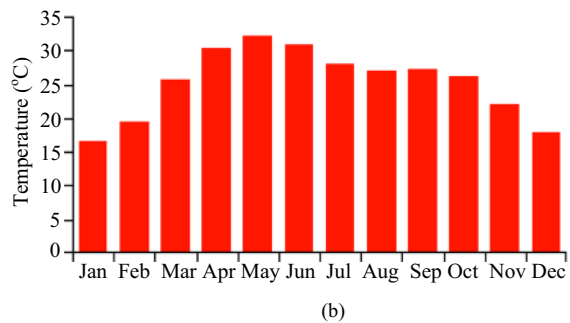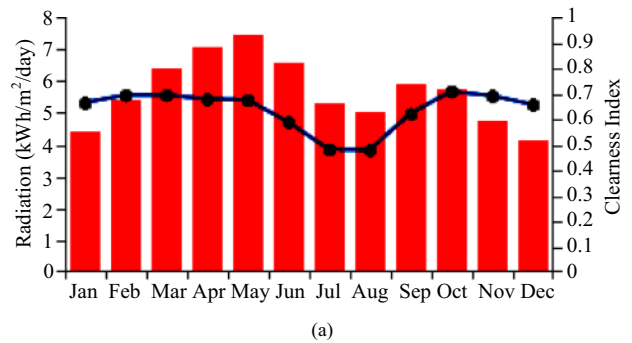

(a)

(b)

Fig. 4 (a) Monthly average solar radiation and clearness index, (b) Average temperature

Table 2 Monthly average meteorological data of site

Month	Clearness Index	Average Radiation (kWh/m^2/day)	Average Wind speed (m/s)
January	0.661	4.43	2.640
February	0.691	5.42	3.150
March	0.692	6.41	2.769
April	0.676	7.05	3.790
May	0.673	7.44	4.500
June	0.585	6.58	4.680
July	0.478	5.31	4.060
August	0.477	5.04	3.330
September	0.619	5.91	3.21.
October	0.706	5.76	2.460
November	0.689	4.75	2.410
December	0.654	4.14	2.520
Annual average	0.634	5.69	3.29

(kWh/m^2), A_{PV} is area of PV panel (m^2), η_{PV} is conversion efficiency of PV unit and I_{PV} is global solar irradiance (W/m^2). Derating factor refers to discrepancy between rated performance and actual performance of PV array due to dust, temperature variation, shading, snow cover, aging, wiring losses, etc.

The efficiency of PV module depends on PV cell properties including PV module efficiency (η_{md}), conversion efficiency of inverter (η_{inv}), module factor (F_{md}) and number of connected PV cells (N_{md}). It is given as:

$$\eta_{PV} = \eta_{md}\eta_{inv}F_{md}N_{md} \tag{3}$$

Efficiency of the PV cell depends on its reference efficiency (η_{ref}), efficiency coefficient as a function of temperature (β), cell temperature (T_c) and reference cell temperature (T_{ref}). Thus, PV cell efficiency (η_{cell}) is estimated as:

$$\eta_{cell} = \eta_{ref}\left\{1 - \beta\left(T_c - T_{ref}\right)\right\} \tag{4}$$

Cell temperature depends on global solar irradiance, ambient temperature (T_{amb}) and nominal operating temperature (T_{NOC}) of PV cell and given as:

$$T_c = T_{amb}I_{PV}\left(\frac{T_{NOC} - 20}{800}\right) \tag{5}$$

Wind Generation Unit

Generation from wind turbine depends on wind speed and hub height. The vertical wind profile is adjusted for a given height by using power law. Wind speed for specific height is given as:

$$v(h)/v(h_b) = (h/h_b)^\alpha \tag{6}$$

Where, $v(h)$ is mean wind speed at hub height (h), $v(h_b)$ is mean wind speed at reference height and α is power law coefficient of wind speed. Average value of α is approximately 0.143 across the world and obtained as:

$$\alpha = [\log v(h) - \log v(h_b)]/(\log h - \log h_b) \tag{7}$$

For HOMER application, only mean wind speed is not enough and time series data of wind speed is required. So wind frequency distribution information is also necessary. Commonly used technique like Weibull distribution, Rayleigh distribution, etc. is used to obtain this information. Weibull distribution function characterized by shape parameter 'k' and scale parameter 'c' for wind is given as:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \tag{8}$$

Output power of wind turbine $P_W(v)$ can be obtained as:

$$P_W(v) = \begin{cases} P_{nr}\left(v^2 - v_{ci}^2\right)/(v_r - v_{ci}); & \text{for} \quad v_{ci} \leq v \leq v_r \\ P_{nr}; & \text{for} \quad v_r \leq v \leq v_{co} \\ 0; & \text{for} \quad v_{ci} > v > v_r \end{cases} \tag{9}$$

Where, P_{nr} is nominal rated power, v_{ci} is cut in wind speed and v_{co} cut off wind speed.
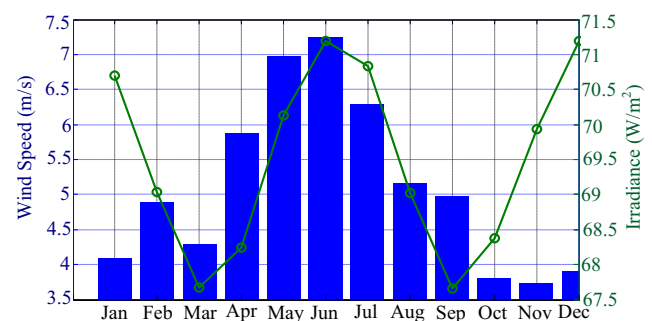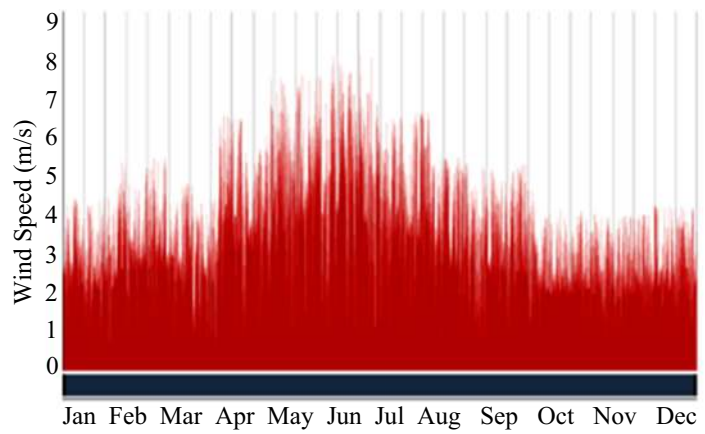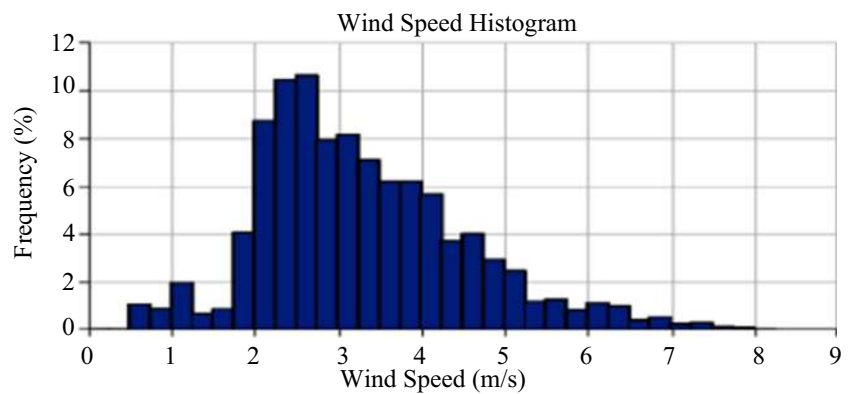

Fig. 5 Monthly wind and solar characteristics

Fig. 6 (a) Daily Wind speed, (b) Frequency distribution of wind speed

(a)

(b)

Battery Bank

Deep cycle discharge battery has been used as backup unit. Selection of battery depends on factors like depth of discharge (DOD), state of charge (SOC), operation and maintenance (O&M) cost, storage capacity, rate of charge/discharge, ambient temperature, life cycle, etc. [20, 21]. The SOC of a battery is defined as the ratio of its current capacity ($Q(t)$) to the nominal capacity (Q_n). The nominal capacity is given by the manufacturer and represents the maximum amount of charge that can be stored in the battery. For an ideal battery, SOC can be given as:

$$SOC = SOC_0 + \int_{t_0}^{t_1} \left(\frac{I_{batt}}{B_s}\right) dt \tag{10}$$

Where, SOC_0 is battery initial state of charge, t_0 & t_1 are starting and ending time (hours), I_{batt} is battery current, and B_s is battery storage capacity. Considering self discharging (σ) and charging/discharging efficiency (η_{batt}) losses during charging and discharging of battery for storing period, SOC is given as:

$$SOC = SOC_0 \left[1 - \frac{\sigma}{24}(t_1 - t_0)\right] + \int_{t_0}^{t_1} \left(\frac{I_{batt} \cdot \eta_{batt}}{B_s}\right) dt \tag{11}$$

Battery storage capacity (B_s) and number of batteries (n_{batt}) is given as:

$$B_s = \frac{P_c}{\eta_{batt}} \cdot V_b \cdot DOD = \frac{n_{ad} \cdot P_{load}}{\eta_{batt}} \cdot V_b \cdot DOD \tag{12}$$

$$n_{batt} = S_{AH}/S_1 \tag{13}$$

$$n_{string} = n_{batt} \cdot V_b/48 \tag{14}$$

Where, P_c is power demand for continuous autonomous days ($P_c = n_{ad} * P_{load}$), P_{load} is daily energy consumption,
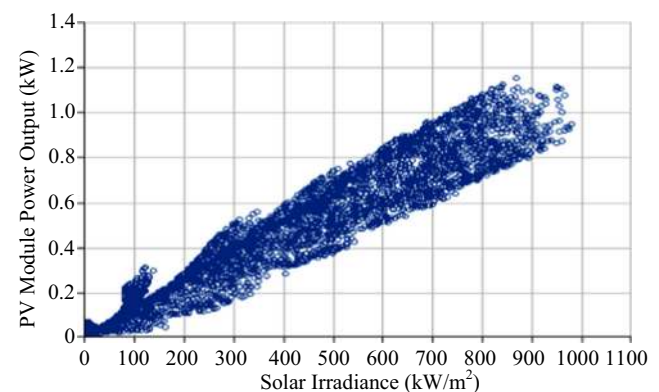

Fig. 7 PV power output for solar radiation

Table 3   Technical data of PV module

Technical data	Value	Unit
Manufacturer	TATA Power Solar	
Model	TS250	
Electrical parameters at standard test conditions (STC)		
Nominal power output	250	(W)
Power tolerance	± 2.5	(%)
Module efficiency	15.00	(%)
Voltage at PMAX VMPP	30.7	(V)
Current at PMAX IMPP	8.16	(A)
Open-circuit voltage VOC	38.1	(V)
Short-circuit current ISC	8.58	(A)
Electrical parameters at NOCT (47 ± 2 °C)		
Power output PMAX	180.0	(W)
Voltage at PMAX VMPP	27.2	(V)
Current at PMAX IMPP	6.64	(A)
Open-circuit voltage VOC	33.5	(V)
Short-circuit current ISC	7.15	(A)
Module general characteristics		
Operating temperature range	−40 and + 85	(°C)
Module dimensions L x W x H	1667 × 1000 × 33	(mm)
Module weight (approx)	19.1	(kg)
Module efficiency	−0.06 ± 0.01	(%/°C)

η_{inv} is inverter efficiency, $\eta_{bi} = \eta_{inv}.\eta_{batt}$ is overall battery and inverter efficiency, V_b is battery rated voltage, n_{ad} is number of autonomous days powered by battery, S_{AH} is battery bank charge storage capacity, S_1 is storage capacity of unit battery, n_{batt} is total number of batteries, and n_{string} is number of strings.

Storage capacity of battery (B_s) depends on temperature and given as:

$$B_s = B'_s(1 + \Phi_{batt}(T_{batt} - 298.15)) \tag{15}$$

Where, B'_s is rated capacity of battery, Φ_{batt} is temperature coefficient and T_{batt} is battery temperature in Kelvin scale.

For hybrid PV-wind system, neglecting the cable losses, battery current (I_{batt}) is given as:

$$I_{batt}(t) = \frac{P_{PV}(t) + P_{WT}(t) - P_{AC,load}(t)/\eta_{inv} - P_{DC,load}(t)}{V_{batt}(t)} \tag{16}$$

Where, P_{PV}, P_{WT}, and P_{load} are power of PV array, wind turbine, and load respectively in Watt. V_{batt} is battery voltage in Volts.

Peukert equation [42, 43] is used to approximate available capacity of a battery capacity to discharge rate is expressed as:

$$B_s = I^n_{BSU}.t \tag{17}$$

Where, I_{BSU} is discharge current, t is the time to discharge current, and n is Peukert constant. Peukert constant is directly related to internal resistance of battery and indicates battery performance under continuous heavy currents. Discharge current at one discharge rate is related to another combination of current and discharge rate as:

$$B_{s1} = B_{s2}.\left(\frac{I_{BSU2}}{I_{BSU1}}\right)^{n-1} \tag{18}$$

Where, B_{s1} and B_{s2} are capacities of the battery at different discharge-rate states.

SOC at a constant discharge rate can be obtained as:

$$SOC(t) = 1 - \left(\frac{I_{BSU}}{B_s}\right).t \tag{19}$$

The current is continuously variable over time. Considering constant current at time t_k, change in charge state of the cell is given as:

$$\Delta SOC(t_k) = \frac{I_{BSUk}}{B_{s1}}.\left(\frac{I_{BSUk}}{I_{BSU1}}\right)^{n-1}.\Delta t \tag{20}$$

Considering recharging phase of battery when current in cell becomes negative, SOC increases and expressed as:

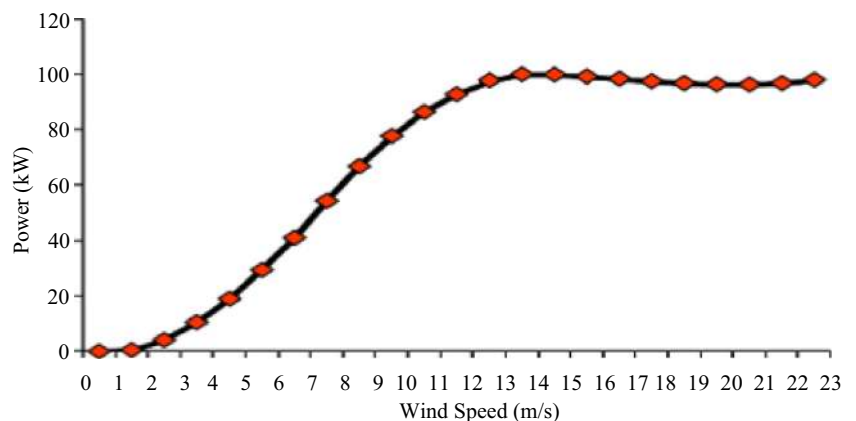**Fig. 8** Power characteristics of wind turbine

Table 4 Technical data of wind turbine

Technical Data	Value	Unit
Tower Type	Tubular steel monopole	
Rated Electrical power	100, 3, 400, 50	kW, phase, Volts, Hz
Rated wind speed	15	m/s
Minimum wind speed	2	m/s
Maximum wind speed	25	m/s
Extreme wind speed	59.5	m/s
Weight of rotor and nacelle	6500	kg
Rotor diameter	20.7	M
Height from the ground	37	M
Power factor	0.9 lagging to 0.9 leading	
Temperature	−20 to +50	°C
Life cycle	20	Years

$$SOC(t_k) = SOC(t_{k-1}) + \Delta SOC(t_k) \qquad (21)$$

Battery storage unit autonomy is defined as ratio of storage unit size and electrical load given by:

$$Batt_{Autonomy} = \frac{N_{batt}V_{bnom}Q_{bnom}\left(1-\dfrac{SOC_{\min}}{100}\right)(24h/d)}{P_{lprim,avg}(1000Wh/kWh)} \qquad (22)$$

Where, N_{batt} is number batteries in battery bank, V_{bnom} is nominal voltage of unit battery (V), Q_{bnom} is nominal capacity of unit battery (Ah), SOC_{min} is minimum SOC of battery bank, and $P_{lprim,avg}$ is average primary load (kWh/day).

Cost Components

Cost component includes cost involved in performing economical analysis of the system. It includes initial capital cost (C_{icap}), replacement cost (C_{rep}), annualized cost (C_{annu}),

Table 5 Technical data of battery bank

Technical Data	Value	Unit
Make	Gildemeister Energy Solution	
Model	Cellcube FB10	
Voltage (DC)	48	V
Voltage (AC)	400	V
Maximum charge current	200	A
Maximum discharge current	312	A
Nominal power	100	kW
Nominal capacity	2083	Ah
Round trip efficiency	64	%
Self discharge during standby	<150	W
Self discharge in tank	<1%	per year
Life cycle	20	Years

salvage value (C_{sal}), net system cost (C_{net}), and unit energy generation cost (C_{unit}). Initial capital cost is the purchase cost of equipments and establishment cost of the system. Replacement cost includes component replacement cost at the end of its useful life cycle. Replacement cost may be same as installation cost or differ as some part thereof may not have reached its life cycle. O&M cost is sum of major and miscellaneous expenses made for smooth functioning of the system during project tenure. Salvage value includes cost of system or component after completing its life. It depends on replacement cost, remaining life of component (T_{rem}) and rated life of component (T_{life}). Salvage value of each component is calculated as:

$$C_{sal} = C_{rep}.T_{rem}/T_{life} \qquad (23)$$

Life cycle cost (LCC) includes total cost of installation and operation for specified time span. It is important for financial evaluation of hybrid system and given as:

$$LCC = C_{icap} + C_{rep} + O\&Mcost + fuel\ cost - C_{sal} \qquad (24)$$

Other economic consideration includes annualized cost, operating cost, net present cost and levelized cost of energy.

Annualized Cost It includes annual cost components like capital cost, replacement cost, fuel cost, salvage value and O&M cost. It is likely to occur equally in every year of project life so as to give same net present cost as the actual cash flow associated with particular component. Annualized cost (C_{annu}) can be obtained by multiplying net present cost (C_{NPC}) with function of capital recovery factor ($C_{f,rec}$), given as:

$$C_{annu} = C_{NPC} \times C_{f,rec}(i_r, T_{proj}) \qquad (25)$$

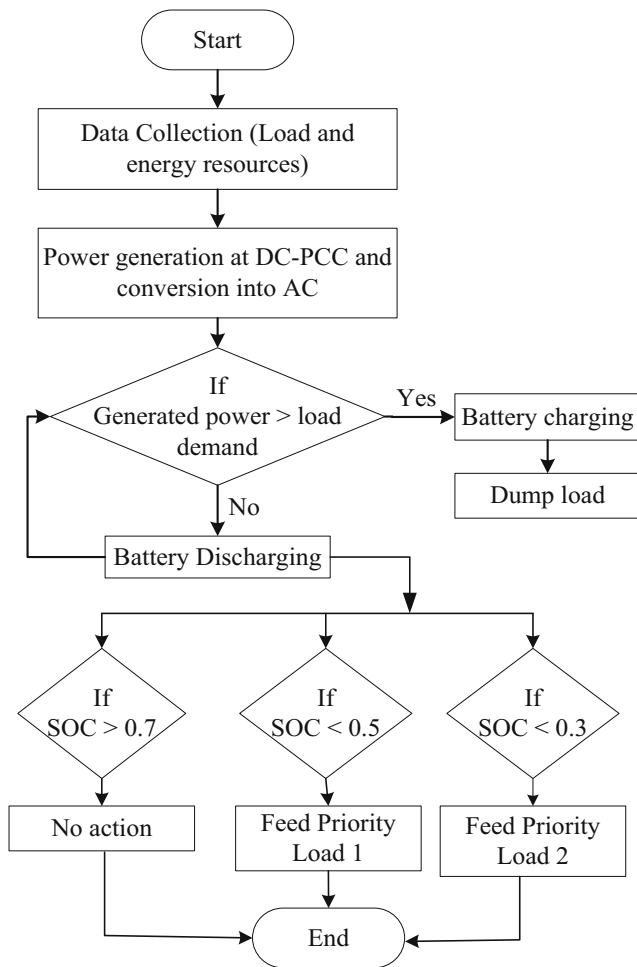Where, i_r is annual interest rate and T_{proj} is project lifetime.
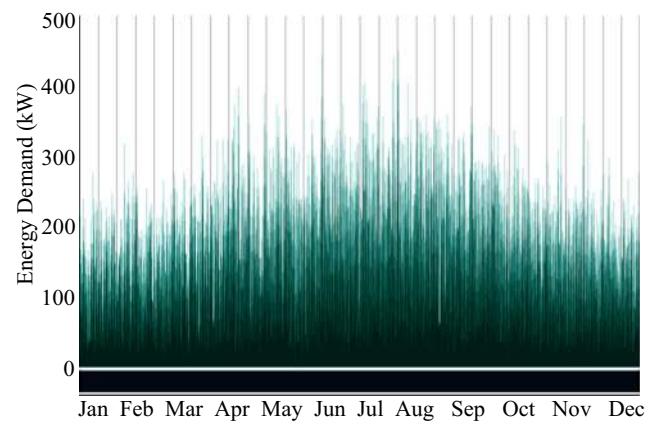
Fig. 9 Flow diagram of battery operation

Fig. 10 Average hourly energy demand (kW)

taxes and penalties. Revenues include salvage value and sales revenue. Thus economic analysis is done by ranking system as per their *NPC* and assume flat price rise over project tenure. *NPC* is given as:

$$NPC = \frac{C_{tot,annu}}{CRF(i_r, T_{proj})} \quad (26)$$

Where, $C_{tot,annu}$ is total annualized cost and *CRF* is capital recovery factor as a function of annual interest rate i_r and project lifetime. *CRF* is given as:

$$CRF(i_r, T_{proj}) = \frac{i_r(1 + i_r)^{T_{proj}}}{(1 + i_r)^{T_{proj}} - 1} \quad (27)$$

Net Present Cost (NPC) It is difference between present values of all costs that incur over its lifetime and present value of all revenue that it generates over its lifetime. Here, cost includes initial capital cost, component replacement cost within project tenure, *O&M* cost, fuel costs, purchase of power from grid,

Levelized Cost of Energy (COE) It is defined as the average cost per kWh of useful electrical energy generated by system. Annualized cost of generating electricity is divided by total useful electrical load served (E_{served}) to calculate COE and given as:

$$COE = \frac{C_{tot,annu}}{E_{served}} \quad (28)$$

$$E_{served} = E_{prim} + E_{deff} + E_{grid} \quad (29)$$

Where, E_{prim}, E_{deff} and E_{grid} are total amount of primary, deferrable and grid energy (if any) sold to grid respectively.

Table 6 Technical data of converter

Technical Data	Value	Unit
Manufacturer	Leonics Co. Ltd.	
Model	Appolo GTP-505	
Voltage	550	V
Power	90	kW
Current rating	340	A
Frequency	50	Hz
Power facto	>0.98	
THD	< 3%	
Temperature range	0 to 45	℃
Weight	873	kg
Life cycle	10	Years

Table 7   Input economical components

	Capacity (kW)/ Quantity	Capital Cost ($)	Replacement Cost ($)	*O&M* Cost ($)	Lifetime (Years)
TS250	1 kW	1100	1000	10	25
NPS100C	1 Unit	275,000	225,000	100	20
CCFB	1 Unit	2700	2700	5	20
BDI3P	1 kW	600	600	0	10

Table 8 Search pace to calculate optimal system configuration

BDI3P Capacity (kW)	CCFB String	TS250 Capacity (kW)	NPS100 Quantity
0	0	0	0
380	20	600	1
390	21	700	2
400	22	800	3
410	23	900	4
420	24	1000	5

Renewable Fraction (f_{ren}) It is defined as the fraction of electricity fed to load by RES. It is calculated as:

$$f_{ren} = 1 - \frac{E_{nonren}}{E_{ser}} \qquad (30)$$

Where, E_{ser} is total electrical energy served and E_{ninren} is electrical energy generated from nonrenewable sources.

System Components

HOMER is a flexible tool for modeling conventional and RES generation to estimate cost effective system configuration. The required input parameters includes hourly energy demand (electrical loads), RES (PV and wind), hourly metrological data (solar irradiance, wind resource), cost components (installation cost, replacement cost and *O&M* cost), generation unit size, type of dispatch strategy, life span, search space and sensitivity variables. Depending on input hourly data and system parameters, it simulates thousands of simulations to obtain optimal system in terms of generator size and economic considerations. Sensitive variables can be set for sensitivity analysis when parameters like cost of PV and wind turbine can be varied to estimate its impact on overall unit energy cost of the system.

The schematic architecture of studied hybrid system has been shown in Fig. 2. System consists of wind turbine, PV array, converter interface, battery bank and load. Components used in this study are 1 kW solar TATA TS250 model, 100 kW NPS100C-21 wind turbine, Leonics Applolo series converter, Cellcube FB series battery bank and referred as TS250, NPS100C, BDI3P, CCFB respectively. Wind turbine has dedicated converter to provide DC for common DC bus. DC power output of wind turbine and PV array is converted into AC by inverter to feed the load. If generated power is more than load demand, surplus power is fed to battery bank. Excess power is supplied to dump load, when battery bank get charged fully. Stored power in battery bank is delivered when load demand is more than available generation. DC bus has been connected to load center and inverter works as interfacing unit between generator and load center. For the sake of simplicity hourly load demand of each load station has been summed to be assumed as one unit. Thus overall system control becomes easy as generators are connected to common DC bus to feed single AC load via inverter unit and involves one dispatchable power source, i.e. battery bank.

Load Profile

HOMER uses time step load data of per minute (5,25,600 lines) or per 10 min (52,560 lines) or per hour (8760 lines). To obtain scaled data, it multiplies each time step baseline values by common factor to get annual average values.

Architecture				TS250 (kW)	NPS100C	CCFB	BDI3P (kW)	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)
				1,000	4	230	410	$ 0.238	$ 3.62M	$ 42,452	$ 3.07M
				1,000	4	230	420	$ 0.239	$ 3.63M	$ 42,807	$ 3.07M
				1,000	4	240	400	$ 0.240	$ 3.64M	$ 42,439	$ 3.09M
				1,000	4	230	430	$ 0.240	$ 3.64M	$ 43,161	$ 3.08M
				1,000	4	240	410	$ 0.240	$ 3.65M	$ 42,793	$ 3.09M
				1,000	4	230	440	$ 0.240	$ 3.65M	$ 43,516	$ 3.09M
				1,000	4	240	420	$ 0.241	$ 3.66M	$ 43,147	$ 3.10M
				1,000	4	230	450	$ 0.241	$ 3.66M	$ 43,870	$ 3.09M
				1,000	5	150	400	$ 0.241	$ 3.66M	$ 41,895	$ 3.12M
				1,000	4	250	400	$ 0.242	$ 3.67M	$ 42,779	$ 3.12M

Fig. 11 Size and cost optimization result

Table 9   NPC and annualized cost summary of system

Cost	Component	Wind	Battery	PV	DC/AC	System
Capital Cost ($)	Net	11,00,000	6,21,000	11,00,000	2,46,000	30,67,000
	Annualized	85,090	48,037	85,090	19,029	2,37,246
Replacement Cost ($)	Net	2,86,926	1,97,979	0	2,17,326	7,02,231
	Annualized	22,195	15,315	0	16,811	54,321
O&M Cost ($)	Net	5171	14,867	1,29,275	0	1,49,313
	Annualized	400	1150	10,000	0	11,550
Salvage Value ($)	Net	−1,61,701	−1,11,574	0	−29,466	−3,02,741
	Annualized	−12,508	−8630	0	−2279	−23,418
Total Cost ($)	Net	12,30,396	7,22,272	12,29,275	4,33,860	36,15,803
	Annualized	95,177	55,871	95,177	33,561	2,79,698

Here, common factor is obtained by dividing annual average value by baseline annual average. In this paper, hourly load profile of university campus has been taken. Load data is the actual load as obtained from energy meter reading for the months of the year 2014. Hourly load pattern has been observed for typical days and hourly load profile has been fabricated accordingly. Daily base load is estimated to be 32,154.4 kWh/day and average load of 133.98 kW with day-to-day random variability of 11.7%, time step random variability of 19.991% and load factor of 0.3. Annual average load found to be 3215.40 and peak load as 450.06 kW in the month of August. The obtained hourly load profile during months of year 2014 has been shown in Fig. 3. Table 1 provides summary of considered load site.

Energy Resources

Energy resources include solar and wind data for the entire year on hourly basis. HOMER facilitates monthly average data and it converts it into hourly meteorological data to carry out calculations. Meteorological data has been obtained from Synergy Enviro Engineers (India) Private Limited web data [44]. Monthly average solar radiation & clearness index and monthly average temperature is shown in Fig. 4(a) and Fig. 4(b) respectively. Average irradiance and wind speed of considered site is summarized in Table 2. Typical variation in solar radiation is found to be 4.140–7.440 kWh/m^2/day and average scaled annual of daily solar radiation as 5.69 kWh/m^2/day.

North-east Indian state Rajasthan is fairly rich in wind resource and application of wind turbine can reduce extra battery storage requirements. The average monthly wind speed in considered site varies in the range 2.40 to 4.67 m/s with annual average wind speed of 3.29 m/s. Monthly average solar and wind characteristics is shown in Fig. 5. If hourly wind speed data is not available, it can be generated synthetically from monthly average data with help of factors like Weibull factor 'k' (breadth of wind speeds distribution over the year), 1 h autocorrelation factor (wind speed strength in one time step as compared to wind speed in the previous time step), diurnal pattern strength (wind speed strength as compared to time of day), hour of peak wind speed (hour of day that tends to be windiest on average). In this study these factors are assumed as 2, 0.85, 0.25 and 15 respectively. Figure 6(a) shows average hourly area plot of wind speed for the location and Fig. 6(b) shows wind speed frequency distribution.

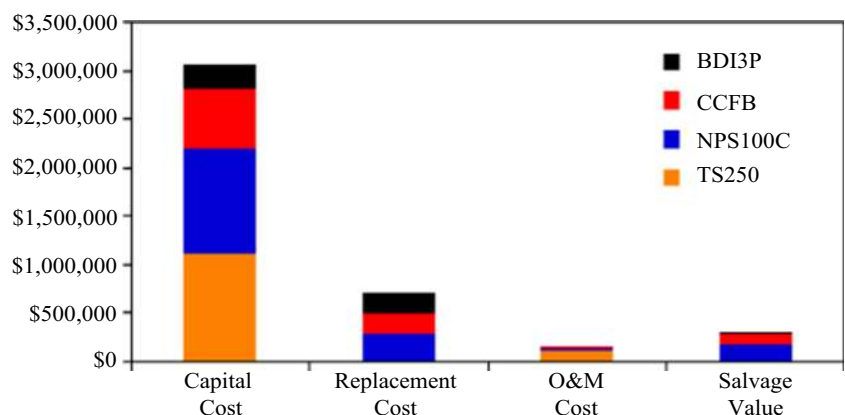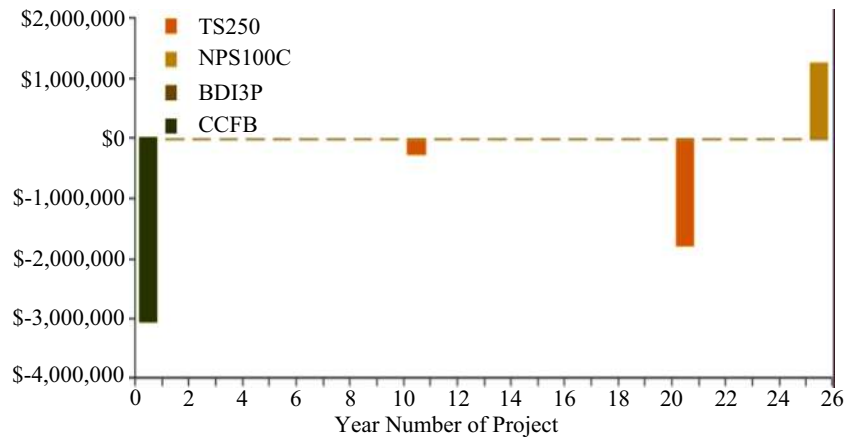**Fig. 12** Cost components of equipments involved in project

Fig. 13 Cash flow due to equipments involved in project

Photovoltaic Unit

Photovoltaic module (TS250) manufactured by 'Tata Power Solar' has been used in this study. Each unit has rated power rating of 250 W and consists of 60 cell poly-crystalline solar photovoltaic module. It has module efficiency of 15% and use efficiency of 95%. PV power output for global solar irradiance has been shown in Fig. 7. Manufacturing specifications of PV module has been given in Table 3. Maximum estimated irradiance (I_{em}) has been taken as 1000 W/m^2 with ground reflectance of 20%. Derating factor in this study has been considered as 80%. 1 kW PV module needs approximately 10–12 square meter of installation area.

WECS Unit

Selection of wind turbine depends on local wind speed and power curve of the turbine unit. In this case study, Northern power NPS100C-21 wind turbine has been taken. Figure 8 shows the power characteristics of considered wind turbine. Manufacturing specifications and economic considerations of this turbine have been given in Table 4. Depending on wind speed and power curve, power is generated for real time wind energy profile.

Battery Bank

Selection of size and type of backup unit is among key deciding factors for establishment of standalone unit. Storage unit ensures better reliability and fills energy gap between generation and load demand. Deep cycle battery is commonly used in standalone RES. Manufacturing specifications of the battery has been given in Table 5. Hybrid PV-wind generation reduces the need of backup unit up to an extent; thus reducing overall generation cost. Flow diagram of battery operation has been shown in Fig. 9. Battery operation is based on generated power, load demand and SOC of battery. When generated power is more than load demand, extra power is used to charge battery till battery gets charged to rated SOC and then supplied to dump load. When overall generation falls short, load demand is met by battery operation. Although proposed system is efficient to meet electrical load demand of considered site, but priority load provisions have been made for deficient generation and low battery SOC during typical time period. If SOC is more than 0.7, no action is required and load is fed by battery. If, SOC falls below 0.7, low priority loads are disconnected to ensure power security to priority load. In Fig. 9, priority load 1 consists of street lighting load, staff quarters, hostels, sport services and university departments; and priority load 2 consists of street lighting load, staff quarters, hostels, and university departments (excluding air cooling and heating loads). In this case study, overall load demand for year 2014 is met by proposed generation unit.

Converter

A power flow converter is used to maintain energy flow between DC and AC component. HOMER gives freedom to adopt bidirectional converter i.e. operation as bidirectional flow of active power. Converter needs input data in terms of relative capacity, efficiency, initial capital cost, replacement cost, *O&M* cost, lifetime of component and condition if it
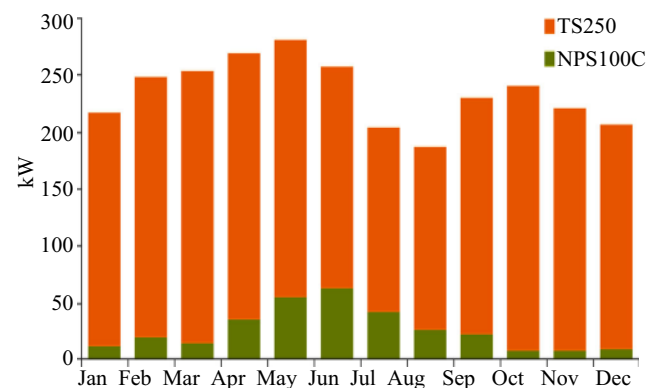

Fig. 14 Monthly average electricty production

Table 10   System components performance summary

| Quantity	Value	Units
Wind turbine		
Total Rated Capacity	400	kW
Mean Output	26.12	kW
Capacity Factor	6.53	%
Total Production	2,28,840	kWh/yr
Minimum Output	0	kW
Maximum Output	182.81	kW
Wind Penetration	19.50	%
Hours of Operation	8542	hrs/yr
Levelized Cost	0.42	$/kWh
Battery		
String Size	10	
Strings in Parallel	23	
Batteries	230	
Bus Voltage	480	V
Nominal Capacity	23,000	kWh
Usable Nominal Capacity	23,000	kWh
Autonomy	171.67	Hr
Lifetime Throughput	20,14,80,000	kWh
Battery Wear Cost	0	$/kWh
Average Energy Cost	0	$/kWh
Energy In	7,87,028	kWh/yr
Energy Out	5,04,820	kWh/yr
Storage Depletion	1403.60	kWh/yr
Losses	2,80,805	kWh/yr
Annual Throughput	6,31,025	kWh/yr
Expected Life	20	Yr
PV array		
Rated Capacity	1000	kW
Mean Output	207.64	kW
Mean Output	4983.40	kWh/d
Capacity Factor	20.76	%
Total Production	18,18,946	kWh/yr
Minimum Output	0	kW
Maximum Output	980.54	kW
PV Penetration	154.99	%
Hours of Operation	4380	hrs/yr
Levelized Cost	0.05	$/kWh
Converter		
Capacity	410	kW
Mean Output	133.94	kW
Minimum Output	2.78	kW
Maximum Output	410	kW
Capacity Factor	32.67	%
Hours of Operation	8760	hrs/yr
Energy Out	11,73,316	kWh/yr
Energy In	12,22,204	kWh/yr
Losses	48,888	kWh/yr
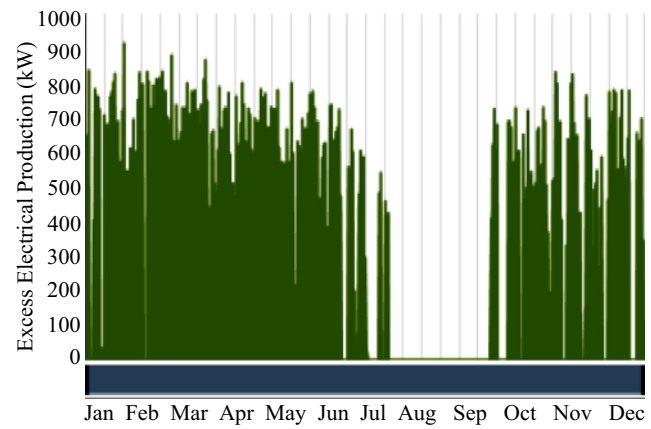
Fig. 15 Excess electricity generated (kW) by hybrid PV-Wind system

has to operate in parallel. Technical data of converter used as conversion unit has been enlisted in Table 6.

Simulation and Results

Hourly time series data is simulated to obtain economical and optimal sizing parameters. It calculates all possible configurations to obtain operational characteristics like annual electricity generation, annual load served, COE, NPC and renewable fraction; considering the metrological conditions, system efficiency and energy demand. Renewable fraction is 100% in this study. Figure 10 shows average hourly energy demand for entire year.

Economical Considerations

The input economical components are capital cost, replacement cost, O&M costs, fuel cost, salvage value and lifetime. In this study considered input economical and component life has been enlisted in Table 7. Project life time has been considered to be 25 years with discount rate of 8% and inflation rate of 2%. Since lifetimes of components like NPS100C,
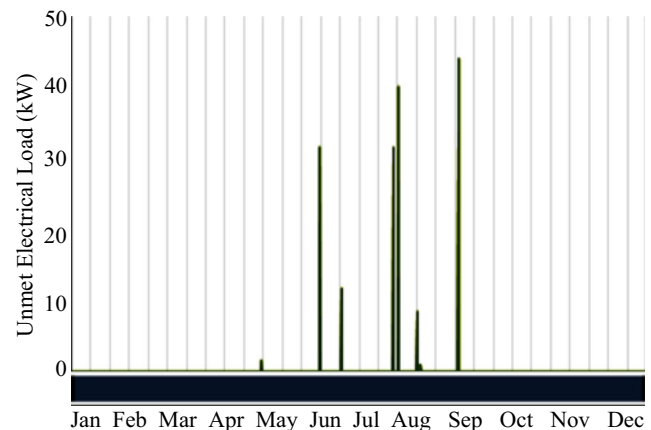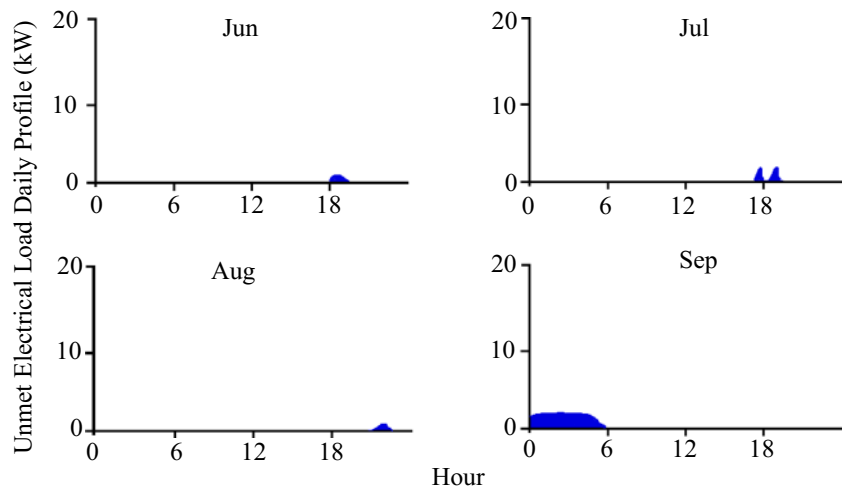

Fig. 16 Unmet electrical load (kW)

Fig. 17 Unmet electrical load daily profile during June to September

CCFB and BDI3P are less than project lifetime, as per manufacturer specification, these components have been replaced in order to complete the project tenure.

PV module generates DC electrical power when solar radiation is incident on it. Derating factor has been assumed to be 80% and ground reflectance of 20%. None of tracking system has been considered.

Search Space and Optimization Results

Search space provides population space to find optimal system configuration and component size in order to meet load requirement economically in terms of NPC. Search space depends on site meteorological condition and installation area limitations. Search space considered to obtain optimal results is shown in Table 8. Search space is initially defined with wide range and then the range is narrowed towards overall winner size. Winner size obtained in this study for BDI3P, CCFB, TS250 and NPS100C are 410 kW, 23 numbers, 1000 kW and 4 numbers respectively as shown in Table 8. Optimization results in terms of size and cost is shown in Fig. 11. First row of this figure shows results with lowest NPC of $3.62 M, COE $0.238, initial capital $3.07 M and O&M cost of $42,452. TS250 and NPS100C cover major part of capital cost.

NPC and annualized costs incurred in project execution has been given in Table 9. Cost components and yearly nominal cash flow has been shown in Fig. 12 and Fig. 13 respectively. In Fig. 13, each bar shows expenditure and income from components during project tenure. Negative bar shows expenditure i.e. outflow of cash. Bar at year zero shows capital cost and consecutive negative bars at 10th and 20th year shows expenditure towards component replacement. At the end of 10th year battery has been replaced while at the end of 20th year battery, wind turbine and converter has been replaced. Positive bar shows the salvage value of components at the end of project tenure.

Electricity Generation

Optimization results give annual production from PV, wind and battery as about 1,818,946 kW, 228,840 kW and 631,025 kW respectively. Monthly average electricity production has been shown in Fig. 14. PV and wind contribute to about 67.9% and 8.5% of total electricity served. Performance of system components has been summed up in Table 10.
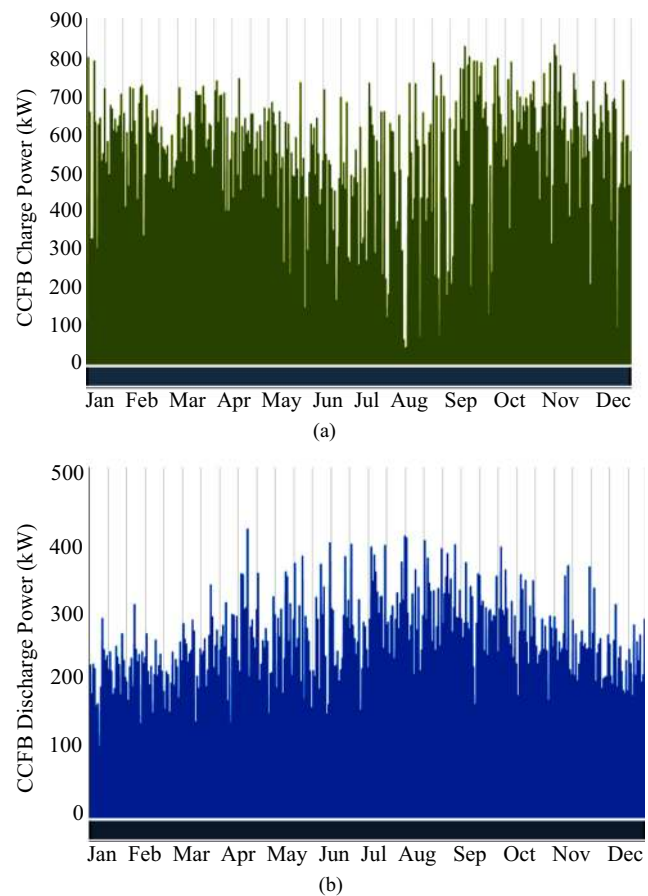

Fig. 18 Battery hourly (a) charging and (b) discharging

Excess electricity generated by hybrid PV-wind system is about 5,43,378 kWh/yr. and accounts to about 26.5% of total generated power as shown in Fig. 15. This surplus power can be supplied to water pumping station situated adjacent to university campus to pump and purify drinking water. Aside surplus power, Fig. 16 shows unmet electrical load which is about 305.2 kWh/yr. in the month of June–September. This is due to monsoon rain prevailing in north east Indian states during June–September. Unmet load is during non-academic working hours of university i.e. evening 6:00 p.m. to morning 6:00 a.m. as shown in Fig. 17. Capacity shortage of 1034 kWh/yr. has been recorded, which accounts to about 0.1% of total generation and can be compensated by battery unit. Figure 18 shows battery hourly charging and discharging power for the entire year. Deep cycle discharge battery has capacity to discharge to minimum value to meet load demand without affecting battery life and its further charge storing capacity.

Conclusion

The techno-economic feasibility of hybrid PV-wind generation system has been investigated for technical university campus, Kota, India. Real time load data has been analyzed. Proposed hybrid system lies in low wind region and wind energy contributes to only 8.5% of total served power. Solar energy needs larger space and needs to be established in open space to get exposure of sun light. These constrains does not affect wind turbines having sufficient ground clearance. Considerable amount of wind power has been generated during the month of April to September. Site location is rich in solar resource and PV power has contributed to about 67.9% of total served power.

No fossil fuel based power source has been considered in this study and thus renewable fraction is 100%. The COE found in optimization result is $0.238, which is less than present COE (grid connection with diesel generator) of $0.295 and likely to increase in near future. Obtained COE is competitive with hybrid PV-BSU-diesel system COE of $0.239/kWh [38], $0.413/kWh [11]; hybrid PV-wind-battery generation system COE of $0.488/kWh [39], $0.59/kWh-$0.61/kWh [26], $0.425/kWh [11]; and hybrid PV-BSU generation system COE of $0.073/kWh-$0.75/kWh [26]. Therefore, despite of lying in low wind region, proposed site is suitable for potential generation from RES. COE of renewable energy based generation approaches have been found to follow reducing trend in last decade due to improved efficiency and technical upgradation of conversion components. On the other hand, fossil fuel based generation have revealed increasing COE trend. Useful life of the components has been taken to standard rated period as prescribed by manufacturers and components can be used further with little or no maintenance, thus reducing net COE further.

Challenges and Opportunities

In this paper, standalone system has been proposed to meet load demand and its feasibility study. No any reserved provisions have been made during die period of BSU. Fuel cell has been found to be potential backup unit to overcome such requirements. Other shortcomings in widespread usage of RES based generation includes high manufacturing cost of conversion components, O&M cost, replacement of component after completing its life period, selection of conversion components, selection of backup ESU, proper disposal of equipments after completion of project tenure, suitable control unit, grid control, system stability, conversion losses, adequate load management, stochastic meteorological conditions, lack of technical skill among common user, lack of public interest and government policy. These factors need to be properly attended through performing adequate research in terms of technical improvements and techno-economic feasibility performance analysis.

High manufacturing cost is associated with longer payback time. Subsidization of the components by central to state government can reduce overall installation cost and help in increasing public interest. RES components have generally lower O&M cost, but need to be taken care of periodically to obtain optimal generation. Deposition of sand particles on solar panel can degrade conversion efficiency of PV module. Wind generators need periodic maintenance to avoid wear and tear due to deposition of dust particles or damaged part. Similarly, backup ESU unit need constant keen check-up to avoid damages due short-circuit or leakage of acidic/basic contents. Other inconvenience associated with ESU includes power packs, space requirement, disposal of parts after completion of useful life-time, and requirement of proper storage compartment to assure extended life of batteries. In order to ensure power security, storage and conversion equipments need to be replaced at the end of rated life-time as per manufacturer specification. However, actual life-time of component is generally more than rated life-time and extended component life can reduce overall COE. Conversion losses and component damage incurred in power converters are responsible in degraded efficiency of overall installed generation unit. Therefore conversion components need to be equipped with suitable and robust control unit to work satisfactorily under variable load and meteorological conditions. Aside these factors, optimal utilization of generated power is assured by proper grid control, load management policy and system stability in installed site location.

RES are of interest due to its environment friendly generation; and capability of operation under grid connected and standalone mode. Initial capital and dedicated land space requirement is the bottleneck for such project. Installation price of PV module and wind turbine have reducing trend and may likely reduce the initial capital burden.

Compliance with Ethical Standards

Conflict of Interest   Authors have no conflict of interest in publication of this article.

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